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# ESSAYS ON ECOLOGICAL ECONOMICS AND THE METABOLIC RIFT THEORY

CHANDNI DWARKASING

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**Supervisor:**
Prof. Simone D'Alessandro
**Scientific disciplinary sector:**
SECS-P/01

**Ph.D. Program coordinator:**
Prof. Michelangelo Vasta
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Signature

Digitally signed by
DWARKASING CHANDNI
KAELAH
C=IT

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# Contents

# List of Figures

# List of Tables

# Introduction

For anyone who has kept themselves informed on developments regarding climate change over the past two to five decades, 2020 has been a gripping year. Nations were stifled by the speed at which an universal threat encroached their citizenries. This led to a near-universal consensus that resolute actions had to be taken *fast*. Amidst rapidly increasing death tolls, medical workers found themselves in distress, confusion and short moments of praise and solidarity. Essential workers, too, kept the wheels spinning and risked their health for those staying at home. Some say that this type of conformity and adaptation to a collective risk is precisely what society need to stave off climate change. That is, to slow down the occurrence of hurricanes, droughts, landslides, biodiversity loss, soil erosion, rising tides, disease outbreaks and so on and so forth. Others argue that the COVID-pandemic should already be characterized as a climate change impact.

In *COVID-19 and the Circuits of Capital*, Wallace et al. (2020) describe how capital-led deforestation has drastically reduced the complexity of tropical forest ecosystems; impeding the extent to which viruses and pathogens encounter their "typical" host species. As a result, an increased variety of novel pathogens has been able to migrate from remote reservoirs into urban areas and capital cities. Clearly, this wide-scale reduction of ecosystem complexity went hand in hand with an increase in the complexity of the supply chains and trade networks that support commodity agriculture. On the one hand, the cultivation of crops and husbandry of animals with roughly identical genetic material accelerates the evolution of a pathogen's virulence. At the same time, the geographical lengths travelled by food commodities diversify and extend a pathogen's "host menu". Against this backdrop, the similarities between the COVID-19 pandemic and climate change are once again highlighted but from a different perspective. While the speed, with which COVID-measures were taken, showcase a desirable urgency with respect to climate change, these measures only represent a reaction to the *outcome* and not the *root-source* of the pandemic. In other words, the COVID-19 pandemic bears a closer similarity to a climate-change induced natural disaster event — one of many more to come.

Recent estimates show that policy measures against the spread of COVID-19 have led to a 7.1 percent decline in cumulative emissions compared to 2019; most of which is the result of suspended ground transport (United Nations Environment Programme, 2020: pp. 9). At the same time, the United Nations Emission Gap Report argues that 2020's unprecedented fiscal spending has thus far primarily supported the "global status quo of high carbon production".

If COVID-19 recovery packages are not used as a window of opportunity for the low-carbon transition, the estimated 2030 emission gap[1] will remain unchanged with respect to 2019. Apart from face masks, social distancing and online clubbing, climate change impacts are VIP's to society's latest spectacle called "the new normal". This brings us back to the necessary and COVID-like urgency required to *halt* the intensity of climate change impacts instead of merely dealing with their manifestation *post-factum*. In pointing out the *root-source* of disease outbreaks, a mass re-organization of agricultural trade and production seems paramount. Similarly, a significant reduction of climate change impacts seems to require a mass re-organization, or better yet an abandonment, of the fossil fuel industry. The burning question for anyone concerned about the climate then becomes: *how?*

While this is a question of cardinal importance, an answer is not present in the upcoming pages. This is not because an answer is not available. Quite the contrary: social movements, civil society, academia, think-thanks, governments and corporations are laden with creative, disruptive, feasible, utopian, democratic, technocratic, inadequate and effective recipes against disaster. Unfortunately, a great lot of these proposals have yet to be scaled up to significant levels, but both great and ignorant ideas *are out there*. Entire dissertations could be and have probably been written on the wide-range of climate policy proposals; estimating their effectiveness, in terms of the emissions gap for example, but also their local and international social impacts. Now more than ever, this research is necessary not only to curtail those daunting climate change impacts but to understand to what extent climate policies exacerbate, diminish or entirely eliminate the *other* side-effects of this burning socio-economic system.

If the upcoming pages fail to contribute to the above-mentioned research field, one may wonder if the precious printer ink on the paper you're reading or the energy spent in lighting up your screen has gone to waste. The answer to that curiosity depends on your interest in taking a step back from the observable and material realm into that of ideas and abstraction. Bearing in mind that climate change is but one, yet vigourous, material manifestation of the wicked configuration among economic production and ecological and biophysical processes — a not-so urgent question then becomes "what kind of abstraction processes govern the dominant portrayal of economic production with reference to ecological processes?" If abstraction is defined as the emphasis of one facet of a material phenomenon to the temporarily neglect of other facets, the aforementioned question can be simplified as follows: "how are economy-ecology configurations abstracted?"

The essays contained in this dissertation limit an exploration of the above-mentioned question to the realm of economics; (in)famous for its deployment of formal and mathematical

[1] The 2-degree emission gap for 2030 is calculated by subtracting estimated global greenhouse gas emissions as the result of the *full* implementation of nationally determined contributions from the global total greenhouse gas emissions resulting from least-cost scenarios that keep global warming below 2-degrees (United Nations Environment Programme, 2020: pp. 51)

abstraction as a method of analysis. At the moment, the two main fields that deal with ecological phenomena are Ecological and Environmental & Resource Economics. With reference to abstraction, one of the ways to distinguish the two fields is to argue that Environmental and Resource Economics relies more on orthodox economic theory and mathematically informed depictions of economy-ecology configurations. Whether the production or usage of a commodity causes air pollution, affects biodiversity or drives climate change, this kind of *interaction* with economic production is framed as a negative externality. The solution to the problem is formulated as the internalization of externalities. This would allow assumed rational agents to recalibrate their decisions on consumption and production by taking into account an additional cost which reflects the burden of the negative externality. A tax or subsidy on pollution is not only said to reduce production and consumption levels to a new optimum but also stimulates the development of technologies that eliminate or minimize the externality.

Ecological Economics on the other hand, a trans- and interdisciplinary field by birth, criticizes this determined faith in markets, optimizing agents and technological advances. Which is a reasonable critique given that carbon taxes, credits and offsets as well as renewable energy subsidies have thus far been unable to close that dreadful emissions gap! Instead of treating the economy in *isolation* and assessing what happens "outside of it", the more accurate abstraction according to Ecological Economics is to treat economic production as an activity which is *embedded in* and *intertwined with* biophysical and ecological processes. Such a portrayal requires an assessment of the characteristics of *the thing* the economic system is said to be embedded in. Doing so results in the delineation of limits to economic activity. The mere internalization of externalities which is supposed to lead to optimal allocations or technological advances is unable to guarantee that such limits are respected. In fact, Nicholas Georgescu-Roegen famously argued that when a system is characterized by the continuous transformation of low entropy into high entropy, the only way to guarantee extended survival is to *decrease* the scale of this transformation process. In other words, economic activity should falter, or as an increasingly prominent sub-strand of Ecological Economics argues: the economy should *degrow*.

Indeed, an increasing amount of scholarly works indicate that economic growth or the absolute size of an economy in terms of GDP has seized to be a significant determinant of planetary well-being. Yet, sectors such as advertising and marketing are heavily investing in the development of complex algorithms whose only aim is to increase the probability of consumption — a temporary cure for alienation. Ironically, in information theory, entropy can also be used with reference to the fact that customized advertisements on social media are increasingly able to predict an individual's consumption preferences. The higher the complexity of these preferences and thus lower frequency of patterns, the higher the entropic value of a prediction.

But training an algorithm results in thermodynamic entropy as well; think of the amount of data an algorithm must be fed (where and how is it stored?) as well as the energy required to "scrap" this data. And the outcome? A multifaceted increase in the intensity of the transformation of low entropy to high entropy material or waste.

To discuss the limits that economic activity or the ideology of economic activity is progressively provoking is one field of inquiry. Another field could be related to the *organization* of economic activity as society's known it for the past 300 years or so. Does capitalism, apart from accumulation driven throughput increases, bear secondary characteristics which determine the extent to which the production of commodities degrade ecological processes? So far, the field of Ecological Economics has predominantly (there are exceptions) engaged in the process of mathematical abstraction in order to elucidate the wicked trade-off between increased economic activity and ecological degradation. As alluded to in the previous paragraph, this has resulted in the generalized call to formulate alternatives which constrain economic activity but increase planetary well-being. It is possible to argue, however, that the *specificity* of capitalism in such formulations is partial. Of course, one key characteristic of capitalist relations of production is production for the sake of increasing the capacity to produce. Another, equally important characteristic is wage-labour and the idea of formal freedom and equality among "partners in exchange".

With emphasis placed on the latter characteristic, the selection of essays in this dissertation represents an attempt to amend the existing practice of mathematical formalization in Ecological Economics with considerations on the configuration between waged-labour and ecological processes. To do so would obviously require a consolidation between capitalism's greatest critic, Karl Marx, and the scientific assessment of ecological degradations. Luckily, such a consolidation already exists and is commonly referred to as Ecological Marxism (eco-Marxism). One of its fundamental concepts is the metabolic rift which represents the irreparable break between society's and nature's metabolism. Such a rupture can be addressed in terms of capitalism's tendency towards expansion but also in terms of the system's reliance on waged-labour and the significance thereof with respect to the state of ecological processes. The journey characterized by the aspiration to formally depict the metabolic rift in relation to both expansion and the *organization* is bumpy and non-linear. Each essay draws on both Ecological Economics and eco-Marxism to gain insights on how to achieve the aforementioned goal — this is their common denominator. In turn, their heterogeneity is the result of trial and error when it comes to the interpretation and formulation of eco-Marxism's versatility against the back-drop of Ecological Economics' common practice of mathematical formalization.

### A brief overview of the essays

With the above in mind, this dissertation organized as follows: the first essay, titled *Rifts, Shifts and Intermissions in Modern Considerations on Marx & Ecology*, offers an introduction to the modern synthesis between Marx & Ecology in the field of economics. Its aim is manifold; first it provides a summary of ecological/environmental critiques which took Marx's analysis of capitalism as given. Simply said, this meant that ecological degradations were treated as *yet another* negative outcome of an accumulation driven socio-economic system. As such, the essay argues that these "first-stage" economists developed and built upon Marx's ideas in order to provide an environmental and thus stronger critique of capitalism. With the worsening of environmental conditions across both capitalist and socialist nation-states, however, a burgeoning green movement came to denounce Marx on the basis of anthropocentrism and productivism. The economists who still engaged with Marx at that time either "ecologized/environmentalized" Marxist theory or "Marxified" ecological/environmental theory. This brings us to the second aim of the essay: to familiarize the reader with the fact that ecological considerations are far from absent in the writings of Marx. In essence, the second part of the essay summarizes Marx's metabolic rift theory by drawing on the works of sociologists and historiographers in the late twentieth century. This sheds light on Marx's insights with respect to the effects of both industrialization and waged-labour on ecological processes. The third aim of the essay is show that the application of the metabolic rift theory to contemporary environmental issues is wide-spread across various non-economic scholarly fields. Finally, the last section of the essay is dedicated to a discussion of world-ecology, a more recent iteration and adjustment to the metabolic rift school of eco-Marxist thought. In this section, it is argued that both schools of thought are useful and that precisely their dispute is trivial in the face of the aim to formalize eco-Marxist insights. A stronger iteration of this argument is presented in the third essay.

If the idea of a collapsed metabolism between society and nature forms the crux of Marx's ecological insights, it would be a mistake to disregard the scholarly works which engage with the concept of social metabolism. The second essay, *Considering the role of distribution: a conceptual adaptation to the MuSIASEM framework*, embarks from a deliberation on contemporary approaches to ecological degradations in the field of post-Keynesian Ecological Macroeconomics. While such approaches are compelling in that they offer a more accurate depiction of the capitalist economy than orthodox macroeconomics, their analysis of ecological degradations is limited to output-based greenhouse gas emissions. As mentioned in the first paragraphs of this introduction, agriculture, plays an equally important role when it comes to the drivers and impacts of climate change. This is why the essay proceeds to draw on the Multi-Scale and Integrated Assessment of Social and Ecological Metabolism framework to bring agriculture to the foreground of analysis. This is done with the aim to understand its compatibility with eco-Marxist insights. The third section of the essay is a short summation of eco-Marxism and it emphasizes the world-ecology concept of the ecological surplus. This is a ratio between appropriated and capitalized inputs and it is used by eco-Marxists to describe how the system-wide reliance on human and extra-human labour either speeds up or slows down capital accumulation. The third section offers a thorough introduction to the concepts that make up the MuSIASEM framework; social metabolism, thermodynamic principles, the distinction between stocks and flows and the treatment of socio-ecological systems as complex, adaptive and self-organizing. In the fourth section of the essay we introduce a hypothetical 3-sector economy and describe it from an eco-Marxist and MuSIASEM perspective in order to assess to what extent their abstraction processes are compatible. A conceptual adaptation to the MuSIASEM framework is presented to argue that the two abstraction processes can complement each other from a biophysical perspective. Eco-Marxism equips the standard MuSIASEM framework with a distributional component while MuSIASEM allows a quantitative assessment of ecological and biophysical processes. The various economic dynamics such as price-formation, competition, investments, international trade etc., however, are left unaddressed. Hence, the essay is concluded with the recommendation to direct future research into the realm of economic considerations on such dynamics. Furthermore, the paper over-emphasizes agriculture as a unit of analysis while disregarding eco-Marxist considerations on labour exploitation and alienation with respect to state ecological processes. So far, one can argue that the essays in this dissertation have i) introduced eco-Marxist insights and ii) sought to integrate core eco-Marxist concepts with *existing* approaches in the field of Ecological Economics. Apart from a concise introduction to post-Keynesian Ecological Macroeconomics, the actual status-quo of mathematical formalization practices in Ecological Economics has not yet been examined. This is precisely the gap the third essay aims to fill and it does so by contesting the way in which Ecological Economics distinguishes itself from Environmental & Resource Economics in its theoretical representation of economy-ecology configurations. In *An eco-Marxist reinterpretation of formal abstraction in Ecological Economics*, the reader is introduced to the *weak* and *strong* sustainability paradigms which differentiate themselves on the basis of theorized substitution possibilities between human-made and natural capital in economic production functions. This third essay can be complemented with an auxiliary essay found in Appendix B which treats the difference between *strong* and *weak* sustainability in economic modelling approaches. Instead, the third essay quickly proceeds to review the actual manifestation of an avowed triumph of the *strong* over the *weak* sustainability paradigm. It is argued that the call to conserve natural capital, given that it is treated as a complementary input to human-made capital, has nevertheless supported the monetary valuation of nature. After a short overview of carbon credits, carbon off-set projects and ecosystem service payments schemes the essay draws on literature on *commodification* in order to highlight how the aforementioned incentives are subject to contradictions. It then seeks to reiterate these contradictions bearing in mind world-ecology's concept of the ecological surplus and Marx's theory of the labour process. The ecological surplus treats the monetary valuation or commodification of nature as an instance of capitalization and some time is dedicated to discuss why the capitalization of previously appropriated ecological processes fits within the broader logic of capitalism. Thereafter, it is argued that abstraction of ecological processes through the concept of natural capital is an incomplete representation of economy-ecology configurations. This is because appropriated ecological processes, which most certainly *do* contribute to the production process, are not taken into account. Marx's theory of the labour process allows the essay to build upon this argument through its close consideration of the configuration among labour and ecological processes in terms of *material metabolism* and *purpose realisation*. The capitalization of appropriated ecological processes in the face of ecological degradations is then interpreted as an instance of *capital bargaining on behalf of nature* since purpose realisation remains intact. Perhaps what is truly necessary to redefine the contemporary and debilitated economy-ecology configurations is for *labour to bargain on behalf of nature*. The final section of the essay is dedicated to a discussion of *labour environmentalism* and *working-class ecology* in order to understand what that may look like. Moreover, it should be noted that this essay was written for an audience which is not as familiar with the field of economics. This is particularly clear in the sections which discuss the difference between *dualism* and *duality* and its application to economy-ecology configurations.

The final essay of this dissertation, *A computational approach to the metabolic rift in a 3-sector Sraffian model*, can be seen as a culmination of foregoing ideas, thoughts and deliberations. In essence, the essay comprehends an elementary attempt at translating these ideas to the realm of economic mathematical abstraction. With the aim of providing an alternative to Ecological Economics' status-quo, a 3-sector economy is described through a series of equations which showcase how an appropriated agro-ecological system is configured within the economy through waged-labour. Different than under the second essay, which engaged in a similar exercise but on a conceptual level, this essay provides a more complete representation of economic variables through the adoption of the Sraffian/neo-Ricardian/surplus approach. After a short review of the economic literature which substantiates the various assumptions presented in the succeeding set of equations, the results of a computational analysis based on external expansion shocks are discussed. The main novelty presented in this essay is the consideration of an appropriated ecological process and its interplay with economic reproduction and waged-labour. The way this appropriated ecological process feeds back into the production process is not as an input which *enters* the production function, but as a constituent of a technical coefficient. Furthermore, the behaviour of the agro-ecological system is modelled as the function of i) nutrients returned to the soil by the agricultural labour force and ii) the working conditions of the agricultural labour force. In a way, this represents a formal abstraction of the material metabolism and purpose realisation elements of Marx's labour process theory. Capitalization of the agro-ecological system is modelled as the deployment of fertilizers, which *enter* the production function and temporarily "enhance" the behaviour of the agro-ecological system but permanently disrupt the previously established configuration with waged-labour. Our computational analysis (simulation) allows us to assess the relationship between the intensity of an exogenous expansion shock, distribution, exploitation and agro-ecological degradation. Within the confines of our model, we find that the link between the intensity of expansion and agro-ecological degradation is mediated by the labour shortage strategies deployed by each sector. In this way we introduce an interpretation of ecological degradation where the *organization* of labour in production processes plays a significant role. We conclude the essay and thereby this dissertation with some short reflections on the relevance of this insight for climate change.

## Chapter 1

# Rifts, Shifts and Intermissions in Modern Considerations on Marx & Ecology*


### Abstract

Ecological disruptions such as climate change, pollution, waste build-up and rapid biodiversity loss are generally seen as the result of human activity; economically, socially and culturally determined. When it comes to the economy, heterodox macroeconomic tools and models are becoming prominent as they supply assessments/scenarios of the complex interactions between the the economy, climate change and climate change policies. At the same time, we witness the increasing recognition of the incompatibility between capitalism and ecological restoration among non-economists. Specific theories that criticize the ecological consequences of capitalism from a Marxist vantage point have yet to formally manifest themselves in the field of economics. As part of an effort to fill this gap, this paper provides an introduction to the modern synthesis between Marx & Ecology through a literature review from the 1950s onwards. In doing so we identify that a possible reason for the lack of considerations on Marx & Ecology in economics is due to the asserted incompatibility (by ecological/energy economists) between Marx & Ecology in the 1980s. By providing some insights that counter these accusations we hope to shed light on the conceivable benefit of these considerations in the realm of economics. Furthermore we distinguish between two theories that developed from the synthesis between Marx & Ecology. We contend that the so-called antagonism between the metabolic rift and world-ecology view is counter-productive from an economic point of view. All of the above, is to pave the way for an actual attempt at the economic formalization of the metabolic rift in subsequent research endeavours.



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## 1.1. Introduction

Nowadays, it is common knowledge that ecological disruptions materialize or are yet to materialize in various shapes and sizes. They may take place on a local, interregional or global scale and the main object of deterioration can be a body of water, land, forests, air, species or even a single microorganism. Regardless of the differentiation, the main point is always that human activity is causing fissures in the natural system humanity itself depends on. Doubtlessly, one of the most recognized set of ecological disruptions is climate change — the accumulation of greenhouse emissions predicted to severely disturb the stability of the earth's weather and climate patterns. Each increase in the average temperature compared to pre-industrial levels, augments both the risk and intensity of irreversible changes.

The IPCC, one of the leading intergovernmental bodies in charge of scientifically assessing the current state, impacts and risks of climate change, has recently estimated that human activity will cause a 1.5°C increase of average global temperatures between 2030 and 2052. Historically accumulated emissions in the pre-industrial era are said to be one of the causes of long-term changes in the climate system but they are not the only factor driving the global average temperature increase to 1.5°C (Masson-Delmotte et al., 2018). In order to prevent an increase in the risks, uncertainty and vulnerability, society as a whole will need to drastically *reduce* the additional amount of greenhouse gas emissions.

This isn't breaking news for anyone who is slightly familiar with ecology, environment and even economics. In fact, from a macroeconomic perspective, the various schools of economic thought have each treated ecological disruptions and climate change from their own theoretical vantage points. Perhaps, one of most obvious distinctions is that found between integrated assessment models used by neoclassicals (Farmer et al., 2015; Hassler and Krusell, 2018), computable or dynamic-stochastic general equilibrium models used by new-Keynesians (Babatunde et al., 2017; Cai et al., 2015) and system dynamics, input/output or (agent-based) stock-flow consistent models used by post-Keynesian economists (Hardt and O'Neill, 2017; Rezai and Stagl, 2016). On the basis of the distinction between strong sustainability and weak sustainability, one can associate post-Keynesian models with Ecological Economics (EE) while the neoclassical and new-Keynesian models are associated with Environmental Economics (Munda, 1997).

The bulk of these models highlight i) the ecological consequences of economic activity, ii) the effect of ecological disruptions on the economy in terms of the prospective impacts on infrastructure and natural resource availability and/or iii) the economic implications of climate change policies such as taxes, subsidies, tradeable permits and green financial instruments. Other more radical scholars in the field of EE accentuate that ecological deterioration is simply the certain and sustained outcome of any economic paradigm which is centered around growth. As a consequence, the only way an economy can minimize ecological damage is either to stop growth and shift to a post-growth paradigm (Anderson, 2012; Antal, 2018; Booth, 2006; Daly, 2016; Jackson, 2019; Johnsen et al., 2017) or to reverse growth completely and shift to a degrowth paradigm (D'Alisa et al., 2015a; Kallis et al., 2018; Martínez-Alier et al., 2010; Schneider et al., 2010; Weiss and Cattaneo, 2017). Post-growth is usually seen as an umbrella term for the general idea that the economy cannot sustain infinite growth on a finite planet while degrowth represents a specific strategy of post-growth.

One can also argue that post-Keynesian Ecological Macreoeconomics is seemingly receptive to post-growth approaches since their research considers different growth types, e.g. green vs. brown growth, as well as policies that reduce working time (D'Alessandro et al., 2018; Jackson et al., 2016; Monasterolo and Raberto, 2018). Although these approaches are highly relevant in that they challenge the body of orthodox economic thought, they seldom focus the relationship between the economy as a *capitalist* system and its biophysical environment. Conceivably, this is the result of the fact that academia has long thought that Marx & Ecology were two separate and starkly opposed scientific domains. Yet, over the last 30 years, scholars outside the economic field have wrought their way to demystify this hypothesis and assert that Marx's analysis of capitalism is just as much of an analysis of ecological degradation (or a at least a good starting point).

The above-mentioned argument is what constitutes the main topic of this paper. Its first aim is to provide the reader with an overview of the myriad considerations on Marx & Ecology in a limited period ranging from the 1950s to the 2010s.[1] We argue (in truth, the paper is structured in this way) that while early and relatively incomplete considerations on Marx & Ecology managed to find their way in the publications of economists, the particular break between Marxist Economics and EE around the 1980s and 1990s *pushed* economists away from a later synthesis. This is arguably why this synthesis is currently limited to the field of politics, sociology, anthropology, history, geography and philosophy. In fact, with the passage of time, the most renowned considerations on Marx & Ecology are currently found in two separate spheres - the *metabolic rift theory* and the *world-ecology theory*. We contend that the tension between the metabolic rift theory and world-ecology theory, even if valid in the aforementioned scientific fields, could potentially be eased by an abstraction process which is grounded in the field of economics. In this way, we hope to set the stage for future research which could motivate the benefit and examine the possibilities of formalizing the synthesis between Marx & Ecology.

In order to arrive at this point, Section 1.2 introduces a historical division of literature on Marx & Ecology (found in: Foster et al., 2017: pp. 1-12) and elaborates how respective authors conceived the interaction between ecological crises and capitalism. Throughout the section,

[1] For an overview of late 19th and early 20th considerations on Marx & Ecology, we advice the reader to consult Franco (2018).

a distinction is made between early first-stage and late first-stage scholars writing on Marx & Ecology. In Section 1.3 we describe the way in which second-stage scholars arrived at the metabolic rift theory. This is done by highlighting some of Marx's most important passages with respect to ecological degradation under capitalism.

Section 1.4 is dedicated to a review of scientific literature which has applied the metabolic rift theory in its analysis of ecological disruptions and restorations. Section 1.5 highlights an alternative approach to *the metabolic theory* called world-ecology; we provide a general introduction to this approach and highlight the main differences between the approaches. Finally, Section 1.6 concludes and summarizes the authors' main reflections on i) the possibility of economically formalizing the metabolic rift ii) the ineffective character of the dispute between metabolic rift and world-ecology in light of economic formalization and iii) the main challenges for future research.

## 1.2. First-stage considerations on Marx & Ecology

> *Only in the proportion as our movement progresses and demands the solution of new practical problems do we dip once more into the treasure of Marx's thought, in order to extract therefrom and to utilize new fragments of his doctrine.*
>
> - Rosa Luxemburg and Waters, 1970: pp. 111

As mentioned in the introduction, we commence our review of Marx & Ecology by regarding how an environmental/ecological critique of capitalism was brought forward by economists in the period ranging from the 1950s to the 1970s. We limit this review to the field of economics since the broader aim of this paper is to awaken interest in the economic formalization of Marx's ecological insights. Having this in mind, it made sense to explore whether and how any of these insights found their way in the field of economics.

The quote at the beginning of this section is meant to highlight (as did Foster et al., 2017) the fact that the application of Marx's scientific achievements is so vast that its various specificities would only re-emerge in parallel to the maturation of capitalism's contradictions. Thus, it shouldn't be a surprise that Marxist ecological thought had started to gain momentum alongside the development of the environmental movement in 1960s and '70s. This established what this paper refers to as the *first-stage* of the synthesis between Marx & Ecology: a pre-figurative phase in which these considerations had not yet been consolidated as distinct fields of inquiry. Ibid, 2017 have identified a break in this first-stage and consequently divide it into two sub-stages. We follow this division and present subsections that discuss the *early* and *late* first-stage deliberations on Marx & Ecology by economists.

### 1.2.1. Early first-stage

Characteristic of early first-stage considerations is that the convergence between Marx & Ecology was perceived as an organic evolution of his critique. This meant that the considerations paid little attention to whether Marx did or did not treat ecological degradation in his own works.

**Kapp on social cost theory**

One of the earliest formulations of environmental disruption in an anti-capitalist framework is that of the economist William K. Kapp in the publication *The Social Costs of Business Enterprise* from 1950. Kapp's formulation of social costs is derived from the American School of Institutional Economics which became particularly renowned through Thorsten Veblen's insights into the institutions of American capitalism. Kapp argued that social costs reveal the *mis-allocation* of resources which is the result of institutionalized economic calculus that; inducing economic agents to take insufficient account of the harmful effects of their production and investment decisions (Berger and Forstater, 2007). The way Kapp treats social costs closely echoes Marx's description of capitalism as a class-based society:

> *... political history of the last 150 years can be interpreted as a revolt of large masses of people (including small business) against social costs ... an integral part of the gradual access to political power by groups formerly excluded from such power ...*
>
> - William Kapp, 1950: pp. 15-16

One can argue that Kapp's Marxist political economy approach to social costs embeds a critique of the treatment of social costs by welfare economists at that time. More specifically, the promotion of marginal corrections (of social costs) by the principle of compensation. Kapp's approach emphasized the interaction between economic processes and technological change, sociological perception, anthropological development and more importantly legal and political institutions; each of which putting weight on the shape and form of social costs. Moreover, Kapp argued, without formally accepting the labour theory of value, that Marx's theory of surplus value already implied a concept of social costs (Ibid, 1950: pp. 32).

This heavily compressed exposé of Kapp's "social cost theory" aimed to show that he found merit in the general ideas of Marx without digging into its concrete ecological aspects. At the same time however, in *Chapter 8: Social Costs in Resource Utilization: Evidence and Estimates* Kapp spends a paragraph discussing Marx's treatment of land in agricultural production systems. He mentions how the dependence of farmers on market prices ultimately encompasses "the robbery of the soil". This discloses that Kapp understood the main gist of Marx's account of ecological disruptions in his critique of capitalism.

### Tsuru on environmental disruptions and economic regimes

In a short homage by Suzumura (2006), Shigeto Tsuru is described as one of the greatest political economists and a highly influential opinion leader in post-war Japan. Tsuru's academic contributions to the field of economics are widespread across topics, one of which was environmental disruptions and the design of economic policies to deal with their emerging urgency. Suzumara notes that Tsuru was explicitly interested in the scientific analysis of the causal link between the environment and the economic regime. For example, Tsuru stressed that a break from market mechanisms was necessary to ensure effective measures against environmental degradation. Much of Tsuru's key-works in this area are focused on the scientific analysis of pollution and energy use in Japan. In *Environmental Pollution Control in Japan*, found in Tsuru (1994), we can highlight a particular quote that expresses how he related environmental disruption to economic regimes from an anti-capitalist perspective:

> *The question of spillover effects or external dis-economies is not independent of the institutional characteristics of the particular economy concerned. Japan's economy is that of capitalism where private capitalistic firms constitute the basic autonomous units of activities.*
>
> - Shigeto Tsuru, 1994: pp. 292

It is evident that much like Kapp (1950), Tsuru regards environmental disruption from an institutional economic vantage point. This is clear in his treatment of environmental disruptions in light of the global *North-South* division. His contribution *"North-South" Relations on Environment* in (Tsuru, 1994) was a response to the United Nations Conference on Human Environment in 1972. In it, he highlights the benefits as well as the difficulties of coordinating a world-wide approach to environmental issues. He also considers the necessity to combat "hidden information" as the result of industrial secrecy — a strategy used for the expansion of knowledge on favourable technical coefficients of various materials used in production processes. As a response to this phenomenon, Tsuru proposes a centrally-planned economy, claiming that a socialist firm, unlike a competitive capitalist firm, would not experience disadvantages in making industrial details public.

### Sweezy on urbanization as a catalyst of accumulation

Another economist in the Marxist tradition who dedicated some of his writing to discuss the environment was Paul. M. Sweezy. In his article *Cars and Cities* from 1973, he confronts Marx's treatment of technology in *Capital Volume I*. He argues that while it succeeds in the provision of a discussion of technological impacts on the means of production, it fails to address consumption and its subsequent influence on the process of accumulation and development. For Sweezy (1973), it is obvious that technological change involves fundamental alterations in societal consumption patterns; resulting in far-reaching consequences for the functioning

of the global capitalist system. To illustrate this argument Sweezy discusses the political economy of the motor car ever since its introduction in the United States. He argues that its mass-commodification, as a result of technological change, spurred capitalist expansion and accumulation beyond the car-manufacturing sector itself. Expansion was also experienced in the manufacturing industry, the services industry (e.g. wholesalers of vehicles, gasoline stations and repair facilities) and the construction industry in charge of road construction.
While Sweezy only briefly mentions the impact of auto-mobilization on environmental pollution, he dives deep into the transformation of strict country-city *borders* into *spheres*. The latter are characterized by decreasing urban densities as one moves away from their core. As a result, the economy and society adjusted to the pushes and pulls of the accumulation process in a more rapid and complete way. This is what Sweezy conclusively coins as a self-reproducing cumulative process, where the movement of residences stimulates the movement of jobs which in turn stimulates the movement of residences.
The main gist of Sweezy's, somewhat cloudy, considerations on Marx & Ecology lies with the observation that the spread of the car and its fossil fuel reliance heightened existing ecological degradation and subjected the countryside to *additional* ecological degradation as a result of relocated business activity.[2]

This concise overview of first-stage economists indicates that the treatment of Marx & Ecology was done in a way which barely scratched the surface of the inherent ecological critique carried forward by Marx himself. Furthermore, attempts to either include ecology in a theoretical model à la Marx or to include Marxist considerations into a green theoretical model are absent. Instead, each of the aforementioned economists are exceptional in their own development of Marx's ideas as a way to construct a modern and stronger critique of capitalism. It just happened to be that they were also strongly aware of capitalism's co-determination of environmental destruction. By the late 1970s and early 1980s, however, the relatively ease with which anti-capitalist ecological critiques were made, dissolved. And this for reasons mentioned in the following subsection.

### 1.2.2. Late first-stage

The seemingly natural relationship between capitalism and environmental decline experienced a compelling shift with the emergence of "green theories" in the late 1970s and '80s. Particularly the ascent of *deep ecology* introduced by Naess (1973) and the *Gaia Hypothesis* by Lovelock

[2] In a later publication from 1988 and republished in 2004, Sweezy writes more clearly on the processes of environmental detoriation in relation to capitalism. He writes: "As far as the natural environment is concerned, capitalism perceives it not as something to be cherished and enjoyed but as a means to the paramount ends of profit-making and still more capital accumulation" (Sweezy, 2004). The reason a deeper treatment of Sweezy's ecological and Marxist contemplations were excluded from the main-body of this text is because these were written at a later point in time. Even though the above quote clearly reflects the organic and natural way in which ecological crises are seen as an outcome of capitalism — characteristic of the early first-stage

(1979) popularized the idea that only the entire removal of industrial civilization would allow the earth to return to its natural state. At the same time, this period is characterized by i) the ever-growing tendency on the left to denounce the USSR's vast industrialization and related pollution and ecological rampage Komarov (1981) and ii) the association of Marx with anthropocentrism (Catton and Dunlap, 1980; Lee, 1982). Much of these critiques and insights solidified into activist movements and intellectual currents characterized as *The New Left* (Davis, 2017; Kitschelt and Hellemans, 1990). Because late first-stage thought on Marx & Ecology essentially depicted Marx and the environment as starkly opposed to each other, the scholars who still engaged with the works of Marx either implanted Marx's theory into ecological theory or implanted ecological theory into Marx's theory — thus taking for granted Marx's own ecological considerations (Burkett, 2006; Foster et al., 2017, 2011).

**O'Connor's second contradiction**

One of the most notable late first-stage scholars was James O'Connor, a sociologist, economist and co-founder of the journal *Capitalism, Nature, Socialism: A Journal of Socialist Ecology* launched in 1988. Up to this day, the journal publishes peer-reviewed articles on political ecology with an eco-socialist perspective. O'Connor is famously known for the formulation of the *second contradiction of capitalism*, which serves as an example of how Marx's contribution was "greened" to fit the emergent ecological problems at the time. The *first contradiction* states that when individual capitals try to defend or recover profits through an increase of labour productivity or a cut in wages, the unintended effect of such a process is a reduction of consumer demand (Dunn, 2011).

Variously, the second contradiction has to do with the undermining of "conditions of production" such as human labour power, external nature and the built environment. This subversion increases the costs of production and thereby generates supply-side tendencies for economic crisis (O'Connor, 1994). Differently said, in traditional Marxist theory, the first or primary contradiction between production and the attainment of value takes the shape of a "realization crisis" or the overproduction of capital. According to the second contradiction theory, economic crisis can also take the shape of a "liquidity crisis" or the underproduction of capital (translated from: Ibid, 1989: pp. 17).

In the development of this "second contradiction theory", O'Connor draws heavily on Polanyi's discussion of capitalist growth and how this impairs or destroys capitalism's own social and environmental conditions (see Polanyi, 1944). According to O'Connor, this insight was heavily neglected in Marx's original writings:

> *In sum, Marx believed that capitalist farming (for example) ruined soil quality. He was also clear that bad harvests take the form of economic crisis. However, (...) he never considered the possibility that ecologically destructive methods of agriculture might raise the costs of the elements of capital, which, in turn, might threaten economic crisis of a particular type,*

> *namely, underproduction of capital. Put another way, Marx never put two and two together to argue that "natural barriers" may be capitalistically produced barriers, i.e., a "second" capitalized nature. In other words, there may exist a contradiction of capitalism which leads to an "ecological" theory of crisis and social transformation.*
>
> - James O'Connor, 1988: pp. 14

Having extended the Marxist theory of contradiction and crises in an ecological manner allowed O'Connor to further theorize that if capitalism is both crisis-ridden and crisis-dependent; the second contradiction stemming from ecological crises is able to push capitalism into more social forms of productive forces and relations (O'Connor, 1988). All in all, the theory of the second contradiction is quite powerful given that one could argue its logic is apparent in e.g. insurance against climate change impacts. At the same time however, it places a mountain of faith in the ability of capitalism to recognize ecological crises as not only a threat to its functioning but a *result* thereof. Perhaps this misplaced faith is related to the significant momentum gained by international environmental movements and the belief that this would lead to ambitious efforts. Unfortunately, in 2019, we have yet to witness supply-side crises that induce significant changes in the social relations of production.

**Martinez-Allier on Marx's negligence of energy flows**

Joan Martinez-Allier is a highly distinguished Spanish economist whose contributions in the field of EE are very much inspired by scholars who considered the relationship between energetic flows and the economy (see Georgescu-Roegen, 1971; Podolinsky, 1883; Soddy, 1924). In a publication co-authored with J.M. Naredo in 1982, Martinez-Allier extensively discusses Sergei Podolinsky and his contribution to Marxist economics from an energetic point of view. Contrary to O'Connor, Martinez-Allier does not explore a green extension of Marxist theory but explores the compatibility of Marxist theory with green theory (which in this case particularly refers to the study of energy flows within the economy). The article is structured such as to build the argument that energy analyses are rather difficult to fit into the Marxist framework since it i) treats the economy as a closed system ii) holds on to a theory of value which does not allow integration with quantities of energy and iii) is based on the works of Marx and Engels who are said to have believed that economics should not be mixed up with physics and thus discarded the "socio-energetics" of Sergei Podolinsky (Martínez-Alier and Naredo, 1982: pp. 208).

According to Martinez-Allier & Naredo, Marx's main contribution to the analysis of natural resources is said to be purely Ricardian (not ecological), since it fixates on land rent and how this pays the land-owning class. Engels, on the other hand, is said to have scorned Podolinsky's attempt to give an energetic foundation to the labour theory of value. Given the importance of energetic analyses in EE and bio-economics, the negligence of Marx &

Engels allows us to conclude that later Marxists were incapable of "greening" the theory due to both epistemological and ideological obstacles Martínez-Alier and Naredo (1982: pp. 219).[3] Martinez-Alier was also among the first to publish a monograph on the relations between economics and the study of the flow of energy in human societies and ecological systems; one of the key-tenets in the field of EE. In it he dedicates a section to discuss Marx & Ecology, closely resonating what was mentioned above though in a more expansive fashion. He mentions Marx's considerations on the metabolism between man and the earth and how Marx was in favour of small-scale agriculture (Martínez-Alier and Schlüpmann, 1990: pp. 218-225). But the crux of the argument remains Marx's thoughtlessness on energy flows (his expression of the metabolism between man and the earth only referred to nutrient cycles).

Furthermore, Martinez-Allier mentions that Marx's *Critique of the Gotha Programme* from 1875 propagates the idea that production only increases according to the development of the productive forces which capitalism would, at some point, be unable to deliver. Socialism, in contrast, would allow infinite development. It is on the basis of this statement that Marx additionally gets discarded as anti-ecological or "Promethean": disdaining the biophysical limits to any socio-economic system, be it capitalism, socialism or communism.

**Bunker on ecological unequal exchange**

Intimately related to energy flows and their importance in the field of EE, is the development of ecological unequal exchange in the 1980s; an extension of the Marxist notion of unequal exchange between "developed" and "developing" countries (see Amin and Pearce, 1976; Emmanuel and Pearce, 1977). Theorists of unequal exchange drew directly from Marx's realization that unequal exchange is not only restricted to the relationship between capitalists and workers (in the sphere of production), but also occurs between different nations as a result of product differentials (in the sphere of trade). Marx said: "One of the nations may continually appropriate for itself a part of the surplus labour of the other, giving back nothing for it in exchange ..." (Marx, 1973: pp. 791). This led scholars at that time to engage in in-depth quantitative analyses of the trade between nation-states and with particular regard to colonial and post-colonial relationships. Closely related to the examination of dependency between core and periphery are e.g. the observations made by Singer (1950), Prebisch in: United Nations and Economic Commission for Latin America (1950) and Ibid, 1959.[4]

The theory of ecological unequal exchange took inspiration from Marx but ultimately deemed his quantitative method based on the labour theory of value as deficient and anti-ecological. An

[3] The critique of Podolinsky raised by Martinez-Alier is an interesting one and the reader is invited to read Chapter 6 in Burkett (2009a), Chapter 2 in Foster et al. (2017) and Foster and Holleman (2014) for some counter-arguments to the claim.

[4] It is argued that the authors of the "Prebisch-Singer Hypthesis" never explicitly based their theories on Marxist conceptions (Love, 1980). Instead they were more inspired by Ricardo and Keynes and are nowadays seen as major contributors to the structuralist school of economic thought. This is to show that meaningful accounts on global relationships were far from restricted to Marxist analyses.

example is the work of Stephen G. Bunker in *Underdeveloping the Amazon: Extraction, Unequal Exchange and the Failure of the Modern State*. This publication argues that the development or underdevelopment of regions is i) the result of the combination, coordination and organization of both human and nonhuman energies and ii) the distribution of resources derived and/or transformed in the region's environment or iii) the distribution of traded resources derived and/or transformed in other regions. In this context, Bunker (1988) deploys a distinction between productive and extractive economies. He maintains that economic theory had only been successful in analytically describing industrial production systems while neglecting the extractive origins of the materials the industrial processes had to transform.
Bunker goes on to argue that the internal dynamics of underdeveloped extractive economies are based on the exploitation of natural resources. This destroys the values which are embedded in the energy and material which measures of labour or capital are unable to represent. The destruction and loss of this value occurs as a result of global trade relationships and degenerates an extractive region's economy while the resource-consuming productive (industrial) economy prospers. This is the essence of an ecologically unequal exchange where "value" is no longer measured in terms of labour time, but in terms of energy flows.
Lonergan (1988) presents a comparison between a Marxist and energetic theory of value in the assessment of unequal exchange. The argument that Marx and Marxists had thus far not carefully considered the thermodynamic nature of the economy is what inspires him to devise an energetic theory of value. Apart from that, he asserts that the fundamental dilemma between Marxists and environmental/ecological scientists is that the former treat resources and the natural environment as external elements to the mode of production that utilizes them. The latter sees society as but one element in the whole of nature. Concluding: "We are not, then, able to relate Marxist perspectives with those of environmental scientists; they are ideologically variant and diametrically opposed" (Lonergan, 1988: pp. 130). The author arrives at an additional conclusion, however, through the provision of an account of the myriad quantitative methods used for the estimation of unequal exchange (in terms of labour or energy). He mentions that Marxists and "energy economists" ultimately arrive at the same conviction. Namely, that developed economies import more labour and embodied energy than they export. Thus the exchange of commodities at their prices by no means implies that they exchange at an equal "value". The bottom line being a dispute on the "correct" determination of value.

The current inquiry into first-stage literature on Marx & Ecology, allows us to draw a clear distinction between its *early* and *late* sub-stages. The early stage roughly treated environmental and ecological problems as an outgrowth of capitalist development without questioning whether Marx was ecologically enlightened enough or whether an ecological concern could fit in a Marxist economic framework. The late stage is characterized by the exposition of shortcomings in Marx's writing and suggestions that Marxist economic theory should either be broadened or discarded. The latter is based on the argument that Marxist economic theory is insufficiently compatible with a thorough ecological characterization of economies. It is exactly these statements that have subsequently been challenged by scholars who considered Marx & Ecology in the second-stage. The result of their deliberation is what ultimately led to the establishment of what is now referred to as eco-Marxism. A handful of scholars arrived at the conclusion that Marx's writings were inherently ecological by means of the metabolic rift theory; this concept will be the main subject of the following section.

## 1.3. The Metabolic Rift Theory

Second-stage literature on Marx & Ecology can be summarized as one that provided an anti-thesis to the late first-stage conclusion of "limited or no compatibility" between Marx & Ecology. Profound inquiries into the works of Marx and Engels led to the rediscovery of ecological considerations in classical Marxist thought. As a result, the main aim of second-stage scholars became the exploration of possibilities of an ecological science grounded in a historical-materialist methodological approach. The key concept derived from granting Marx a "second ecological chance" was that of the *metabolic rift* between human beings and nature. This rupture or break is argued to form the basis of capitalism's existence as a system. This section is dedicated to a thorough exploration of the *metabolic rift theory*, how its pillars were theorized by Marx and how it has been interpreted by second-stage scholars from the 1990s onwards. To the best of our knowledge, the metabolic rift theory has only been elaborated upon by non-economists (apart from Marx) which is why the current section draws on non-economic literature precisely to explore the implications for economic analyses.

In sum, the counter-arguments provided by second-stage scholars are based on Marx's later works regarding political economy as well as his early philosophical works (the main object of study for first-stage scholars). This is because the former seem to prove that Marx had indeed provided a concise treatment of issues concerning soil fertility, organic recycling and sustainability. Having reviewed the bulk of the literature in 1990s we assert that the claim that Marx overcomes many of the ecological shortcomings he is accused of, takes the shape of the following sequential treatment of topics:

- Marx's Critique of the Classicals and the Second Agricultural Revolution
- Marx's appraisal of Justus Liebig
- Marx's formulation of Metabolism between Man and Nature

In our view, these are the main ingredients that elucidate the eco-Marxist metabolic rift theory and we shall now discuss each of them as they appear in the second-stage literature.

### 1.3.1. Classicals and the second agricultural revolution

Karl Marx lived from 1818 to 1883 and spent periods of his life in Germany, France, Belgium and the United Kingdom. His last stop was London and he had lived there from 1849 until his death in 1883. During the period of his stay in London he wrote his well-known magnum opus *Capital* and completed the first volume thereof. Because of this, second-stage scholars argue that Marx's critique of capitalist agriculture (from which one can extrapolate contributions to ecological thought) should be understood in conjunction with the agricultural revolution happening at that time.

Various historians have different estimates about the period in which said agricultural revolution occurred or what determines an agricultural revolution in the first place. As an example, Overton (1996) argues that there was a "general" agricultural revolution from 1750 to 1850 and that this fact is established by the remarkable increases in the agricultural output as well as labour productivity — a process accelerated by the English enclosures. On the other hand, Allen (1999) advocates the division into two agricultural revolutions, the first ranging from 1520 to 1739, followed by a period of stagnation from 1740 to 1800. The second agricultural revolution took place from 1800 to 1850. He proves these breaks by providing data on both farm output and real rents as a proxy for overall productivity and concludes that enclosure had no role in determining the increases.

In any case the broad period "mid to late 19$^{th}$ century" was also characterized by a period where soil chemistry came to play an important, but not all-determining, role in the regulation of agricultural productivity (Allen, 2008). During the second agricultural revolution, farmers were increasingly seen as factory managers; engaging in the purchase of raw materials and utilizing the farm to produce higher-value goods. The raw materials that were purchased, manure and fertilizer, had made farmers less dependent on the rotation of crops and the use of unsold crop harvests as plant biomass (Coombs, 1994; Thompson, 1968). Marx was aware of this development and it led him to assert that the classical economists at that time neglected a crucial component in their analysis of agricultural land exhaustion. Ricardo was the first to analyse agricultural land rent in a systematic way by assuming free competition among capitalists and landowners together with diminishing returns to labour and capital as the consequence of the fixed availability of fertile lands (Belloc et al., 2008).

Foster (1999) argues that even if Ricardo allowed for agricultural improvements (see Gehrke et al., 2003), his previous idea of diminishing returns would theoretically still slowdown the growth of productivity in agriculture. This would ultimately lead to his comprehension of the long-run tendency of the economy towards a stationary state. For Ricardo, these diminishing returns could, for the most part, be attributed to the sequential cultivation of inferior grades of land in response to increased demand. This fell perfectly in line with Malthus' earlier claim on the tendency of the population to outgrow the supply of food. As mentioned by Brezis and

Young (2003), Malthus' demographic theory argued that if any population shows unbounded growth, and so it will according to the "general laws of nature", it will reach the limit of its food production possibilities. Ergo, equilibrium could only be maintained through preventive checks that reduce the human fertility rate or positive checks that increase the human mortality rate.

One of the many responses Marx gave in reply to the articulation of the aforementioned stationary state is quoted below:[5]

> *Rather than tracing to their origin the real natural causes leading to an exhaustion of the soil, which, incidentally, were unknown to all economists writing on differential rent owing to the level of agricultural chemistry in their day, the shallow conception was seized upon that any amount of capital cannot be invested in a limited area of land.*
>
> - Karl Marx, 1967: pp. 569

This naturally leads us to the following section, in which we discover what/who made Marx's understanding of agricultural productivity different from that of other Classical economists.

### 1.3.2. The engagement with the works of Justus Liebig

As shortly mentioned above, Marx was acutely aware of the role of agricultural chemistry during the second agricultural evolution as well as the implications it had for population growth and the capitalist economy (and vice versa). Lands with soils that were less fertile could easily be used for agricultural production if one increased their fertility. This awareness was a result of Marx's encounter with "the crisis of the earth or soil" in the works of the German soil chemist Justus von Liebig (Baksi, 1996; Bocking, 2002; Foster, 1997, 1999; Foster and Magdoff, 1998; Stanley, 2002). Liebig was the author of the work *Organic Chemistry in its Applications to Agriculture and Physiology* released in 1840. Its main message can be summarized by taking a quote from the opening paragraph:

> *The object of organic chemistry is to discover the chemical conditions essential to the life and perfect development of animals and vegetables, and generally to investigate all those processes of organic nature which are due to the operation of chemical laws.*
>
> - Justus Liebig, 1840: pp. 1

Liebig's work provided one of the first convincing explanations of the role of soil nutrients in the growth of plants; this at a time where Europe and North America had grown increasingly

[5] For a detailed overview of responses to Malthus and how Marx was inspired by the Scottish agronomist and political economist James Anderson see (Burkett, 1998) and (Foster, 2000). Anderson held contrasting views on Ricardo and Malthus regarding the differential rent and the relative productivity of the soil. He also introduced the division between town and country as a main driver of the loss of natural sources of fertilizer. This notion is crucial for the development of Marx's metabolic rift theory.

concerned over "worn-out soils" (Hillel, 1991). Thus, Liebig had made Marx aware that in order for crops to grow, it was necessary for the soil to contain specific nutrients such as nitrogen, phosphorus and potassium.

Liebig's work also influenced the agronomist J.B. Lawes, who set-up experiments with artificial fertilizers in 1842 and built a factory for the production of "super-phosphates" in 1843 (Browne et al., 1942; Foster and Magdoff, 1998). These fertilizers were produced by treating material with high amounts of phosphate minerals with acid. The findings of Lawes led to the further development of the chemical fertilizer industry and by the late 1840s the main fertilizers were imported bones — rich in phosphates, low in nitrogen content, highly insoluble in their natural state and slow-acting.

It soon became clear, however, that the range of crops and soils to which bones could be applied was rather limited, e.g. it was insufficiently nitrogenous for cereal crops and almost incompatible with wet soils (Mathew, 1970). This is why Peruvian guano imports became fashionable rather quickly in Britain. Compared to the previously mentioned "super-phosphates", guano was more soluble, performed very well on both heavy and light soils, contained both nitrogen and phosphate in sufficient quantities and was applicable to a wider range of crops. Due to guano's effectiveness and popularity, Peruvian guano was eventually exhausted and had to be replaced by Chilean nitrates; indicating that British agriculture had become dependent on artificial fertilizers. In his later works, Liebig expresses a deep concern for the state of farming at his time:

> *It is not the land in itself that constitutes the farmer's wealth, but it is the constituents of the soil, which serve for the nutrition of plants, that this wealth truly consists. By means of these constituents alone, he is enabled to produce the conditions indispensable to man for the preservation of the temperature of his body, and of his ability to work. Rational agriculture, in contradistinction to the spoilation system of farming, is based upon the principle of restitution; by giving back to his fields the conditions of their fertility, the farmer insures the permanence of the latter.*
>
> - Justus Liebig and John Blyth, 1859: pp. 178-179

Additionally, Liebig & Blyth expressed a condemnation towards the use of guano as a means to overcome the deplorable conditions of the soil:

> *Agriculturists must not rely upon guano; its price at the present time, as compared with an earlier period, is already doubled; and no sensible man would entertain the idea of marking the production of an entire country dependent on the supply of a foreign manure. Agriculturists must in the first place learn to turn to the best account all the means and resources at their command; when they have done this, but not till then, will chemistry be*

*able to do them good and useful service. But so long as they expect this science to present them with the potent charms for fertility, there is no help for them. They must bear in mind, that wherever success does not attend a good cause, the fault lies in want of energy in using the proper means; for these are always to be found.*

- Ibid, 1859: pp. 269-270

In the introduction of Liebig's revised edition of *Organic Chemistry in its Applications to Agriculture and Physiology* released in 1862 and renamed *Agricultural Chemistry*, Liebig once again accentuates that modern industrialization diverges the aim of agriculture from sustainability to the maximization of profits. This, by providing artificial soil nutrients to crops in the shortest possible period (Liebig, 1862).
Following Foster (1997, 1999), Marx is said to have become convinced of the unsustainable nature of agriculture under capitalism due to i) the increasing reliance of Europe and North America on imported fertilizers during the second agricultural revolution, ii) his studies on the importance of nutrient cycles and Liebig's critique[6] of the "spoilation system" of farming and iii) the implications this had for Ricardo's land-quality based law of diminishing returns.[7] It is not a surprise that in a footnote in Volume I of *Capital*, Marx mentions Liebig and writes that: "His brief comments ... although not free from gross errors, contains flashes of insight" (Marx, 1887a: pp. 357).

In the following section, we will finally present the final element used by eco-Marxists to argue that Marx was far from ecologically illiterate.

### 1.3.3. On the metabolism between Man and Nature

The previous section exemplified that Marx had access to scientific information which allowed him to carry forward a systematic critique of the capitalist exploitation of the soil. This critique is based on a discussion of large-scale industry and large-scale agriculture and how they contributed to the impoverishment of both the worker and the soil. This realization and the writings thereof are what essentially constitute the backbone of the metabolic rift theory.

[6] A more recent exploration divulges that Marx was also well-read and informed about the controversy around Liebig's "law of replacement and soil exhaustion theory" which took an increasingly Malthusian tone in Liebig's later works (Saito, 2016). According to Saitō (2017); Saito (2016) one particular anti-Liebig work Marx was quite pleased with, was Carl Fraas' *Climate and the Plant World Over Time* published in 1868. In it, Fraas expressed that Liebig's Malthusian pessimism is a result of his ignorance of the fact that nature is also capable of sustaining fertility on its own through the provision of alluvial materials (earth, sand, gravel and stones containing high mineral content). His conclusion that desertification is a natural outcome of uncontrolled cultivation was appealing to Marx in that it carried an unconscious socialist tendency.

[7] It is worth re-iterating that Ricardo's law of diminishing returns was based on the realistic assumption that arable land is heterogeneous. This is pre-determined by natural processes. What Marx came to realize by taking agricultural chemistry into account is that the use of fertilizers on an inferior plot of land could result in an agricultural output which was equal to the output on a superior plot of land (without the use of fertilizers). The consequence however being that in the medium to long-run the inferior plot of land would become *even more* inferior due to soil exhaustion.

But before we discuss the passages that elucidate this theory, it is worthwhile to discuss Marx's earlier philosophical works with respect to the *historical materialist* tratment of the relationship between man and nature. According to Wurst and O'Donovan (2008), historical materialist approaches mostly emphasize:

i) socially and historically contained contexts
ii) issues concerning production and reproduction of everyday life
iii) the examination of multiple and multi-scale material and historical evidence for the identification of contradictions
iv) an explanation for how contradictions mentioned in iii) relate to the internal dynamics of society and
v) the use of the above understandings to engage in praxis

This is in stark contrast with idealism, which subsumes the material reality/existence under a thought. Hence, whatever Marx had to say about nature, he did so from a materialist perspective.[8] Marx's treatment of the relationship between man and nature through the concept of estrangement/alienation is found in *Economic and Philosophical Manuscripts* from 1844:

> *Species-life, both for man and for animals, consists physically in the fact that man, like animals, lives from inorganic nature; and because man is more universal than animals, so too is the area of inorganic nature from which he lives more universal. Just as plants, animals, stones, air, light, etc., theoretically form a part of human consciousness, partly as objects of science and partly as objects of art – his spiritual inorganic nature, his spiritual means of life, which he must first prepare before he can enjoy and digest them – so, too, in practice they form a part of human life and human activity. In a physical sense, man lives only from these natural products, whether in the form of nourishment, heating, clothing, shelter, etc. The universality of man manifests itself in practice in that universality which makes the whole of nature his inorganic body, (1) as a direct means of life and (2) as the matter, the object, and the tool of his life activity. Nature is man's inorganic body – that is to say, nature insofar as it is not the human body. Man lives from nature – i.e., nature is his body – and he must maintain a continuing dialogue with it is he is not to die. To say that man's physical and mental life is linked to nature simply means that nature is linked to itself, for man is a part of nature.*
>
> - Karl Marx, 1959: pp. First Manuscript - Wages of Labour

According to this conception, human beings produce a specific historical relation to nature through the production of their means of subsistence. Nature comes to bear a practical meaning

8 For a comprehensive overview of Marx's philosophical journey, from Hegel's idealism to Feuerbach's materialism see Balibar (2017); Foster (2000)

for humanity as the result of simply "being alive" and producing the means of life; not only in the economic sense, but also according to aesthetic values (Foster, 2000). According to Marx, alienation or estrangement under capitalism "estranges man from his own body, from nature as it exists outside him, from his spiritual essence *(Wesen)*, his human existence" (Marx, 1959: pp. 32).

The penultimate passage we quoted from Marx specifies nature as man's *inorganic* body and this is one of the aspects that has been heavily criticized by ecological thinkers from the late first-stage. Foster et al. (2017) notes that this is because of the specific modern interpretation of these words; organic referring to naturalness, connectedness, a non-instrumental approach while inorganic signifies the opposite. Seen in such a light, nature being man's unnatural body does indeed sound very anti-ecological and anthropocentric. Marx is thus faulted for holding a dualistic conception of the human-nature relationship; positing that human beings and nature exist in ceaseless antagonism (Clark, 1989; Lee, 1980; Routley, 1981).

In order to understand the error in the formulation of these accusations, it is important to refer to the historical meaning attached to the word *organic*. In addition, it is useful to recall the use of the word in Hegel's dialectics. The ancient Greek definition of the word organ(on) refers to *tool for making or doing, that with which one works*. Instead, in early modern times the scientific term organic referred to *bodily organs, structures and organization of living beings*. Thus, inorganic came to be defined as *not characterized by having organs or members fitted for special functions; not formed with the organs or instruments of life* (OED Online, a,b,c).

In the end, it was Hegel's deployment of the concepts in the aforementioned sense which had led Marx to use them to describe the alienation between man and earth in a materialist fashion (Foster, 2000; Foster et al., 2017; Hughes, 2000; Saitō, 2017). Even though Hegel's *Philosophy of Nature* from 1830 is idealist, Marx drew on his dialectical insights to develop his own understanding of the organic unwinding from the inorganic. Hegel's depiction of how the organic is connected to the inorganic can be summarized in the following way (Foster and Burkett, 2000): i) the organic and the inorganic form a unity since each organism carries the inorganic within itself, as part of itself ii) the organic and inorganic are also in conflict given that the organic feeds off the inorganic as a condition of existence and iii) together the organic and inorganic form a unity-in-difference in reproduction, development and death.

What Marx took from Hegel is the specific dialectical perception that humanity, as objective and organic creatures are also subordinate to inorganic nature as a constituent of its own species-being. The main difference between Marx's and Hegel's interpretation is that Marx's dialectical conception of nature never took the shape of idealism. For Hegel, the object of analysis was the estrangement/alienation of the spirit where nature is "defective" in that it represents an "antithesis to thought". For Marx, it was necessary to explain how human and natural history were enmeshed within humanity's sensuous existence.

Marx's approach to the organic/inorganic throughout his entire analysis of capitalism can therefore be characterized by being a) *scientific*, in using the terminology of the organic (subject to bodily organs) and inorganic (not subject to bodily organs) found in Hegel b) *dialectical*, in insisting that nature is both external and internal to the biological foundation of human beings and c) *materialist*, in accentuating that the human-nature relation evolves through the use of inorganic nature, which extend the organs of the human body in the production of the means of subsistence (Foster et al., 2017).
Having shortly mentioned the relationship between Marx and Hegel in the specific context of human-nature relationships while at the same time clearing out some misconceptions that fault Marx for referring to nature as man's inorganic body, we can finally head to an exposition of the eco-Marxist metabolic rift theory. Its onset was clearly visible in *Grundrisse* written by Marx in 1857-1858:

> *The original conditions of production (...) cannot themselves originally be products - results of production. It is not the unity of living and active humanity with the natural, inorganic conditions of their metabolic exchange with nature, and hence their appropriation of nature, which requires explanation or is the result of a historic process, but rather the separation between these inorganic conditions of human existence and this active existence, a separation which is completely posited only in the relation of wage labour and capital.*
>
> - Karl Marx, 1973: pp. Notebook IV/V - The Chapter on Capital

What Marx points out here is that when nature and the forces of science are subsumed under capital, they gain an alienated social power over producers. The scientifically recognized powers of nature merely appear as material conditions for the exploitation of labor power. This ultimately results in the mass separation of human beings from the inorganic conditions of their being (Burkett, 1996). In Marx's later work, Volume I of *Capital*, he refers to the metabolic relation between man and nature as an introduction to his conception of the labour process:

> *Labor is at first a process between man and nature, a process by which man mediates, regulates and controls his metabolism with nature through his own actions. He confronts natural materials as a force of nature. He sets in motion the natural forces that belong to his own body, his arms and legs, head and hands, in order to appropriate the natural materials in a form useful for his own life. While acting upon external nature and changing it, he also changes his own nature. He develops the potentialities slumbering within his nature, and subordinates the play of its powers to his command.*
>
> - Karl Marx, 1890: pp. 283

Interestingly, in this passage Marx places the interaction between the labourer and nature at the forefront of the analysis of labour under capitalism. In our opinion, what is especially important to notice is that Marx is describing a general labour process, not the one characteristic for the capitalism since he does not mention alienation or estrangement. The distinction will become clearer once we discuss world-ecology in Section 1.5. In any case, further along Volume I of *Capital* Marx gives us an insight into the societal origins of the *metabolic rift* between the organic and inorganic: the antagonism between town and country:

> *Capitalist production, by collecting the population in great centres, and causing an ever-increasing preponderance of town population, on the one hand concentrates the historical motive power of society; on the other hand, it disturbs the circulation of matter between man and the soil, i.e. prevents the return to the soil of its elements consumed by man in the form of food and clothing; it therefore violates the conditions necessary to lasting fertility of the soil. By this action it destroys at the same time the health of the town labourer and the intellectual life of the rural labourer ... Moreover, all progress in capitalistic agriculture is a progress in the art, not only of robbing the labourer, but of robbing the soil; all progress in increasing the fertility of the soil for a given time, is a progress towards ruining the lasting sources of that fertility ... Capitalist production, therefore, develops technology, and combining together of various processes into a social whole, only by sapping the original sources of all wealth - the soil and the labourer.*
>
> - Karl Marx, 1887a: pp. 329-330

Here, Marx does not explicitly use "metabolism" but speaks of the "circulation of matter between man and the soil" which essentially entails the same.[9] Nevertheless, the above passage points out the dynamic and reciprocal relationship between humans and nature, as mediated by the labour process. Furthermore, we can clearly disseminate the influence of Liebig's agricultural chemistry in Marx's discussion of nutrient cycles and soil fertility. Thus, metabolism, according to Marx, is subject to a historical character and changes at every stage of social development. Alienated labour in modern capitalist society is said to mediate the metabolic relationship between humans and nature in a way that is different than under pre-capitalist societies.[10] Marx then extended his observation on the rift between the town and country to criticize, much like Liebig did, large-scale industry and large-scale agriculture as a whole. This is apparent in his treatment of capitalist ground rent in Volume III of *Capital*:

> *On the other hand, large landed property reduces the agricultural population to a constantly falling minimum, and confronts it with a constantly growing industrial population crowded*

[9] It is quite likely that the free online edition of Capital Volume I, from which the above quote was taken, has translated metabolic interaction into circulation of matter. The same quotation used in Foster (2000); Foster et al. (2017) *does* contain metabolic interaction.

[10] This argument differs greatly from the world-ecology interpretation by Jason. W. Moore. In the subsequent section we will present Moore's contention of an already disrupted metabolic interaction between nature and humans dating in pre-industrial mercantilism.

> *together in large cities. It thereby creates conditions which cause an irreparable break in the coherence of social interchange prescribed by the natural laws of life. As a result, the vitality of the soil is squandered, and this prodigality is carried by commerce far beyond the borders of a particular state (Liebig).*
>
> - Karl Marx, 1967: pp. 329-330

Here, the separation between town and country is reiterated in a different way: as a consequence of large landed property and resulting in a irreparable *break* in the coherence of social interchange. It is not hard to derive that Marx makes another reference to the *metabolic rift*[11]. Furthermore, the comments made with regard to the extension beyond borders demonstrates that Marx was aware of the use of imported artificial fertilizers in large-scale agriculture.

The quotes presented in the paragraphs above are intended to illustrate that the assertion of an incompatibility between Marx and Ecology is not as plausible as it may seem. By taking into account Hegel's *Philosophy of Nature* in his distinction between organic and inorganic as well as various insights gathered from agricultural chemistry, Marx's concept of a metabolism between man and nature captures aspects of society that *do* include material exchanges. As a result, this metabolism is regulated through nature and the laws that govern physical processes (the biophysical limits) as well as through society which imposes institutionalized norms that direct the division of labour and the distribution of wealth (the economic system). Just as there exists a unity-in-difference between the organic and inorganic for Hegel, Marx extends the application of this unity-in-difference and regards nature and the economic system in the same fashion (after concretely applying it to capitalist agriculture).

Recognizing that Marx's critique of capitalism has an ecological character often leads to the idea that Marx believed that the alternative to capitalism, be it socialism or communism, is green/sustainable/ecological by default. Drawing this conclusion and consequently confronting the weak ecological performance of countries in which socialism was proclaimed to exist (Edmonds, 1999; Komarov, 1981; Sanders, 1999; Shahgedanova and Burt, 1994; Thomas and Orlova, 2001) automatically triggers the tendency to discard anything Marx had to say in the first place. It's no wonder then, that early first-stage scholars were not as hostile towards Marx as the late first-stage scholars. Since they were mainly writing before the fall of the Soviet Union (therewith the fall of communism as a desirable alternative or societal aspiration) and before the international awareness of pollution in both the People's Republic of China (PRC) and the Soviet Union. Without getting into tedious discussions about whether the

[11] It should be noted that the eco-Marxist interpretation of Marx in terms of a metabolic rift does not completely fall in line with every mentioning of "metabolism" by Marx throughout *Capital* and *Grundrisse*. As Saitō (2017) points out, Marx uses three different metabolisms throughout the aforementioned works; i) metabolic interaction between humans and nature ii) metabolism of society and iii) metabolism of nature.

USSR and the PRC were/are actual examples of socialism/communism or not, we can for a moment wonder if Marx himself was so optimistic about the ability of socialism/communism to eradicate all environmental problems. For now we can atleast agree that Marx's concept of the metabolic rift carries with it, a kind of notion that human beings in capitalist society are alienated from their natural conditions of existence.
Burkett (2009a) mentions that expressing the rift in terms of capitalist agriculture meant to point out that agricultural producers under capitalism were incapable of (social) rational action. Instead, this could only be achieved by a future society of associated producers, or in other words socialism, the stage before communism. Marx writes:

> *Freedom in this field [conditions of production] can only consist in socialised man, the associated producers, rationally regulating their interchange with Nature, bringing it under their common control, instead of being ruled by it as by the blind forces of Nature; and achieving this with the least expenditure of energy and under conditions most favourable to, and worthy of, their human nature.*
>
> - Karl Marx, 1967: pp. 593

This passage expresses a future society in which humanity is still in dialogue with its society's natural limits, but this dialogue is, in contrast to capitalism, achieved through the "rational and conscious domination of nature" in conjunction with a "rational and conscious domination over their social organization". Yet, at the outset, the "domination over nature", even in its collective form, sounds like it is in strict contradiction with ecological thought. This is because it seems to suggest that humanity under socialism can overcome all natural limits through technological progress and the ability to trounce natural forces. But this may become a far-sought conclusion once we recall the following passage pointed out by Foster (1999):

> *From the standpoint of a higher economic form of society, private ownership of the globe by single individuals will appear quite as absurd as private ownership of one man by another. Even a whole society, a nation, or even all simultaneously existing societies taken together, are not the owners of the globe. They are only its possessors, its usufructuaries, and, like boni patres familias, they must hand it down to succeeding generations in an improved condition.*
>
> - Karl Marx, 1967: pp. 567

This goes to show, that "the collective domination over nature" Marx mentioned in the previous passage does not automatically translate to an overexploitation of natural resources as a result/for the sake of technological development. In other words, Marx's idea of a rational regulation of the interchange with nature is not a kind of mindless extractivism as many take it to be. Indeed, the last sentence should sound impalpably familiar to those acquainted with the concept of sustainability and perhaps even stretching beyond it by covertly implying a negative discount rate.

Burkett (2005) further clarifies what Marx meant by domination over and rational regulation of Nature. He quotes Marx and explains that associated producers would set aside a portion of their surplus product as a kind of insurance which would be able to help society (and not the rate of profit) against natural disturbances. Together with the aid of scientific development this would allow preciser calculations of extreme-weather probabilities. It is well known, that Marx and Engels never provided a blueprint or an utopian vision in which they describe the details of everyday life under socialism or communism. This is because their vision is grounded upon the self-emancipatory nature of a break away from capitalism. A blueprint would foreclose the application of their thought to the times we are living in now. What we *do* see in their works is a concrete analysis of our current economic system, subject to critique and improvement to fit our times, but nevertheless not failing to stress the general importance of nature and society's relation towards it.

## 1.4. Third-stage considerations on Marx & Ecology

The previous section provided a glimpse of the arguments constructed during the 1990s and early 2000s by what are today, the most prominent defenders of the metabolic rift theory. While we did not address every single argument, hopefully we gave a basic insight into the existing synthesis between Marx & Ecology. In the following section, we highlight how a variety of scholars have applied the metabolic rift theory as a means to describe ecological degradations. These studies will be referred to as third-stage considerations. Table A.1 in the Appendix A provides an overview of the metabolic rift applications in the fields of Agriculture, Aquaculture, Extraction and Land-Use Science. Table A.2 on the other hand, discusses literature that considers urban metabolism, urban agriculture and philosophical insights into urban development. Apart from concluding that the third-stage literature is truly vast, we can also conclude that the literature in Tables A.1 and A.2 provide concrete and case-specific examples of the aggravation of the metabolic rift under globalized capital accumulation. In addition, Table A.3 in the Appendix provides third-stage literature on Theoretical Advancements. This includes adjustments and/or reconsiderations of the "raw" second-stage conception of the metabolic rift. Even if it is certainly not claimed that the tabular overview provided in the Appendix is all-encompassing, the journal row of each table accentuates the evident lack of considerations on the metabolic rift theory in economic literature.

Before we discuss the potential economic formalization of the metabolic rift, we find it necessary to take into account what is progressively seen as a separate reading of Marx &

Ecology — the world ecology theory. Jason W Moore's contribution is perhaps one of the most influential theoretical advancements of the metabolic rift theory and instead of discussing it in Table A.3, it is introduced in the following section.

## 1.5. World-Ecology

Having introduced the metabolic rift theory and its application in the contemporary analyses of ecological issues, this section sets out to discuss an alternative apprehension of eco-Marxism. This is the *world-ecology* approach formulated by Jason W. Moore at the beginning of the 2000s. While Moore recognizes the metabolic rift theory in Marx, he treats it from a historical and "world" perspective by embedding Immanuel Wallerstein's world-system theory into ecological analyses.

A restricted selection of Moore's work will be discussed in this section. Additonally, we provide a summary of the recent polemic between Foster and Moore which will highlight some of the concrete differences between the two approaches. A profound philosophical treatment of metabolic rift theory and world-ecology inevitably results in the choice of one approach over the other. However, we argue that a first attempt at an economic and formal treatment of Marx & Ecology is better off blurring their borders since both offer useful perspectives.

### 1.5.1. A world-systems approach to the metabolic rift

In *Environmental Crises and The Metabolic Rift in World-Historical Perspective* from 2000, Moore extensively introduces the main ingredients for what now is called world-ecology. His aim in the article is to develop an alternative argumentation in which one can study the dialectic between capital and nature over the long-term historical development of capitalism. This is achieved by drawing on the historical political economy developed by Marx, Foster, Arrighi and Wallerstein and subsequently formulating a theory of *systemic cycles of agro-ecological transformation*.

Moore (2000a) argues that our current global ecological crisis has its roots in the transition to capitalism during the sixteenth/seventeenth century (from 1450 to 1640). Here, we recognize a first departure from the metabolic rift theory since Foster originates the current eco-crises in the classical Marxist division between town and country and therefore as the result of capitalist industrialization at the beginning of the nineteenth century. Moore does not deny this observation, but recognizes it as the cause of regional/localized eco-disruptions while asserting that fundamental reorganizations of the world-economy a couple of centuries back (under feudalism) had already led to eco-disruptions in colonized lands (Ibid, 2000a). Thus, the process of zooming out and assessing the developments of metabolic rifts on a larger geographical scale and over a longer period is what led Moore to perceive that there exists a kind of affinity between metabolic rift theory and Wallerstein's *world-system* theory.

With the help of Wallerstein's *The Modern World-System I* from 1974, Moore describes the feudal system in the 1300s as a social organization that had encountered insurmountable limits as a result of the limitations set on the surplus available for agricultural improvement.[12] Such improvements were necessary as settlements began to expand due to population growth. Agricultural lands were undergoing the process of exhaustion and medieval agriculture became increasingly dependent on favourable weather conditions. Together with epidemic diseases, this contributed to what Wallerstein (1974) called the "cumulative woes" which were pushing the feudal system to a breaking point.

Hence, by the end of the fourteenth and at the beginning of the fifteenth century, geographical expansion was necessary because the possibilities for inner expansions had become increasingly exhausted. It's important to mention that limitations to inner expansion in medieval Europe were not only the result supply-side constraints in the face of population growth; the social structure of the feudal system also served as a constraint. Wallerstein mentions that seigniorial revenues had begun to decline because of a stronger bargaining position of the peasants, partly *as a result* of previous favourable conditions (physical room) for a growing peasantry population. As a consequence, the European nobility desired a more manageable (exploitable) labour force to support the further expansion of its economy (Ibid, 1974). Put differently, a labour force that could compensate for the decline in seigniorial revenues and pose less of a violent threat.

Before the aforementioned feudal crisis took the stage, land-expansion through wars was common since economic contraction had not occurred yet. But as the feudal crisis set in, wars became too expensive and set back processes of "state-building". This is why overseas expansion came to be seen as the path of least resistance. At this point however, it is important to note that Moore (2000a) augments the treatment of the feudal crisis by Wallerstein (1974) with that of Arrighi (1996). This is because the latter not only considers the position of feudal lords in the crisis but also discusses the city-state capitalists or *merchant bourgeois*. For this particular group, the feudal crisis resulted in the economic contraction of Afro-Eurasian trade causing a vicious competition between various state-capitalists. In a nutshell, the Geneose championed overseas expansion in cooperation with the Iberians in order to break away from Venice's monopoly on spice trade. Here, Moore (2000a) argues that European expansion can be seen as a process of unification that brought North Sea and Mediterranean world-economies into a more or less allied capitalist world-system.

For us, the crucial aspect of this historical side-step is that overseas expansions grew out of a crisis in Europe in which food and fuel were seen as the two most important commodity groups. Not only did this crisis-driven and commodity-specific expansion lead to the creation

[12] According to Dimmock (2014) the extraction of surplus value under feudalism was political and *extra-economic*. Under feudalism peasants were largely shielded from the market while lords extracted surplus by political and military domination to maintain themselves. In capitalism on the other hand, the extraction of surplus value is still political but also fundamentally *economic*, it is now the threat of unemployment that embodies the economic coercion of the market.

of new peripheries in the Atlantic and Americas but it also induced the prioritization of short-run profits; efficiency and concrete specialization between agrarian and commercial activities were obviously valued more than ecological sustainability.

For example, if we take a particular look at sugar, Moore (2000b) uses the concept of a "commodity frontier" to provide a world-system explanation of ecological disruption at the hands of global expansion in sugar trade. The concept of the commodity frontier is derived from the idea of a commodity chain in the world-system literature. A commodity chain refers to "a network of labour and production processes whose end-result is a finished commodity" (Hopkins and Wallerstein, 1986). Apart from embedding the above, the concept of a commodity frontier also captures how the production and distribution of said commodities have restructured the geographic space at the margins of the system such that the system itself requires further expansion.

Moore (2000b) treats the sugar frontier as one that played a crucial role in the development of capitalism from the 1300s to the 1800s. Since sugar monocultures rapidly exhausted soil fertility it can be seen as a primary example of the *metabolic rift* during the transition from feudalism to capitalism. Products from the periphery in the Americas and Atlantic flowed to European cities and broke the nutrient cycle over a geographical distance far wider than that between the town and country in a European country at the height of industrialization. Given that British workers consumed sugar products and Caribbean sugar plantation slaves almost starved because other crops were scarce, one can additionally affirm that the sugar commodity frontier resulted in ecologically unequal exchange. Many historical accounts of global sugar production correctly point out that its geography experienced long-run changes. In the second half of the 1400s sugar production mainly took place on Atlantic islands, by the late 1600s its production locus shifted to Brazil and in the late 1800s and early 1900s, Cuba and Jamaica had become the most important hubs. These treatments, however, fail to recognize the ecologically tainted determinant of these production shifts. Moore fills this gap and argues that apart from changes in labour supply and technological innovations the primary factor behind these relocations were eco-systemic changes (Ibid, 2000b). This culminated in a substantial chain reaction of metabolic rifts across the colonized world.

For the moment we will only highlight these eco-transformations as they occurred on the island of Madeira in the mid 1400s and as exemplified by Moore (2003); Patel and Moore (2017). The first ecological transformation materialized before the Portuguese actually settled and brought cows, sheep and pigs to the island for grazing. Pre-Portuguese settlement on Madeira was the consequence of relocation from the nearby island Porto Santo. Inhabitants of Porto Santo had accidentally released rabbits in the 1420s and this increased the island's vulnerability to wind and soil erosion. The relocated settlers on Madeira engaged in the cultivation of wheat, tobacco and other cash crops. Since these early settlers were not compelled to sell their commodities on the capitalist world-market they are said to have practiced a "subsistence-surplus" type of agriculture. In hindsight, this type of agriculture can be seen as the preparation for a more intensive stage of commodity production — countries where subsistence agriculture had not taken place failed to successfully cultivate sugar.

Madeira's rapid transition to commodity production for capitalist markets occurred at the hands of Genoese and Flemish capital which displaced earlier settlers and introduced the first sugar plantations. Because wheat crops were now replaced with cane sugar, Madeira's wheat had to be imported from other regions while the subjection to capitalist world markets led to an increase in the average size of estates vis-a-vis those of wheat and tobacco. In other words, the introduction of sugar led to an overall expansion of agricultural land use. This was achieved by clearing much of Madeira's forest cover and building proper infrastructure to accommodate irrigation given the island's low rainfall. By the 1450s Madeira was ready for the commencement of sugar exports and with financial inputs provided by Genoa the sugar plantation was able to employ slave labour, securing Madeira's position as the world-economy's largest sugar producer by the end of the 1400s.

However, the overproduction of sugar cane monocultures on the island led to an increase in soil erosion and productivity quickly stagnated. Soon, Brazil was to become the center of sugar production, where sugar grew a lot better thanks to high amounts of rainfall. This is all to show that already in the fifteenth century, the obligation of produce towards capitalist world markets radically simplified the natural ecological order. When the dynamics of competitive pressures in the world market are not in sync with those of agroecological regeneration, a produced commodity, in this case sugar, reaches its "frontier" in Madeira and "shifts" the means of expansion to the Americas where it eventually reaches new frontiers. It should be noted that these frontiers need not take a transnational character, frontiers also manifest themselves on local scales e.g. the fact that Madeira had to burn its forests to make place for sugar cane estates. The reason why the sugar commodity frontier is seen as such a key development is because it also catalysed major economic activities and hence distinct commodity frontiers i.e. the slave-trade and the slave commodity frontier, shipbuilding and the timber commodity frontier, ranching and the cattle commodity frontier etc. Each of the above is unequivocally characterized by deforestation, biodiversity loss, soil exhaustion and the appropriation of labour — all in all cultivating a chain of metabolic rifts across the globe as the seeds for industrial capitalism were planted.

As hinted at in a previous paragraph, the expansion of capital and the effects on world-ecology can be expressed in terms of *systemic cycles of agro-ecological transformations* which is an ecological adaption of the world-system systemic cycles introduced by Arrighi. According to Moore (2000a, 2015a), each cycle/world-ecological regime is characterized by a fundamental reorganization of the current world ecology such that it guarantees increased returns during the consecutive cycle/world-ecological regime:

> *During the early phases of each new system wide material expansion, capitalists develop new, more intensive modes of agro-ecological exploitation. This establishes, in a fundamental way, the conditions for renewed material expansion in commerce and manufacturing. As inter-enterprise competition increases over the course of the system wide expansion, so the capitalist exploitation of nature increases. Escalating ecological exploitation leads to rising costs, which over time necessitates a fundamental reorganization of world ecology, not to mention the world-economy as a whole. Each reorganization is not merely organizational and technical, it is crucially a new phase of the geographical expansion of the world-economy, which is accompanied by the deepening subordination of agriculture to the law of value in regions where capitalism has long held sway.*
>
> - Jason Moore, 2000a: pp. 141

In a later works, Moore shies away from the above conceptualization of systemic cycles by recognizing that the concept carries a tangible ecological component which is not sufficiently able to divulge how capitalism, through its historical cyclical developments, affects a type of "abstract" nature in the absolute sense (Ibid, 2011a; 2011b).[13] In other words, clarifying systemic crises as a result ecological degradation and the implications this had for the costs of production falls short. Instead, one should additionally accentuate how systemic crises in the world-ecological order are caused by dynamics in specific and complex nature-society relations. From one world-ecology regime to the other, there simultaneously exists an absolute exhaustion of organizational structures (spurred by e.g. the scarcity of resources) and a relative exhaustion of relations that were once governing the reproduction of biophysical and human natures. In sum, world-ecology is more than a world-system perspective of historical metabolic rifts, it captures the relationality of nature and presents a method that grasps humanity-in-nature as a world-historical process (Ibid, 2015a).

So how does one define the current world-ecological regime?[14] In a historically specific sense, world-ecologists claim that capitalism is currently facing the end of cheap nature which should be seen as more than just a "tap" or "sink" in terms of physical quantities of resources (Moore, 2014, 2015a,b; Patel and Moore, 2017). Cheap nature is what defines the strategy humanity undertook since the early sixteenth century. It is a strategy that perceives nature as an external component to human activity which means that the work of "uncommodified"

[13] Another reason why Moore decided to abandon his adaptation of Aghiri's systemic cycles is because it represents a Carthesian dualism. The last subsection of the current section will further highlight this aspect since it is very relevant for the polemic between Foster and Moore

[14] The current paper consciously omits the world-ecological regimes *between* the first one described in the paragraph above and our current world-ecological regime. For a detailed account see Moore (2015a); Patel and Moore (2017).

human and extra-human natures were all placed in service of labour productivity gains during the production process. Cheap nature as a strategy also meant that a new law of value was introduced:

> *The new law of value was quite peculiar. Never before had any civilization negotiated this transition from land productivity to labor productivity as the decisive metric of wealth. This strange metric—value-oriented the whole of west-central Europe towards an equally strange conquest of space. This strange conquest was what Marx ... calls the "annihilation of space by time," and across the long sixteenth century we can see a new form of time—abstract time—taking shape.*
>
> - Jason Moore, 2014: pp. 286

As time became abstracted so too became space and together they culminated to the strange solidification Marxists refer to as *abstract social labour*.[15] Instead of blaming anthropogenic drivers for the biospheric turbulence we experience today, world-ecologists place the blame on the aforementioned law of value which embodies the current relations of capital, capitalist power and the multi-layered relation towards species and environment. The whole of cheap nature can be characterized by different commodity frontiers and the movements thereof, particularly in the following categories that Moore refers to as the "Four Cheaps" — labour power, food, energy and raw materials.[16]

Having explained what cheap nature encompasses, why are we currently facing the end of it? To explain this, world-ecologists make a distinction between the appropriation of unpaid work and the capitalization of commodified work (resulting in paid work). Both of these categories refer to humans and extra-humans and are necessary for the accumulation of capital and reproduction of value. Movements in both appropriation and capitalization are said to historically determine socially necessary labor time.[17] Each successive world-ecology regime is then characterized by capitalist technics who seek "to mobilize and to appropriate the (unpaid) "forces of nature" so as to make the (paid) "forces of labor" productive in their modern form (the production of surplus value)" (Ibid, 2014: pp. 295).

In terms of the "Four Cheaps", over the twentieth century (more specifically, the neoliberal era starting in 1983) capitalism developed such that labor power, food, energy and raw materials

[15] In Marxist jargon, the different types of concrete labour are seen as the original source of use-values in society. In capitalist societies, production occurs for the purpose of profit rather than immediate use and in this process concrete labour is abstracted from. The resulting commodities still embody social use values, but also social labour in the abstract sense: which expresses a equivalence between different types of concrete labour and denominates it in terms of exchange value (Fine and Saad-Filho, 2010).

[16] This is later expanded and adjusted it to the "Seven Cheaps" in Patel and Moore (2017): nature, energy, food, money, care, work and lives.

[17] The simplest definition of socially necessary labor time is the amount of labour time performed by a worker of average skill and productivity, working with tools of average productivity (Marx, 1887a: pp. 29). It can be defined for specific commodities and can be seen as a Marxist type of measure for labour productivity.

had gotten cheaper and cheaper. World-ecology explains that this trend was facilitated by increased productivity (or decreased socially necessary labour time) which was only possible by setting in motion small amounts of capital and large volumes of unpaid work (Ibid, 2015b). This development is then characterized by a *high world-ecological surplus*, which is the ratio between the system-wide contribution of unpaid work to the system-wide mass of capitalized work and according to world-ecology. Every capitalist accumulation cycle is said to begin with a high ecological surplus which tends to fall over time. This is what Moore uses to express the decline in the prices of "Four Cheaps" until the onset of the 2003 commodity boom; characterized by price upswings. Another way of framing a declining ecological surplus is to state that any capitalist accumulation cycle will at some point run into peak *appropriation*. This is when the contribution of unpaid work is at its highest point relative to the capital deployed. Once unpaid work stagnates or declines, the expanded accumulation of capital will become more dependent on the capitalized/commodified inputs which increase the costs of accumulation and results in increased prices. It is important to re-emphasize that the notion of unpaid work not only encompasses extra-human nature; e.g. a decline in unpaid work can be related to the exhaustion of natural resources. Yet, unpaid work is also said to entail labour-power in the domestic sphere and its exhaustion can be expressed as the dramatic rise in mental health problems in the Global North since 2008.

Another approach is to specify the domain of paid work or capitalization/commodification as that which involves the conflict between capital and labour while the domain of unpaid work involves the struggle over the specific relation capital has towards non-monetized social reproduction (domestic work and the "work of nature"). For all that, the decrease of unpaid work identifies that capitalist accumulation has reached its frontiers and that *shifting* to new frontiers in order to pick up accumulation is a costly process. Once new frontiers are found, the cyclical tendency of the ecological surplus gets reinstated. Given that the ecological surplus is a ratio between, simply said, paid and unpaid human/extra-human work, its dynamics are not only affected by changes in unpaid work, but also by changes in paid work. The increased access to low-wage workers as a result of liberalized markets in the Global South have also widely contributed to the rise in the ecological surplus as the outsourcing of paid work was beneficial for accumulation.

While the current world-ecological regime is still unquestionably supporting strategies that are able to guarantee capitalist accumulation, Moore (2014) notices that this cheap nature strategy is failing in a double-sense. First, streams of unpaid work are depleted and new streams are becoming harder and more costly to find (also in the historical-geographical sense). Second, heightened waste generation is either exhausting streams of unpaid work and/or threatening the health of human and extra-human paid work. A great example of such a development is climate change and its implications for capitalist agriculture. It captures that we are currently living and will probably keep living in a period of *expected* ecological surplus decline. This is because the productivity of unpaid work in capitalist agriculture is worsening; causing the expansion of capitalist agriculture to increasingly rely on paid work. Unpaid work in this regard can be seen as soil fertility and favourable weather conditions. Instead of arguing that the climate poses a strict barrier/boundary/limit to growth or capitalist accumulation, Moore contends that climate change co-shapes a *new* set of contradictions in the totality of capitalism (Ibid, 2015b; 2015c):

> *Negative value refers to the ferocious combination of rising costs of production (an old cumulative dynamic) with the novel global conjecture of planetary instability and unpredictability expressed by climate change. The paired, but spatially and temporally uneven, processes of extracting nature's "free gifts" (including human work) and toxifying the biosphere (including humans) have now reached a breaking point. The accumulation of negative value, immanent but latent from the origins of capitalism, is now issuing a layer of contradictions that can no longer be "fixed" by technical, organizational, or imperial structures.*
>
> - Jason Moore, 2015b: pp. 5-6

Negative value comprises the limits that capital and its supporting state encounter in the circumvention of rising production costs and the removal of increasing waste. Hence, the current world-ecological epoch is an accumulation of previous epochs but also novel in that for the first time, there seems to be boisterous transition from surplus value to negative value. The emergence of negative value is said to introduce costs that cannot be externalized because these costs directly interfere with the conditions of production. By means of a hypothetical example: it's one thing if the exhaust of a factory pollutes an aquatic ecosystem, it's an entirely different story if the exhaust of a factory destroys the machinery. Contradictions that were present *within* capital are now mutating and will presumably act *against* capital. For Moore, the only way to recognize negative value is by shifting away from "limit"-thinking, that is to stop asking "what capitalism does to nature" and instead ask "how nature works for capitalism".

### 1.5.2. The polemic between Foster and Moore

Perhaps the succinct manner in which the world-ecology view was presented in the pages above only led the reader to treat world-ecology as an extension of the metabolic rift theory. This is because Foster traces the origins of the metabolic rift to capitalist industrialization (remaining faithful to Marx's initial analysis) while Moore traces its origins to the "long" sixteenth century. Yet, as this subsection will show, there exists a deeper dissension between metabolic-rift theorist John Bellamy Foster and world-ecology theorist Jason W. Moore. Some of them were rapidly mentioned but this subsection will shed some more light on the matter by covering some of the critiques they have towards each other.

The main point of contention between Moore and Foster lies with Moore's delineation of Foster's metabolic rift theory as grounded in *Cartesian dualism*. This is what leads metabolic-rift theorists to locate the ecological crises of capitalism in one box and accumulation crises of capitalism in another. According to Moore, this view paints environmental degradation as a *consequence* of capitalist development or an output of the system instead of treating environmental degradation as a *constituent* of capitalist development (Moore, 2011b: pp. 2). By ignoring the latter, nature and society are treated as binary and distinct categories where the dialectical relationship between the two is reduced to an analysis of how nature and society interact and transform each other. Moore's approach to nature and society on the other hand, is a different interpretation of dialectic relations. It is one that embodies a synthesis between nature and society considers how this synthesis has been reconfigured over the course of history. In order to part ways with Cartesian dualism, Moore introduces the *oikeios*, a Greek name for "favourable place". The *oikeios* is used to name "the creative, historical, and dialectical relation between, and also always within, human and extra-human natures" (Ibid, 2015a: pp. 46). This conception, Moore contends, allows one to pinpoint the relations through which humans and nature create the conditions of life. Nature-as-*oikeios* can never be seen as an additional factor to society or the economy, it is instead the field upon which human activity unfolds.

In an interview, Foster responds to the accusation of Carthesian dualism by coining Moore's understanding of nature as a double-internality (nature-in-humanity and humanity-in-nature) as a view that, in contrast to dualism, is monist and relational. Foster argues that this understanding of nature represents the philosophical position called "neutral monism" which argues that even in an abstract sense, mind and matter are inseparable. This position, according to Foster, was introduced as an opposition to materialism, idealism and Marxian dialectics. What Moore disregards from Foster's metabolic rift theory is that it applies Marx's inherently dialectic ecological critique of capitalism:

> *Dialectics is always about appearance and essence, identity in difference, the interpenetration of opposites, and the negation of the negation. It is never a choice, as Moore seems to think, between crude dualism and crude monism. There is no contradiction in seeing society as both separate from and irreducible to the Earth system as a whole, and simultaneously as a fundamental part of it. To call that approach "dualist" is comparable to denying that your heart is both an integral part of your body and a distinct organ with unique features and functions.*
>
> - John Bellamy Foster, 2016

Thus, a proper dialectic is capable of recognizing that the world is indeed an open-ended context in which human beings participate as historical beings. By accusing scholarly work which applies a strict nature/society divide as Cartesian dualism (never answering "what capitalism does to nature"), Moore is said to reject the bulk of progress in eco-Marxism.

Another point of contention between the two authors is related to Moore's framework of the "Four Cheaps" which regards commodity frontiers and the dynamics between appropriation and capitalization. Foster argues that the placement of labour on the same level as food, raw materials and energy is equal to seeing ecology from a capitalist perspective (Ibid, 2016). Which is to say that the analysis is shifted to the threat of rising prices for capitalist accumulation instead of regarding the effect of capitalism on nature. In other words, Moore's conception reduces ecological problems to "tap" problems while downplaying the "sink" problem and how capitalism degrades the earth as a whole by imposing waste on it. In a way, Foster seems to imply that Moore's work reflects late first-stage considerations, such as O'Connor's second contradiction theory. Moore is said to radically modify not only Marxist dialectics but also Marxist value analysis — which brings us to the last point of belligerency between the two authors.

In a nutshell, Foster's metabolic rift theory is accused to be orthodox because he treats value the way Marx first conceptualized it; also known as adherance to the labour theory of value (LTV). Moore's world-ecology theory on the other hand can perhaps be described as post-Marxist; he transcends the LTV in order to incorporate not only physical and material elements as determinants for the value formation but also *relational* elements. It is this kind of adjustment to Marx's theory that makes Foster particularly hostile to Moore. Is this animosity really justified though? As we shortly mentioned in the above outline of world-ecology, Moore understands capitalism and its development as a in terms of capitalization and appropriation. Capitalization represents the orthodox Marxist aspect of his theory, as it regards the class-struggle over the distribution of surplus value. Appropriation on the other hand represents the so-called post-Marxist aspect of his theory since it reflects the part of capitalist accumulation which is based on "taking things for free". The focus on the dynamic between capitalization and appropriation allows Moore to bypass the perception of nature as an independent system which is "insufficient for understanding how capitalism reaches limits, how capitalism has transcended limits historically, and how capitalism has remade successive historical natures in a way that may pose intractable problems for its survival today" (Moore, 2015a: pp. 69).

In order to further clarify the difference between Foster and Moore's approach to value theory we find it useful to iterate their respective usage of expropriation and appropriation. Foster (2018) highlights the difference between appropriation and expropriation through an assessment of the polemic between Marx and Proudhon. It was based on the latter's famous expression that "property is theft" in *What is Property? Or, an inquiry into the Principle of Right and of Goverment* from 1840. Marx contested this expression because in his opinion, Proudhon failed to take into account the various forms of property. As recounted by Foster and Clark (2018), Marx insisted that by characterizing all kinds of property or appropriation as theft, Proudhon placed common property and small peasant holdings in the same category as bourgeois private property. In defence of small peasant holdings, Marx treats the appropriation of nature as a fundamental element of social life since it established the metabolism between humanity and nature in the first place. Alienated laws of capitalist appropriation "rifted" the entirety of human metabolic interactions with the environment but appropriation in and of itself is not necessarily detrimental.

There exists a specific kind of appropriation which Marx came to refer to as *expropriation*; the appropriation without equality in all actual exchange relationships. Expropriation is a general all-encompassing term for buying cheap and selling dearer through the dispossession of someone's right to property. It entails that there is no exchange of equivalents. What is important to understand with regard to Marx's treatment of expropriation in general, is that it is not necessarily a characteristic of capitalism, merchants and feudal lords engaged in the same exercise through exploration & trade and the enslavement & extortion of peasants for their surplus product. However, under developed capitalist production, class-based expropriation is hidden by a market system which claims that the exchanges it fosters *are* of an equal nature. Workers who engage in a wage-contract are paid a value which perfectly represents the value of their expended labour power. Nonetheless, capital can still extract a surplus from the unpaid fraction of labour. It is this specific form of expropriation (or appropriation without exchange) occurring within the value circuit of capitalist production, that Marx calls the *exploitation* of labour power.

What does the distinction between appropriation, expropriation and exploitation imply for Foster's metabolic rift theory? Nature in pre-industrial capitalism was dominated by merchant capital and has been expropriated to the benefit of accumulation. And so was labour since it was performed by either slaves or peasants; the disparity in exchange was visible from the outset for *both* nature and labour. This type of expropriation is what historically prepared the ground for exploitation under developed capitalism. Indeed, industrial capitalism, characterized by markets shaping the circuit of capital and advertising the "illusion" of equivalent exchange, subjected nature to exploited instead of expropriated labour.

According to Foster and Clark (2018) it is particularly the combination of expropriated nature and exploited labour that gives rise to the destruction of conditions of reproduction — the metabolic rift. Therefore to theorize the ecological disruption in terms of the ratio between appropriation and exploitation ala Moore, is to disregard, just as Proudhon did the various types of property and the specific type of capitalist appropriation called expropriation. Again, for Foster (2018), ecological disruptions under capitalism are not a result of the appropriation of unpaid work. Rather, they are the result of the expropriation of ecological processes in a unique configuration with exploited labour which leads to an alienated metabolism between humans and nature. Put very simply, Foster envisions ecological disruptions as the dialectical tension between expropriation and exploitation while Moore envisions ecological crises as the dialectical tension between appropriation and exploitation (capitalization). In our view, Foster's analysis is ignorant of the fact that ecological disruptions do not *require* exploited labour. As indicated by Moore's historical treatment of sugar, metabolic rifts occurred in periods of slave labour as well.

What are the implications of this discrepancy for the interpretation of a value theory in an ecological context? Foster (2018) grounds his value theory in orthodox Marxist theory, in capitalism, value is the solidification of socially necessary abstract labour and natural material use-values don't play a role in the valorization process; even if material use-values are elemental to each and every commodity and form the basis of all real wealth. This is because capitalist commodity production is built on the contradiction between use values and exchange values resulting in a contradiction between real wealth and value respectively. The commodity value form under capitalism is not one in which bees or energy participate, it is a product of human social-class relations and actively excludes nature from this value form. In this sense, a commodity's value form echoes the neoclassical notion of nature as a "free gift" to capital. Nature is annexed by capital and the entirety of the means of production while wealth in society is monopolized.

In contrast, and in line with his critique of Cartesian dualism, Walker and Moore (2019) argue that the duality between exchange-value and use-value is not a sufficient way to take into account the complex relation that capitalism shapes between nature and society. This is because such a stark distinction obscures the fact that labour is always working alongside nature (unpaid work) in a given production process. Hence, there is a constant interplay between labour and nature and they each shape each other. For this reason, the authors introduce social labour-nature time as a measure for value under capitalism, instead of socially necessary abstract labour. In their labour-nature theory of value, the work by nature and the work by labour is impossible to unravel and so the common measure for both is necessary labour time but it is important to recall the free work of nature is embodied in it. Any measure of "labour time" is therefore always a measure of unified labour-nature time. For example, in the case of a mine, the quality of e.g. coal is decisive for the amount of labour time involved in the extraction and combustion. Of course, this theory of value can also be formulated as the paid-unpaid work theory of value or appropriation-exploitation (capitalization) theory of value. In the end, the commodity form only contains the value of paid work, but the amount of paid work is ultimately shaped by the amount of unpaid work.

Foster (2018) argues Moore's "new value theory" is a complete dismissal of Marx's own analysis, especially when presented through the "Four Cheaps" framework. He goes on by claiming that Moore is as obscure as Proudhon in declaring that "commodity frontiers were so epoch-making because they extended the zone of appropriation faster than the zone of commodification" (Moore, 2015a: pp. 199). Which is to say that the appropriation of the Seven or Four Cheaps (including unpaid labour) grew at a faster rate than the capitalization and exploitation of paid labour. Foster concludes:

> *In Moore's "new law of value," all of material existence, whether paid social labor, unpaid social labor, or the unpaid work/energy of the universe, matters largely to the extent that it is harnessed to the capitalist valorization process ... Physics, ecology, and economy all get rolled into one, erasing fundamental distinctions, crucial to Marx's ecological (and economic) critique. Indeed "the capital relation," for Moore, "transforms the work/energy of all natures into... value.*
>
> - John Bellamy Foster, 2018

The reader may wonder whether Foster is right in accusations of Moore, or what the merit is of strictly clinging on to Marx's original interpretation of ecology. The reader may also argue that Moore's approach is innovative but too abstract. In any case, we argue that while the distinctions between the world-ecology and the metabolic-rift theories exist and are valid, there exists a possibility to mend and consolidate both theories by consciously migrating out of the realm of philosophy and sociology into the realm of (Ecological) Economics. This possibility will be elaborated upon in the conclusion below.

## 1.6. Conclusion

As mentioned in the title, we set out this literature review to emphasize *rifts, shifts and intermissions* in the modern considerations on Marx & Ecology. Evidently, the use of "rifts" is a direct reference to metabolic rift theory which was arrived at through an extensive inquiry into Marx's critique of capitalist agriculture. We have provided a summary of the arguments used to maintain that Marx & Ecology are not as antithetical as they are proclaimed to be. Before arriving at this point, we presented an overview of the academic literature on Marx & Ecology from the 1950s to the early 1990s. This allowed us to present the origins of the metabolic rift theory and formulate it as the outcome of a "shift" away from the automatic and organic way Marx's analysis of capitalism was used to explain eco-systemic changes — this is the shift away from early first-stage and late first-stage considerations.

After acquainting the reader with a tabular literature review concerning the application of metabolic rift theory to various contemporary academic analyses of ecological disruptions, we arrived at a second reference to "shift" captured in the latest theoretical adjustment and interpretation of second-stage considerations on Marx & Ecology. This is world-ecology and it extends the metabolic rift theory by examining the commodity-specific and long-term world-historical culmination of metabolic rifts and how they induced "shifts" from one commodity frontier to the other.

Finally, and more related to the purpose of the overall project this paper aspires to take part of, we exposed that ever since the synthesis between Marx & Ecology was theoretically established by second-stage scholars, it has barely found its way into the field economics. This, while early first-stage economists freely incorporated Marx into their ecological critique of capitalism without thoroughly revisiting Marx's understanding of nature. Hence, from an economic point of view there seems to be an "intermission" in the considerations on Marx & Ecology. This is why the main aim of the paper was to introduce the main theories on capitalist development in conjunction with ecological degradation. Hopefully in this way, we have laid the basis for our subsequent aspiration, which is to mathematically formalize the metabolic rift theory. What particularly encourages us to undertake the aforementioned effort can be summed up in the following way.

1. While the metabolic rift theory is hitherto not considered in the field of economics, the field of EE is not void of metabolic analyses. Indeed, the analyses of *socio-economic* metabolism aim to describe the interaction between human society and nature as a complex self-reproducing system by tracing the flows of materials and energy which society and nature exchange. Since these exchange flows are an essential feature for all human societies, their magnitude and diversity specifically depends on socio-metabolic regimes (Pauliuk and Hertwich, 2015).

   Even if the above introduction of socio-economic metabolism is extremely superficial, it shouldn't be difficult to imagine a certain compatibility with metabolic rift theory and/or world-ecology. This is particularly the case if we consider an approach called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM). Its potential for the formalization of the metabolic rift lies with its ability to present analyses over non-equivalent descriptive domains (Giampietro et al., 2001). This means that it could allow us to formally establish a relationship between i) social metabolism (material and energy flows) ii) ecosystem metabolism (negentropic costs) and iii) the economic system (surplus value extraction). This inaugurates a potential aim for future research; to introduce the MuSIASEM framework and identify to what extent it should be adjusted to formally represent both metabolic rift and world-ecology considerations.

2. We also believe that by taking into account aspects of both metabolic rift and world-ecology in an economic framework, the stark division between them partially dissolves. Our view on Foster & Moore is that the *real* difference between them is rather a question of philosophy and the semantics thereof. To reiterate; Moore's world-historical extension and dynamic interpretation of the metabolic rift is particularly valuable for empirical exercises but also for economic analyses of the relationship between nations when it comes to a particular commodity or one of the "Four/Seven Cheaps". Limiting the attention to this aspect, one can simply view

Moore's theory as a relevant augmentation of Foster's theory. But this simplicity is reduced once one recalls that the authors' disagreement is centred around the whole "appropriation/expropriation/capitalization/exploitation/" lingo.

Foster describes ecological disruptions as the result of a capitalist-driven interplay between the expropriation of nature and the exploitation of labour, the two of them interacting in a dialectic fashion. Moore on the other hand, presents a holistic approach to this dualism by describing the dynamics of the system's ecological surplus, which is the ratio between unpaid human/extra-human work (appropriation) and paid human work (capitalization). Rather than debating whether appropriation is more or less Marxist than expropriation we can also argue that if expropriation were to take into account contemporary and dominant forms of unpaid human labour (e.g. domestic labour), the two definitions eventually plunge into the same category. Especially if one considers that the economic consideration we aim to provide will require at least some kind of measurability e.g. hours of unpaid labour (human) and soil fertility (extra-human).

Furthermore the value-theoretic difference between Moore & Foster also dissipates if we recall that Foster argues that value is the solidification of socially necessary abstract labour while Moore argues that value is the solidification of socially abstract labour-nature time. The latter concept is supposed to reflect that the formation of value under capitalism is a result of the *relation* between capitalized and appropriated work, but in the end, the measures of Foster & Moore are the same. The only difference being Moore's appeal to realize that the measure of labour time *embeds* the unpaid work of both humans and extra-humans. We agree with the complex character of Moore's conception but an economic consideration (especially a preliminary attempt) is likely unable to represent such degrees of complexity. Ultimately, the difference between Foster & Moore merely dissolves into a difference in the descriptions of measurable units. As a result, we maintain that a "dualist" approach to the difference between Foster & Moore is noticeably unproductive when it comes to the attempt to formalize the synthesis between Marx & Ecology, instead we will attempt to "holistically" incorporate both of them for the purpose of formalization.

## Appendix A

# Literature review on third-stage considerations on Marx & Ecology

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| P Mancus | 2007 | *Nitrogen Fertilizer Dependency and Its Contradictions: A Theoretical Exploration of Socio-Ecological Metabolism* | Rural Sociology | • The increasing use of inorganic nitrogenous fertilizer embeds a contradiction for the state of global food security<br>• There exists an increasing provision of food for growing population vs. ecological disruption as a result of pollution, leaching and erosion<br>• Metabolic rift is induced by the capitalist global food production system characterized by the constant drive of farmers to increase shareholder value to prevent divestment |
| R Gunderson | 2011 | *The Metabolic Rifts of Livestock Agribusiness* | Organization & Environment | • As a result of the global economic system, driven by capital's impulse to expand, livestock production has undergone a rapid mechanized process undermining animals, farmers and landscapes<br>• This development induces a metabolic rift in the global carbon, nitrogen and hydrological cycles<br>• Local food movements carry the potential to mend the rift but disproportionally appeal to the middle classes and exclude the marginalized |

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science *(Continued)*

| Author | Year | Title | Journal | Description |
| --- | --- | --- | --- | --- |
| M Clow & D McLaughlin | 2008 | *Healing the Metabolic Rift between Farming and the Eco-System: Challenges Facing Organic Farmers in Canada and in Sweden* | Socialist Studies/Études Socialistes | • Organic farmers are usually said to carefully plan the production process in order to maintain a diversified and self-balancing agricultural ecosystem - possibly "healing" metabolic rifts<br>• Ethnographic study shows that organic farmers in Canada and Sweden are unable to heal the rift in terms of nutrient cycling and the antagonism between rural and urban populations. This is because fundamental changes are necessary in order to escape the demand of capital accumulation |
| JA McGee & C Alvarez | 2016 | *Sustaining without Changing: The Metabolic Rift of Certified Organic Farming* | Sustainability | • Argue that organic farming has undergone a period of "conventionalization": as certified organic farming grows its idealistically driven counter-cultural characteristics diminish and are substituted by a tendency to mimic conventional farming<br>• Study the process of conventionalization and its implication for the metabolic rift in terms of the hydrological cycle, the authors apply a fixed-effects panel regression over a period of 5 years (2002 - 2007) where the dependent variable is biochemical oxygen demand (BOD)[1]<br>• The results indicate that the proportion of organic land has a significant and positive effect on BOD and supports the hypothesis that organic farming has at least not been able to *decrease* the rift in the hydrological cycle |

[1] This is the amount of oxygen microorganisms in water need to break down waste in natural water systems and serves as an adequate proxy for water pollution.

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| H Wittman | 2009 | *Reworking the metabolic rift: La Vía Campesina, agrarian citizenship, and food sovereignty* | The Journal of Peasant Studies | • Provides an inquiry into more radical alternatives to "conventionalized" organic farming by studying the international peasant's movement La Via Campesina (LVC)<br>• By advocating for food sovereignty and agrarian citizenship LVC bears a potential to mend the metabolic rift caused by corporations and market institutions that currently dominate the global food production system<br>• This potential is still limited by the internal and external contradictions found in LVC due to class, political and ideological differentiations |
| R Clausen, B Clark & SB Longo | 2015 | *Metabolic Rifts and Restoration: Agricultural Crises and the Potential of Cuba's Organic, Socialist Approach to Food Production* | World Review of Political Economy | • Provides a detailed critique of organic farming in the United States which is said to be co-opted by capitalist agribusiness - reducing the metabolic restoration potential by increasing the scale of farming and applying mono-culture production methods<br>• Before the fall of the Soviet Union, Cuba's agricultural system was characterized by the widespread use of pesticides, state maintained ownership of farms and technocratic agriculture regimes<br>• Since the collapse however, facing massive declines in imports, the agricultural practices experienced a shift to a system based on ecological principles and social justice<br>• While Cuba's agricultural system has a metabolic restoration potential which is far higher than that of American organic farming, it came about as a result of the specific and historical position in the global political economy |

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| E Slater & E Flaherty | 2009 | *Marx on Primitive Communism: The Irish Rundale Agrarian Commune, its Internal Dynamics and the Metabolic Rift* | Irish Journal of Anthropology | • Metabolic rift is analyzed in a historical context which was not yet dominated by the capitalist mode of production - The Irish Rundale Agrarian Commune<br>• The Irish Rundale system was a specific form of occupying land; it was divided into discontinuous plots and cultivated & occupied by tenants who lease the plot. The authors argue that the mode of production was that of primitive communism<br>• Due to the inability of the agrarian commune to deal with population growth as well as a general increase of individualism, the Rundale system eventually created metabolic rift in the ecosystem metabolism. |
| JJ Ramisch | 2016 | *"Never at ease": cellphones, multilocational households, and the metabolic rift in western Kenya* | Agriculture and Human Values | • An analysis arguing that labour exportation and spatial separation of migrants from the rural setting is inducing metabolic rifts in the agroecological systems<br>• The ethnographic study shows that the spread of mobile money transfer technologies result in less frequent visits from migrants to their rural household which causes them to grow less knowledgeable about changes in the environment<br>• A patriarchal setting further increases the ability of men to exert decision-making power without first-hand experience on the farm |
| MR Sanderson & RS Frey | 2014 | *From desert to breadbasket... to desert again? A metabolic rift in the High Plains Aquifer* | Journal of Political Ecology | • Explores water depletion problems in the High Plains region, one of the most important agricultural regions in the United States<br>• The region is semi-arid and the original source of water for the aquifers used to be winter runoff from the Rocky Mountains, now it is only recharged by occasional rainfall<br>• 90% of the water from the aquifer is used for irrigation in agriculture, the expansion of export-driven agricultural production in the region is concluded to widen the metabolic rift in the hydrological cycle. |

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| R Clausen & B Clark | 2005 | *The Metabolic Rift and Marine Ecology: An Analysis of the Ocean Crisis Within Capitalist Production* | Organization & Environment | • Point out that the expansion of aquaculture networks by multinational corporations not only threatens the biological integrity of marine ecosystems but also human health, due to the accumulation of organochlorine contaminants; pesticides used in fish farming<br>• Provide a historical materialist interpretation of the development of fishing activities and how society understands the ocean as a natural resource the interaction between socioeconomic structures and marine ecological change is brought to the forefront<br>• Conclude that the awareness of full effects of fishery depletion by the corporate realm of discussion has thus far only led to policy innovations that aim to efficiently allocate fishery rights among open-seas fishermen and thus simply accommodates capital without repairing the rift between society and the ocean. |
| SB Longo | 2012 | *Mediterranean Rift: Socio-Ecological Transformations in the Sicilian Bluefin Tuna Fishery* | Critical Sociology | • Emphasizes the developments in Sicilian bluefin tuna fisheries and argues that traditional trap fisheries in Sicily has historically been of the most fertile method for catching fish<br>• The chambers of these traps are large enough to create favourable conditions for the biological reproduction and the fishermen who operated them deploy an sophisticated set of skills adapted to the local environment - suggesting that traditional fishermen was more aware of the delicate socio-ecological metabolism of their prey<br>• Concludes that modern fishing methods aim to cater the growing global demand for tuna and adopt the complimentary technologies that increase productivity but considerably damage the reproductive cycle of the blue fin tuna and violate the long-term sustainability of its stock |

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| C Perdikaris, P Kozák, A Kouba, E Konstantinidis & I Paschos | 2012 | *Socio-economic drivers and non-indigenous freshwater crayfish species in Europe* | Knowledge and Management of Aquatic Ecosystems | • Investigate non-indigenous crayfish species (NICS) which are said to pose a serious threat to the biodiversity of European freshwaters. • NICS have been imported into Europe from North America in the late $19^{th}$ century and has spread to freshwaters as a result of aquarium trade, the use of crayfish as angling baits and escapes form garden ponds especially during floods • Conduct an empirical study in 26 EU countries and analyze the following variables: NICS, human population density, percentage of urbanization, GDP, biocapacity and ecological footprints • The results indicate that population density has a strong and negative effect on biodiversity (proxied by an increase in NICS) while urbanization has a moderate and negative effect on biodiversity. Furthermore, the effect of GDP is weakly representing the environmental Kuznets curve. |
| R Wishart | 2012 | *Coal River's Last Mountain: King Coal's Après moi le déluge Reign* | Organization & Environment | • Applies metabolic rift analyses in the context of mountaintop removal coal mining in the Coal River Valley, West Virginia and discusses the role of capital in the inability of green energy technologies to substitute the demand for coal mining • The metabolic rift in the global carbon cycle is induced by direct and indirect $CO_2$ emissions from the extraction process (on-site mining, transport and combustion • Mountaintop removal coal mining also affects hydrological and nutrient cycles disrupting the natural habitat and reducing the biodiversity of species |

Table A.1: Third-Stage Literature Review on Agriculture, Aquaculture, Extraction and Land Change Science *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| R Dobrovolski | 2012 | *Marx's Ecology and the Understanding of Land Cover Change* | Monthly Review | • Explains that land cover change entails the substitution of natural habitats (swamps, forests, etc.) for cropland, pasture, roads and urban areas. It is the main driver of species extinction and biodiversity losses which threaten the availability of life-sustaining resources<br>• Argues that traditional approaches that describe the process of land cover change regard the whole of human activity as its main driver without taking into account the overall economic system these activities take place in - capitalism<br>• Proposes an alternative conceptualization of land cover change and argues that the agriculture and extraction activities in the Amazon and their resulting metabolic rift, can be treated as the consequence of the search for differential rent as theorized in Marx's theory of ground rent |
| BM Napoletano, J Paneque-Gálvez & A Vieyra | 2015 | *Spatial Fix and Metabolic Rift as Conceptual Tools in Land-Change Science* | Capitalism Nature Socialism | • The reason why land-change science has been unable to connect land-change to the global territoriality of the capitalist system is because it represents a post-positivist ideology of science and a neoclassical ideology of economics<br>• Combine David Harvey's conception of the spatial rift with the metabolic rift to suggest that the geography of capitalism's cycles of territorial destruction and reconstruction is superimposed by a systemic tendency to reconfigure space such that there is an expansion of volume, rate and distance of material flows - causing a metabolic rift over geographical configurations<br>• Conclude that land change sciences should transform into a tool that is able to take into account the complex political ecologies that underlie land change. |

Table A.2: Third-Stage Literature Review on Urban Metabolism and Urban Agriculture

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| VC Broto,<br>A Allen &<br>E Rapoport | 2012 | *Interdisciplinary Perspectives on Urban Metabolism* | Journal of Industrial Ecology | • Provides a literature review on the deployment of urban metabolism across various displines<br>• One of the key topics in the literature on urban metabolism is the economic drivers of rural-urban relationships; due to the global context increases in the urban metabolism are often linked to the growing demand for resources, the production of waste and ecological conflicts at commodity frontiers that are quite distanced from the city<br>• Other topics include the general normalization of capital accumulation in the neoliberal era and how it worsens metabolic rifts while at the same time giving rise to urban-based struggles at multiple scales |
| MT Clement | 2009 | *A Basic Accounting of Variation in Municipal Solid-Waste Generation at the County Level in Texas, 2006: Groundwork for Applying Metabolic-Rift Theory to Waste Generation* | Rural Sociology | • Empirical study utilizing a robust regression to estimate the effect of population and the quadratic per capita income on municipal solid waste (MSW) in the Texas county in 2006.<br>• Results show that income is significantly and positively correlated to MSW which discredits the ecological modernization theory which asserts that the development of a capitalist economy increases wealth and technological advancements consequently generating less garbage.<br>• Instead the results support the metabolic rift theory - the buildup of garbage is a result of capitalist economic development where the rise in affluence culminates a disproportionate exchange of matter and energy between nature and modern society |

Table A.2: Third-Stage Literature Review on Urban Metabolism and Urban Agriculture *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| N McClintock | 2010 | *Why farm the city? Theorizing urban agriculture through a lens of metabolic rift* | Cambridge journal of Regions, Economy and Society | • Argues that urban agriculture practices are often informed by an ethos of agricultural sustainability, thereby fostering the ability to close nutrient cycles in the traditional Marxist sense<br>• When it comes to nitrogen, the application of compost together with the plantation of nitrogen fixing cover crops and use of cover crops in urban agricultural settings allows its production to rely less on spatial and temporal subsidies.<br>• The greatest obstacle for urban agriculture and its potential to mend the metabolic rift has to do with the assurance of infrastructure for the collection, composting and distribution of compost. |
| M Dehaene, C Tornaghi & C Sage | 2016 | *Mending the metabolic rift: Placing the 'urban' in urban agriculture* | Chapter in: Urban Agriculture Europe | • Take a more critical stance towards the potential of urban agriculture to mend the metabolic rift because if it is economically viable but remains isolated and residual, it does not axiomatically affect the issues of justice, health, resourcefulness or progressive development<br>• To actively restore the metabolic rift, the practices need to adhere to emancipatory goals and require regulatory and conceptual frameworks that represent both social and ecological dimensions.<br>• In this way, urban agriculture becomes more than the cultivation of urban soil for food production but also involves the thorough consideration of all the nutrient cycles at play while simultaneously sharing, reproducing and sharing the knowledge necessary to master these processes. |

Table A.2: Third-Stage Literature Review on Urban Metabolism and Urban Agriculture *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| J Sbicca | 2014 | *The Need to Feed: Urban Metabolic Struggles of Actually Existing Radical Projects* | Critical Sociology | • Investigate urban metabolic restoration in organizations that promote urban agriculture in the United States<br>• Two types of "metabolic rift healing" organizations are identified: i) those that are oriented towards development and aid (Food Not Bombs Orlando) and ii) those that are oriented towards empowerment, entitlement and redistribution (People's Grocery in West Oakland)<br>• The first type supports poor people but strictly depends on the overproduction of commodities under capitalism to achieve their aims. The second type was involved in the provision of resources for urban food production but is now supporting larger food production projects and focusing on nutrition and cooking classes.<br>• Both organizations are said to prioritize the malnutrition rift over the agricultural rift. |
| M Gandy | 2018 | *Cities in deep time* | City | • Initiates the discussion of the "urban question" by listing key-developments in the Anthropocene, the epoch characterized by human-induced ecological disruptions<br>• Offers a philosophical interpretation by postulating that urban development, while not synonymous to capitalism, should be seen as an outcome of the structural, political, ideological and technological characteristics of capital rather than as fundamental attributes of the modern city or modernity as such.<br>• Highlights that heterogeneous urban areas play a dual role in the protection of biodiversity through: i) the foundation of an ecological temple for both flora and fauna and ii) the exploration of different socio-ecological interactions that could be bring global environmental politics into alternative arenas of discourse - a recognition that could open the gap for a true restoration of urban metabolism. |

Table A.2: Third-Stage Literature Review on Urban Metabolism and Urban Agriculture *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| E Swyngedouw | 2006 | *Metabolic urbanization: the making of cyborg cities* | Chapter in: In the nature of cities | • In a philosophical sense, treats cities as dense networks of interwoven socio-ecological processes that are human, physical, discursive, cultural, material and organic.<br>• Nature is said to become urbanized as a result of the reproduction of socio-metabolic processes - the de-territorialization and re-territorialization through circulatory flows<br>• Highlights that urban greening, urban agriculture and other ecological transformations of the urban area cannot be seen in a vacuum. All of these initiatives require a devotion to the political-ecological underpinnings if the socio ecological metabolism is to be improved in a way that returns both the city and the city's environment back to its citizens. |
| VC Broto & H Bulkely | 2013 | *Maintaining Climate Change Experiments: Urban Political Ecology and the Everyday Reconfiguration of Urban Infrastructure* | International Journal of Urban and Regional Research | • Study climate change experiments in Mexico and India which are focused on the reconfiguration of sociotechnical systems to achieve low-carbon and resilient cities.<br>• They conclude that while the efforts are promising, the fact that they are merely experiments and therefore lack maintenance, hampers a radical transformation of the urban metabolism. Furthermore, the experiments over-accentuated "technological" fixes while failing to address the fundamental relations which structure society. |

Table A.2: Third-Stage Literature Review on Urban Metabolism and Urban Agriculture *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| C Ergas & MT Clement | 2016 | *Ecovillages, Restitution, and the Political-Economic Opportunity Structure: An Urban Case Study in Mitigating the Metabolic Rift* | Critical Sociology | • Discuss a case study on the phenomenon of eco-villages which are characterized by consensus decision-making, rational agriculture, land stewardship and surplus sharing<br>• Conclude while the above practices offer a serious potential for metabolic restoration a complete transformation of the town-country divide cannot be achieved within the boundaries of the villages<br>• The obstacles are related to the intimate connection between urban areas and capitalism as well as the class and racial disparity among the inhabitants of eco-villages (most of them being white and of the middle class). |

Table A.3: Third-Stage Literature Review on Theoretical Advancements in Metabolic Rift Theory

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| M Crook & D Short | 2014 | *Marx, Lemkin and the genocide–ecocide nexus* | The International Journal of Human Rights | • Explain why a Marxist interpretation of ecocide is relevant for scholars of human justice and genocide<br>• Contend that capitalist land grabs by industrial farms and extractive industries result in the annexation of indigenous land and metabolic rifts, it is concluded that ecocide can be a method for genocide when conditions of life are destroyed |
| M Schneider & P McMichael | 2010 | *Deepening, and repairing, the metabolic rift* | The Journal of Peasant Studies | • Argue that metabolic rift theory understood as a metabolism in relation to the labour process privileges the organisation of labour over the practice of labour<br>• Metabolic rift analyses overlook that apart from ecological disruptions there is also an knowledge or cultural rift which indicates a separation between the natural and social world. |

Table A.3: Third-Stage Literature Review on Theoretical Advancements in Metabolic Rift Theory *(Continued)*

| Author | Year | Title | Journal | Description |
|---|---|---|---|---|
| G Canavan, L Klarr & R Vu | 2010 | *Embodied Materialism in Action: An Interview with Ariel Salleh* | Polygraph | • Interview one of the main scholars associated with eco-feminism, Ariel Salleh. Eco-feminism is theoretical framework which asserts that capitalist patriarchal economies heavily rely on the critical alienation of humans from nature<br>• Salleh argues that while metabolic rift involves the exploitation of people's labour it also comprises the appropriation of the reproductive labour of women who are said to historically bear a unique metabolism with nature in the first place<br>• To mend the metabolic rift, the end of capital is postulated as a necessary but not sufficient condition for sustainability, it is also necessary to address hegemonic masculinity and the concrete particularities of sex-gendering in everyday life. |
| A Salleh | 2010 | *From Metabolic Rift to "Metabolic Value": Reflections on Environmental Sociology and the Alternative Globalization Movement* | Organization & Environment | • Introduces the following metabolic rift related concepts *meta-industrial labour* and *metabolic value*.<br>• Meta-industrial labour captures labour by workers outside the domain of capitalism but which catalyzes metabolic transformations. Examples are peasants, gatherers or parents, the logic behind their actions is considered to be relational, cyclic, flow oriented and regenerative. Metabolic value denotes a specific value, sustained and enhanced by meta-industrial labour<br>• Concludes that while men in the domestic setting are equally capable of labouring in the meta-industrial sector, as more and more women enter the paid workforce, men fail to maintain the metabolic value provided by women. |

# Chapter 2

# Considering the role of distribution: a conceptual adaptation of the MuSIASEM framework*


### Abstract

Contemporary heterodox approaches to ecological disruptions have substantially expanded in the last decades. Stock-Flow Consistent Modelling in the post-Keynesian tradition has increasingly dealt with the depiction of economy-ecology configurations but the ecological considerations have usually been limited to an analysis of output-based green house gas emissions. This paper provides a brief overview of the aforementioned stream of literature in order to subsequently point out a lack of considerations with respect to economy-ecology configurations in the realm of agriculture. The relevance of agriculture is stressed by highlighting the ecological impact of agricultural intensification pointed out in the fields of eco-Marxism and the Multi-Scale Integrated Assessments of Social and Ecosystem Metabolism (MuSIASEM) framework. The main aim the paper is to explore the compatibility between the latter two streams of literature such as to equip Ecological Economics with a more complete vantage point. Our exploratory results show that the compatibility between eco-Marxism and MuSIASEM exists but that it is limited to a conceptual level. Through the provision of a biophysical analysis of a 3-sector closed economy we conclude that MuSIASEM equips eco-Marxism with the ability to quantify measures of ecological appropriation while eco-Marxism augments the MuSIASEM framework with a distributional component.



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## 2.1. Introduction

In a recent paper called "Roots, Riots and Radical Change – A Road Less Travelled for Ecological Economics" a case is made for the establishment of a new research agenda for Ecological Economics (EE). Thus far, EE has promoted itself as a trans- and interdisciplinary approach to research concerning the environment and the economy. EE's integration of economics, ecology, thermodynamics, ethics, social sciences and natural sciences also became a way to distinguish itself from Environmental and Resource Economics (Van den Bergh, 2001).
In the face of what is now referred to as the global "climate crisis" it is unfortunate to realize that what is supposed to be the most radical approach to the scientific understanding of ecological disruptions, is possibly falling short. Pirgmaier and Steinberger (2019) mention an accomplished set of reasons behind the inability of EE to live up to its name. One of them is that EE fails to provide an accurate account of capitalism and how its underlying mechanisms are intertwined with ecological disruptions. Outside the confines of economic science, the analysis of capitalism and its implication for both ecological crises and ineffective neoliberal environmental policies are far more established (Foster et al., 2011; Ghotge, 2018a,b; Klein, 2015; Lohmann, 2011; Malm, 2016; Moore, 2015a; Vlachou, 2004). At the same time, there are many economists who carry forward the works of Marx and address topics like class & exploitation, value, technological change, rent, accumulation and economic crises (see e.g Basu, 2018; Bellofiore, 2011; Duménil and Lévy, 2003; Galanis et al., 2019; Grinberg, 2013; Kliman, 2015; Mohun, 2016; Moseley, 2016; Olsen, 2015). Yet, an integration between Marx & Ecology in the field of EE is barely visible. Even if, one could easily argue that there exists somewhat of a similarity between EE and Marxist political economy: both acknowledge the exploitation of biophysical values and focus on the physical and material basis of economic activity (Hornborg, 2014).
One of the reasons behind this notable divorce may have to do with the fact that anything related to Marx automatically reminds us of 20$^{th}$ century communist or socialist states, which, compared to their capitalist counterparts, have been just as hostile or even more hostile to the environment. Another reason may be related to the fact that the environmentally-oriented wing of academia has established a narrative in which Marx is portrayed as anthropocentric and anti-ecological. In any case, an obvious consequence of the aforementioned narrative is that most analytical treatments and modelling efforts within the realm of ecological economics lack a characterization of economy-ecology configurations from a Marxist perspective.
In an effort to explore the extent to which considerations on Marx & Ecology can be integrated in economic frameworks, the first section of this paper briefly touches upon the most recent development in the field of EE. When it comes to macroeconomics, it seems that the academic field is experiencing a shift towards post-Keynesian system dynamics, input/output or (agent-based) stock-flow consistent modelling approaches (Hardt and O'Neill, 2017; Rezai and Stagl,

2016). At the same time, this indicates a shift away from orthodox integrated assessment models (Farmer et al., 2015; Hassler and Krusell, 2018) and computable or dynamic-stochastic general equilibrium models (Babatunde et al., 2017; Cai et al., 2015). Generally speaking, post-Keynesian approaches offer a more accurate portrayal of a capitalist economy through their emphasis on the distribution between workers and capitalists, finance & banking, non-frictional unemployment and the important relationship between aggregate demand and investment. With respect to economy-ecology configurations, however, analyses have thus far been limited to climate change and the socio-economic repercussions of climate policies.

While climate change is a pressing issue, the modern synthesis between Marx & Ecology carries forward Marx's idea of an irreparable break in the consistency of the exchange between society and the ecological system it depends on. According to Marx, this break was the result of agricultural intensification under capitalism and Foster (1999), among others, have consolidated Marx's writings on this break as the *metabolic rift theory*. Simply said, Ecological Marxists, or eco-Marxists, consider climate change as a grand culmination of various ecological degradations that capitalism *required* for its development. The second section of this paper expands on this eco-Marxist argument and the relevance of agriculture in addressing economy-ecology configurations.

Fortunately, frameworks which incorporate representations of social metabolism and ecosystem metabolism with reference to agriculture have already been established. An example is the Multi-Scale Integrated Assessment of Social and Ecosystem Metabolism (MuSIASEM) framework which integrates a multitude of non-equivalent descriptive indicators. This characteristic allows a representation of socio-economic metabolic patterns which are based on both biophysical and economic variables (Giampietro et al., 2016). The third section of this paper is dedicated to a thorough discussion of the the MuSIASEM framework and its representation of agro-ecological systems.

Given that both eco-Marxism and MuSIASEM emphasize the metabolism between society and ecological systems, the overarching aim of this paper can be described as an assessment of their compatibility. Our main research question then becomes: "*to what extent is the MuSIASEM framework able to represent eco-Marxist insights?*". In the final section of this paper we attempt to answer this question through a conceptual framework based on a 3-sector closed economy. The economy is described from a MuSIASEM and eco-Marxist vantage point, after which we draw a conclusion on their compatibility.

Given the lack of an analytical treatment, we conclude the paper with some economic reflections which address the limitations of this exercise and designate areas which require further research.

## 2.2. The representation of ecology in post-Keynesian Ecological Macroeconomics

To our knowledge, one of the earliest contributions in the field of post-Keynesian Ecological Macroeconomics is provided by Rezai et al. (2013); in which they lays out the key building blocks for a post-Keynesian approach to ecological macroeconomics. In this publication, the main ecological issue is climate change and how the phenomenon is driven by the energy intensity of economic production processes. The authors suggest that a post-Keynesian macroeconomic analysis of climate change should treat each of the following thematic issues: i) sustainable consumption, ii) reduced working time iii) the role of labour productivity and energy intensity and iv) a demand driven rebound effect.

When it comes to sustainable consumption, it is argued that a reduction/stagnation in consumption is necessary if society aims to respect the earth's system boundaries with respect to greenhouse gas emissions. Working time reduction is then casted as a potential means to achieve sustainable consumption without a necessary reduction in the level of employment. Furthermore, the authors argue that increases in labour productivity are often associated with increases in energy use and therefore emissions. In other words, productivity increasing technical change usually relies on a higher amount of energy used per unit of employment. Finally the authors introduce a demand-driven formulation of the rebound effect (occurs when improvements in efficiency are offset by increases in demand). This basically captures the notion that increases in mitigation expenditures could positively affect the investment multiplier and thereby increase output. In the end, the work of Rezai et al. (2013) can be summarized in Figure 2.1 below:

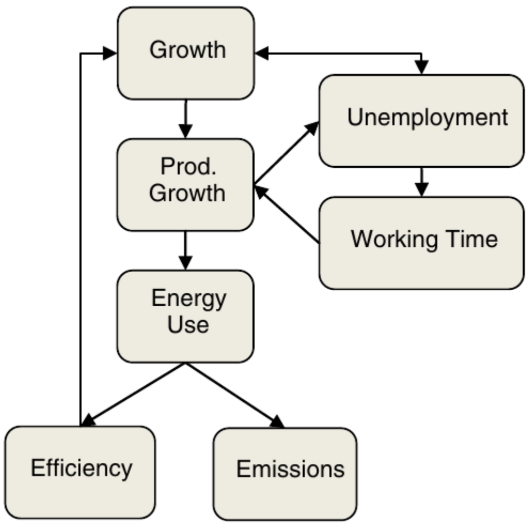



Figure 2.1: Key modelling elements in one of the earliest deliberations on post-Keynesian Ecological Macroeconomics (source: Rezai et al., 2013: pp. 74)

In sum, the central ecological issue in this preliminary deliberation on PKEME is greenhouse gas emission induced climate change and how it is affected by output and the carbon intensity of the economy which are both related to growth, productivity, unemployment and working time. In retrospect, one could argue that Rezai et al. (2013) have indeed fulfilled their aim of developing a "benchmark" for what has later become the bulk of PKEME considerations. A succinct review of PKEME literature reveals to us that climate change is modelled as i) a result of and ii) a threat to economic activity by means of green house gas emissions and the expected damages to capital and labour. Most of these models additionally consider the dependence of economic activity on the extraction of non-renewable resources such as rare metals or fossil fuels (Carnevali et al., 2019; Dafermos et al., 2017, 2018; Fontana and Sawyer, 2016; Monasterolo and Raberto, 2018; Naqvi, 2015). Furthermore, a general conception of hazardous waste as well as the ability to recycle matter that has already been used in the production process is occasionally incorporated in the modelling efforts (Dafermos et al., 2017, 2018).

In any case, one can carefully conclude that climate change and resource-use have been the central ecological issues in the contemporary development of PKEME. If we shift the focus from economy-ecology configurations to the main findings of these publications we can additionally conclude that their novelty lies with the consideration of previously overlooked *economic* or *financial* aspects. Simulated scenarios show how these aspects impact/are impacted by both climate change and innovative climate policies such as consumption and working time reduction, green macroprudential policies, feed-in tariffs for renewable energy, wealth taxes and the role of exchange rates. The *ecological* aspect of each of these models has remained fairly static even if some authors have drawn inspiration from prominent bio-ecological economists such as Georgescu-Roegen and his distinction between stocks, flows and funds.

This paper applauds the progress made by PKEME, but argues that a treatment of economy-ecology configurations which is limited to climate change obstructs the consideration of a more elementary economy-ecology configuration — agriculture. Even if agriculture, forestry and fishery only constituted 3.4% of global GDP in 2017 (World Bank, 2019b), we argue that it is a meaningful component of analyses for a number of reasons. First, to gain a deeper understanding of a capitalist society's relationship to nature through production, second to deliberate on the complex feedback between climate change and the future state of agriculture. The second deliberation is particularly important with respect to the trade relationships between what are broadly defined as the core and periphery. Nonetheless, the focus of this paper is mainly directed at the first reason and the following section will introduce eco-Marxism in order to stress that society's dependence on agricultural production plays a fundamental role when it comes to the analytical treatment of economy-ecology configurations under capitalism.

## 2.3. The modern synthesis between Marx & Ecology

A thorough introduction to considerations on Marx & Ecology would require us to engage in a literature review which discusses writings dated to the mid 20th century[1]. Doing so, allows us to disentangle a few reasons why a synthesis between Marx & Ecology has thus far remained untreated in EE. However, we will limit ourselves to contemporary and most renowned approaches to the synthesis between Marx & Ecology. If the reader is interested in a concise modern history of the considerations on Marx & Ecology as well as a more in-depth version of the following section they are suggested to consult (Dwarkasing, 2019).
Instead, this section will directly jump to a representation of the metabolic rift theory carried forward by among others (Burkett, 2009a; Foster, 1999) and world-ecology theorized by (Moore, 2015a; Patel and Moore, 2017). Even if the two interpretations are currently presented as being starkly opposed to each other, our stance is that from an economic point of view it is more fruitful to consider world ecology as a valid and useful extension of the metabolic rift theory.

### 2.3.1. The Metabolic Rift Theory

In the late twentieth and early twenty-first century profound inquiries into the works of Marx and Engels led to the rediscovery of ecological considerations in classical Marxist thought. By treating Marx's later works on political economy instead of his earlier philosophical works, environmental sociologists, anthropologists and historiographers came to argue that Marx had been aware of ecological issues related to soil fertility, organic recycling and sustainability. These insights became consolidated as the *metabolic rift theory* which is an amalgamation of Marx's awareness of the aforementioned topics through his writings on classical economists, agro-chemistry & the second agricultural revolution and the metabolism between man and nature (see Foster, 2013, 2000; Saitō, 2017).
The second agricultural revolution of the early to mid nineteenth was characterized by the fact that farmers increasingly engaged in the purchase of raw materials in order to produce higher-value goods. Particularly the purchase of manure and fertilizer made farmers less dependent on the rotation of crops and the use of unsold crop harvests as plant biomass (Coombs, 1994; Thompson, 1968). Marx was aware of the fact that lands with low soil fertility could still be used for agricultural production by means of external inputs. This was the result of his engagement with the works of the German soil chemist Justus Liebig (Baksi, 1996; Bocking, 2002; Foster, 1997, 1999; Foster and Magdoff, 1998; Stanley, 2002). Liebig's work provided one of the first convincing explanations of the role of soil nutrients in the growth of plants; this at a time where Europe and North America had grown increasingly concerned over "worn-out soils" (Hillel,

[1] This is not to say that earlier deliberations on Marx & Ecology were non-existent, for an overview of late 19th and early 20th approaches to Ecological Economics by Marxists, we advice the reader to consult (Franco, 2018)

1991).

Prior to Marx's engagement with agro-chemistry through Liebig, he had already formulated ideas on the relationship between man and nature in general. In the chapter *First Manuscript - Wage of Labour* found in Marx (1959) one can discern that Marx envisioned humanity and nature as being in a constant dialogue with each other. The concrete specifications of this dialogue are inherently based on Hegel's idealist dialectic which states that humans are essentially subordinate to nature which is a component of their own species-being (Foster, 2000; Foster et al., 2017; Hughes, 2000; Saitō, 2017). But Marx's historical materialist treatment modifies this dialectic by asserting that human beings produce a specific historical relation to nature through the production of their (material) means of sustenance (Foster and Burkett, 2000). And it is particularly this vantage point which ultimately led to the Marx's critique of agriculture under capitalism - the backbone of the *metabolic rift theory*.

In *Notebook IV/V - The Chapter on Capital* found in (Marx, 1973), Marx points out that when nature and the forces of science are subsumed under the relation of wage labour and capital, they gain an alienated social power over producers. This means that the scientifically recognized powers of nature merely appear as material conditions for the exploitation of labor power — resulting in the mass separation of human beings from the "natural" conditions of their being (Burkett, 1996; Marx, 1973: pp. 335-336). The societal origin of the aforementioned separation, as described in Volume I of *Capital*, is the antagonism between town and country under capitalist industrialization. According to Marx this resulted in a disturbed circulation of matter between man and the soil; as nutrients seized to return to the soil, the conditions for lasting fertility were violated (Marx, 1887b: pp. 329-330).

This concludes our very succinct introduction to Marx's ecological thought and therefore the theoretical foundation used by metabolic rift scholars. In a nutshell, the metabolic rift theory captures the idea that the metabolism/circulation of matter between humans and society, is not only regulated through nature and the laws that govern physical processes (e.g. biophysical characteristics) but also through the society which imposes institutionalized norms that direct the division of labour and the distribution of wealth (the socio-economic system). In our opinion, this is a line of thought that captures the broad outlook of ecological economics as a whole.

### 2.3.2. World-Ecology

An alternative approach to eco-Marxism is called world-ecology, which was formulated by Jason W. Moore at the beginning of the 2000s. While Moore recognizes the *metabolic rift theory* in Marx he treats it from a broader historical by embedding Immanuel Wallerstein's world-system theory into ecological analyses. In *Environmental Crises and The Metabolic Rift in World-Historical Perspective*, Moore develops an alternative argumentation in which one can study the dialectic between capital and nature over the long-term historical development of capitalism. This is achieved by drawing on the historical political economy developed by Marx, Foster, Arrighi and Wallerstein and results in *systemic cycles of agro-ecological transformation*. Moore (2000a) deploys this theory to argue that the current global ecological crisis is rooted in the *transition* to capitalism during the sixteenth and seventeeth century (from 1450 to 1640). Here, we recognize a first departure from the *metabolic rift theory* since Foster argues that ecological disruptions are the result of capitalist industrialization at the beginning of the nineteenth century. Moore does not deny this observation, but argues that the fundamental reorganizations of the world-economy under feudalism had already led to ecological disruptions in colonized lands (Ibid, 2000a).

As mentioned above, the treatment of capital expansion and its ecological effects in terms of *systemic cycles of agro-ecological transformations* (SCAETs) is an ecological adaptation of systemic cycles introduced by world system theorist Arrighi (1996). SCAETs are characterized by world-ecological regimes over the course of capitalist development. In turn, each of these regimes represents a fundamental reorganization which aims to increase returns in the consecutive world-ecological regime (Moore, 2015a). These cycles and reorganizations are particularly clear if one analyses the expansion of sugar cultivation, production and trade in the fifteenth century which resulted in a a chain of metabolic rifts (deforestation, biodiversity loss, soil exhaustion) across the globe as the seeds for industrial capitalism were planted (see Ibid, 2000b).

In a historically specific sense, world-ecologists claim that capitalism is currently facing the end of cheap nature (Ibid, 2014; 2015a; 2015b; Patel and Moore, 2017), where the concept of cheap nature is used to define the strategy humanity undertook since the sixteenth century. This strategy constructed nature as an external component to human activity resulting in the placement of "uncommodified" human and extra-human natures in service of labour productivity gains. In order to explain that society is facing the end of cheap nature, world-ecologists make a distinction between appropriation and capitalization. Appropriation involves the struggle over the specific relation capital has towards non-monetized social reproduction (domestic/reproductive work and the "work of nature") while capitalization refers to that which involves the conflict between capital and labour. Both concepts are used to refer to humans and extra-humans that are necessary for the accumulation of capital and reproduction of value.

According to Moore (2015b), movements in both appropriation and capitalization historically determine socially necessary labor time.[2] Each successive world-ecological regime is then characterized by capitalist technics who seek "to mobilize and to appropriate the (unpaid) “forces of nature” so as to make the (paid) “forces of labor” productive in their modern form (the production of surplus value)" (Ibid, 2014: pp. 295). One way to describe the

[2] The simplest definition of socially necessary labor time is the amount of labour time performed by a worker of average skill and productivity who is working with tools of average productivity (Marx, 1887b: pp. 29). It can be defined for specific commodities and can be seen as a Marxist type of measure for labour productivity.

"optimal" configuration between appropriation and capitalization is the ecological surplus: the ratio between unpaid (appropriated) work and paid (capitalized) work. Capitalism, is said to be subject to the tendency of the ecological surplus to decline and Moore identifies four explanations for this trend (Ibid, 2015a):

- In accordance with the law of entropy, capital accumulation shifts the economic system from a state of low entropy to a state of high entropy. So far, the issue of rising entropy has been dealt with through the by localization of "uncapitalized" low-entropy sources. At the same time, the costs of localization are subject to an increasing trend as these resources become scarcer or more energy-intensive to extract.
- In line with the above, Marx' general law of underproduction postulates that capital's bet on the future embodies an expectation of growth which surpasses the practical activity of locating new "appropriation potentials".
- Capital's drive towards instanteneity results in the artificial compression of ecological reproduction time which compromises the functioning of ecological processes. These compressions are considered is a necessary strategy for the achievement of competitive advantages.
- Waste production, e.g. greenhouse gas emissions, toxify the biosphere and activate negative value; the external conditions that are becoming increasingly hostile to capital accumulation.

In sum, the contemporary declining ecological surplus is the result of negative movements in appropriation. A decrease in the dependency of accumulation on appropriation automatically translates to an increase in the dependency on capitalized inputs, which is hypothesized to drive prices upwards. Climate change and its implications for capitalist agriculture capture that we are currently living and will probably keep living in a period of *expected* ecological surplus decline. Instead of arguing that the climate poses a strict barrier boundary/limit to growth or capitalist accumulation, Moore contends that climate change co- shapes a *new set of contradictions* in the totality of capitalism - negative value (Ibid, 2015b; 2015c). This comprises the limits that capital and its supporting state encounter in the circumvention of rising production costs and the removal of increasing waste.
In applying the idea of a declining ecological surplus to agricultural production one can argue that agro-biotechnological advances are continuously trying to increase the ecological surplus by increasing the productivity of appropriated ecological processes. Energy intensive herbicides, fertilizers and pesticides are increasingly used to alter agro-ecological characteristics in order to provide higher crop yields. At the same time, these technological advances decrease socially necessary labour time. One the one hand, the increased reliance on

capitalized inputs *decreases* the ecological surplus — at least in theory. But if such increases allow a better performance of previously included capitalized inputs, such as labour, as well as the appropriated ecological process itself, the result may well be a constant or even *increasing* ecological surplus. Such gains, however, are usually short-run: fertilizer use may result in soil degradation, herbicides ironically foster the development of resistant weeds and along with pesticides negatively effect biodiversity. Coupled with the negative effects of climate change on the performance of appropriated ecological processes (e.g. droughts, floods, novel plagues & pathogens) one can postulate that capitalization-induced enhancements will soon become neutralized and drive the ecological surplus down once more.

All in all, the ecological surplus is an interesting concept which delineates economy-ecology configurations under capitalism through a distinction between appropriated and capitalized human and extra-human labours. The following section will introduce the reader to MuSIASEM and argue that it offers a possibility to approximate a measure of appropriation in an agricultural context.

## 2.4. An introduction to Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism

The main concepts sustaining MuSIASEM are social metabolism, thermodynamics, Georgescu-Roegen's distinction between stocks and funds and complex self-organizing systems. Each of them are treated in the following paragraphs.

According to González de Molina Navarro (2014) the concept of social metabolism was developed in the field of environmental sociology and deduced from the biological definition of a living thing's metabolism: the totality of life-sustaining biochemical reactions (Fischer-Kowalski, 1997). Most of the contemporary human societies govern their interaction with the environment through an economic channel, where extraction from nature comprises much more than complex organic compounds for food. This recognition spurred the development of social metabolism as a means to represent how entire societies preserve and organize all of their material inputs from nature as well as their outputs to nature. As a result, socio-metabolic analyses have been used to either explain socio-environmental change or design methodological tools to analyze the biophysical behaviour of economies (Martinez-Alier, 2009; Marull et al., 2018; Muradian et al., 2012; Pauliuk and Hertwich, 2015; Sieferle, 2011; Soto et al., 2016). Usually these analyses quantify social metabolism in terms of an amount of energy (e.g. kJ or kcal) or physical quantities of raw material (e.g. tons or kg). This is because renowned attempts at describing the interaction between society and its environment as an exchange of matter and energy are grounded in the field of bioeconomics/thermoeconomics.

The works of Nicolas Georgescu-Roegen have been regarded as fundamental for the development of ecological economics as a singular scientific field since they were among the

first to model economic activity according to the entropy law (Maneschi and Zamagni, 1997). Georgescu-Roegen applies three of the four thermodynamic laws to economic processes as a way to provide an alternative to the dominant and mechanistic treatment of the economy at that time. A mechanistic treatment of the economy implies that processes occur in a circular fashion in a closed system, thus without taking into account the exchanges of matter and energy with the environment. Additionally, it assumes that the process can be reversed at any point at time. Hence, by describing the economy in a thermodynamic fashion the economy is seen as an open, dissipative system where processes move in a definite direction (no reversibility) and imply qualitative changes (see Georgescu-Roegen, 1975).
Such a thermodynamic portrayal of the economy requires one to treat economic processes in terms of energetic dissipation (expenditure). The *First Law of Thermodynamics* states that an open system is able to exchange both matter and energy with its surrounding, but this exchange is subject the Materials Balance Principle (MBP). This principle states that the mass content of a system at a given moment in time is simply given by the initial mass content, the inflows of mass and the outflows of mass up to the specific point in time (Ayres and Kneese, 1989). *The Second Law of Thermodynamics* can be generalized for isolated, closed and open systems and in absence of considerations on thermodynamic equilibria by simply stating that entropy can only be created and never destroyed. Or alternatively; the available and useful energy within a system is continuously transformed into useless energy (heat) until it disappears completely (Georgescu-Roegen, 1975). Entropy, as explained by Georgescu-Roegen, represents an index of the amount of unavailable energy in a given thermodynamic system at a given moment in time (Ibid, 1971). The higher the value of entropy in a system, the higher the amount of energy which has been irreversibly transformed into heat et vice-versa (Swendsen, 2012). According to Georgescu-Roegen, economic scarcity is not determined by the physical quantity of a particular ore or mineral but rather by the low entropy it embodies (Georgescu-Roegen, 1976: pp. 55). Since *The Second Law* dictates that low entropy decreases with the amount of irreversible processes; the economic system as a whole is fundamentally subject to a definite constraint.[3]

In the MuSIASEM framework thermodynamics and considerations of entropy are used to assess the interrelations between the determinants of social metabolism. In order to understand how this is done, it is also important to address how the MuSIASEM framework characterizes resources in terms of terms of stocks, flows and funds. Following Georgescu-Roegen and Giampietro et al. (2016), *stocks* refer to a quantity of material reservoirs which change their identity as a result of being incorporated into an economic process. They are usually consumed

[3] Examples of scholarly work which apply or discuss entropy and the Second Law in economic analyses are Ayres (2004), Baumgärtner et al. (2001), Buenstorf (2000), Hammond and Winnett (2009), Kåberger and Månsson (2001), Krysiak (2006) and Sun et al. (2017).

during the economic process, e.g. a coal reservoir. *Flow* elements refer to quantities which either appear or disappear over the time duration of an economic process. While a *flow* can be defined as a *stock* spread out over a time interval, a *stock* may have an analytical existence only. In this case one can visualize the *stock* of a material if it had not had been instantaneously transformed into another material through a *flow* (e.g. a part of a stock of melted glass *flows* and is transformed into a stock of plate glass). One can also refer to a *flow rate* which expresses the amount of the *flow* per unit of time. Examples of *flows* are food, electricity, process heat and irrigation water. Finally, *fund* elements refer to a quantity of elements of which the identity remains stable as they enter or exit the economic process. The essence of their contribution to the economic process is not subject to a change, allowing them to equally contribute in a separate economic process. Examples are human beings, land and machinery.

MuSIASEM's representation of both socio-economic systems and ecological systems as complex adaptive systems (CAS) can be summarized as follows (Ibid, 2002):

- Both ecosystems and socio-economic systems are said to consist of nested subsystems that operate in parallel on several hierarchical levels. This means that specific patterns of self-organization can only be identified when adopting the appropriate space-time window of observation. At the same time, the metabolic patterns that are relevant for observation are subject to evolution. If the environment a system interacts with changes the system as a whole, some or all of its nested subsystems will adapt their metabolism accordingly.[4]

- The existence of a hierarchical system which embodies nested subsystems means that there are various ways to describe the system as a whole. This implies that both socio-economic systems and ecosystems are subject to non-equivalent descriptions that can be used at the same time in order to discern relevant information.

- Given that a system is subject to non-equivalent descriptions, it is possible to define a descriptive domain according to the researcher's analytical interests. The descriptive domain includes i) an arbitrary selection of variables, ii) a space-time horizon iii) an estimation of the dynamics that drive the selected variables and iv) the specific boundary which separates the system from its environment.

The considerations above reveal an important difference between MuSIASEM's *integrated assessment* approach and standard approaches when it comes to e.g. sustainability. In assessing whether a given socio-economic system is sustainable or not; it is argued that in terms of energy analyses, the reduction of sustainability to *one* specific and *correct* domain is mediocre

[4] In line with hierarchy theory, the components of hierarchically organized systems can be called holons, which is both a whole made of smaller parts and a part of some greater whole (Giampietro and Mayumi, 1997). Thereupon a hierarchical system made of holons can be called a holarchy (Giampietro, 2002).

compared to a variety of well-defined descriptive domains (Ibid, 2006). The MuSIASEM framework also treats the evolution of hierarchical systems in terms of structural and functional "type" categories, impredicativity and multi-purpose grammars (Ibid, 2018; 2006). However, we contend that our introduction to social metabolism, thermodynamics and CASs is ample enough for our attempt to address whether the MuSIASEM framework is able to represent eco-Marxist insights. In order to continue along this line, we will now introduce MuSIASEM-specific conceptual and formal depictions of socio-economic systems and ecological systems.

### 2.4.1. Socio-economic metabolism

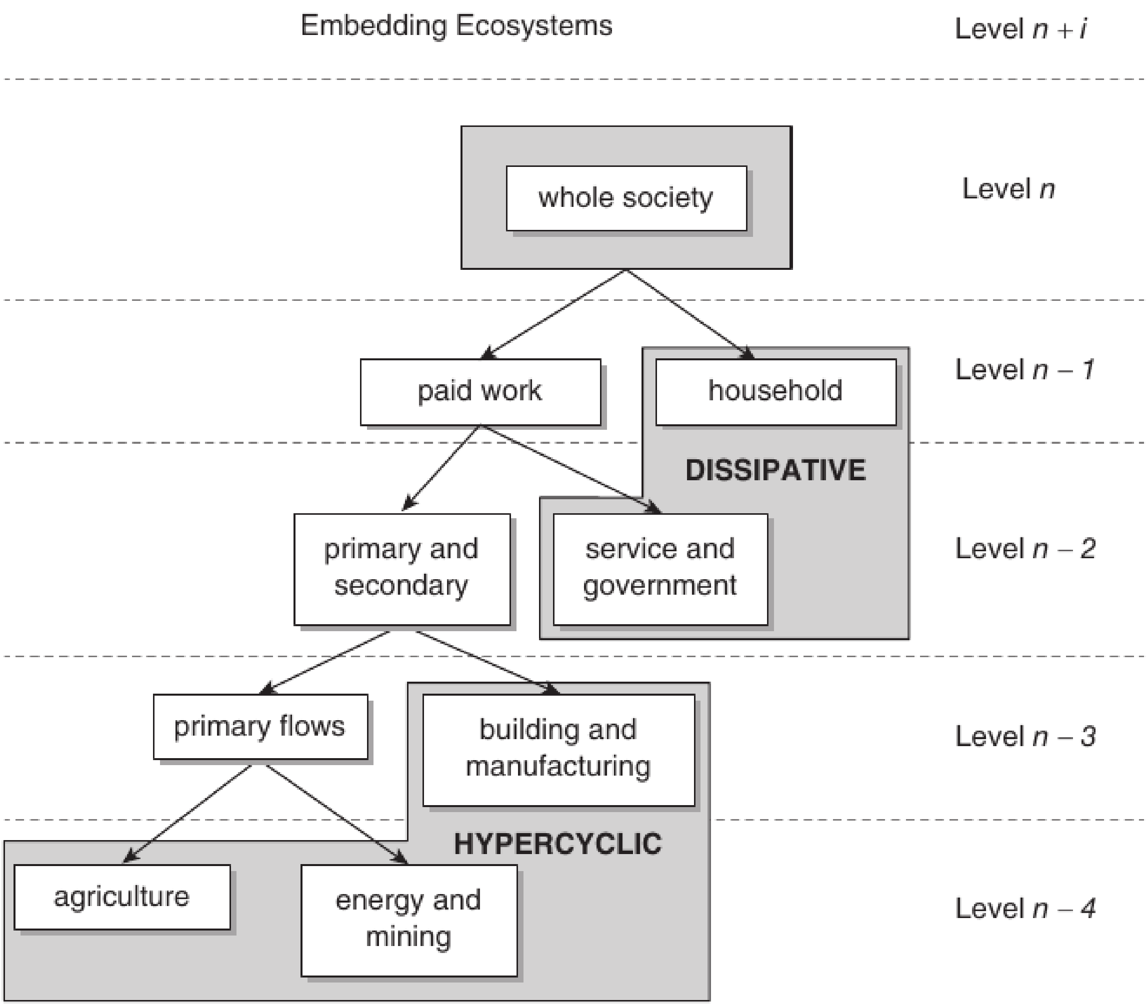
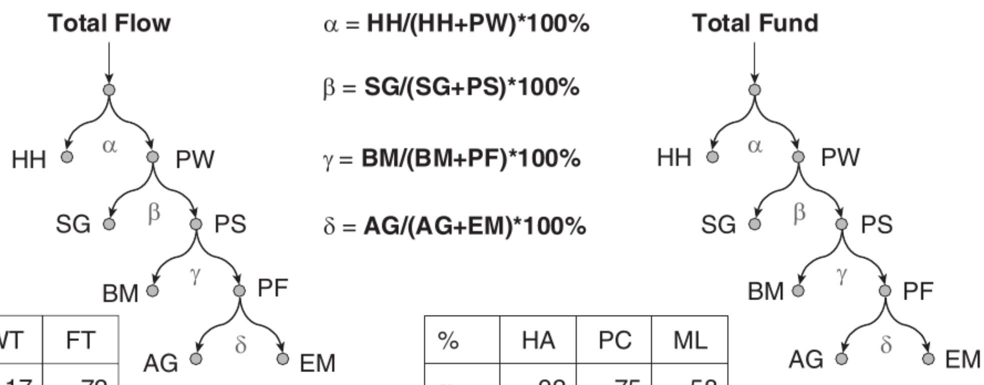



Figure 2.2: Societal Metabolism represented as a nested hierarchical system (source: Giampietro et al., 2016: pp. 14)

Over a given space-time domain, a society's social metabolism is supposed to describe its process of self-organization. This embeds its ability to stabilize a network of matter and energy flows which represent what is produced and consumed in the economic process. This description is heterogeneous as both biophysical and economic descriptive domains are bridged into one single framework. Correspondingly, the constraints on the social metabolism can be economic, technical, ecological or social. The formal characterization of a society's social metabolism is based on the treatment of human society as a nested hierarchical system. For example, if our analytical interest is to describe society as a whole; Figure 2.2 shows the different subsystems $(n+1)$ as well as what influences their boundary conditions $(n-1)$. The figure provides a biophysical representation of social metabolism and additionally displays two further divisions in the respective sub-systems of society as a whole; the *dissipative* and *hypercyclic* subsystems. While the *hypercyclic* subsystems drive the entire functioning of society through the provision of flows (e.g. food, energy, water), the *dissipative* subsystems are those that consume what is provided by the *hypercyclic* subsystems. Essentially the *dissipative* subsystems determine the ability for the system as a whole to reproduce itself as well as the ability of the system to adapt to e.g. changes in boundary conditions. The subsystems in both the *hypercylic* and *dissipative* section are arbitrary and it is possible to divide each of them into additional subsystems (e.g. agriculture can be divided into livestock and crop cultivation or production for import and export). The allocation of flows and funds across each of the subsystems can also be represented by means of dendograms as shown in Figure 2.3.




| % | ET | WT | FT |
|---|---|---|---|
| α | 28 | 17 | 72 |
| β | 53 | 4 | 67 |
| γ | 57 | 6 | 100 |
| δ | 13 | 30 | 0 |

| % | HA | PC | ML |
|---|---|---|---|
| α | 92 | 75 | 58 |
| β | 66 | 67 | 0 |
| γ | 81 | 100 | 0 |
| δ | 81 | 0 | 100 |

Figure 2.3: The allocation of flows and funds across subsystems by means of dendograms (source: Giampietro et al., 2016: pp. 16)

The dendogram on the left refers to the allocation of flows across the aforementioned subsystems. In this example, the examined flows are energy throughput in kilojoules (ET), water throughput in $m^3$ (WT) and food throughput in kilojoules (FT). The symbols $\alpha, \beta, \gamma$ and $\delta$ represent the fraction of the flows allocated to the subsystem on the left-side of the dendogram. For example, the flow table on the left specifies that 28% of total energy throughput is allocated to the household subsystem (HH) then of the 72% allocated to the paid work subsystem (PW), 53% is allocated to the service and government subsystem (SG). Consequently, of the 47% allocated to the productive sector subsystem (PS), 57% is allocated to the building and mining subsystem (BM) and so forth. The rationale behind the fund dendogram on the right side of Figure 2.3 is the same, but in this example it refers to the allocation of human activity in hours (HA), power capacity in watts (PC) and managed land in hectares (ML). The description of flows and funds by means of dendograms is one of the ways one can extract and display information from a specific grammar for the various flows and funds of interest.

Figures 2.2 and 2.3 are meant to portray a general example of how society as a whole can be hierarchically divided into subsystems. Each of these subsystems can be described in terms of i) intensive variables which measure their qualitative aspect in terms of a ratio and ii) extensive variables which measure their quantitative aspect in terms of an absolute values. Furthermore, both of these variables can take on a biophysical or economic character, within the MuSIASEM framework economic representations of social metabolism are expressed in terms of the allocation of Gross Domestic Product across the subsystems.

As mentioned before, the integrated assessment of what constitutes a given society's socio-economic metabolism is fundamentally built on the non-equivalent descriptive domains and in order to bridge them it is necessary to introduce equations of congruence. Giampietro and Mayumi (2000) and Giampietro et al. (2001) introduce these equations with respect to energy throughput; which is said to be a fundamental flow when it comes to the description of socio-economic metabolism. As clarified by Giampietro, equations of congruence allow one to define the viability domain of social metabolism because it takes an explicit inside view of human society (Ibid, 2016: pp. 26). This is particularly relevant if one wishes to deploy the MuSIASEM framework for the quantitative/empirical assessment of a nation-state or region. But given that this paper is more interested in the theoretical realm of possibilities, we will directly shift to the treatment of ecosystem metabolism in the MuSIASEM framework, as this is more relevant with regard to our interest in agriculture and the formal representation thereof from an eco-Marxist perspective.

### 2.4.2. Ecosystem metabolism

A given society's socio-economic metabolism is limited by two factors which are inherently related to ecosystem metabolism. These are i) the socio-economic system's dependence on the availability of natural resources (supply constraints) and ii) the the socio-economic system's ability to dispose waste (sink constraints). This is why it is important to characterize the reproduction of human societies in terms of their dependency and impact on the reproduction of ecosystem metabolism.

Similar to human society's, there are thermodynamic constraints which dictate the compatibility between internal metabolic processes and external process related to the boundary conditions of an ecological system. The metabolic pattern of ecosystems is determined by i) the required congruence between the relative size of elements and the pace of energy dissipation, ii) the expected relation between functional compartments and the compatibility of the entire network with boundary conditions and iii) the availability of inputs supplied to the ecosystem. According to Odum (1971), the interactions between a set of known energy forms are controlled and informed by auto-catalytic loops when an ecosystem reaches a near closure of nutrient cycles. This means that the aforementioned interactions have a tendency to stabilize a given ecosystem network. While 100% stabilization is an impossibility, it is possible to define *expected* metabolic characteristics by consulting a set of benchmarks associated with different ecosystem types. Instead of treating the metabolism of ecosystems in general, we will limit our attention to terrestrial ecosystems as presented in Lomas and Giampietro (2017) and Parra et al. (2018).

A key component of terrestrial ecosystems is standing biomass. It refers to the mass of living biological organisms in a given terrestrial ecosystem at a given time. In this example we treat is as a fund and its reproduction is primarily associated with the carbon and hydrological cycle (see e.g. Heimann and Reichstein, 2008; Quéré et al., 2015; Schimel, 1995). The flows of energy and materials associated with the reproduction of standing biomass as a fund are shown in Figure 2.4 below:

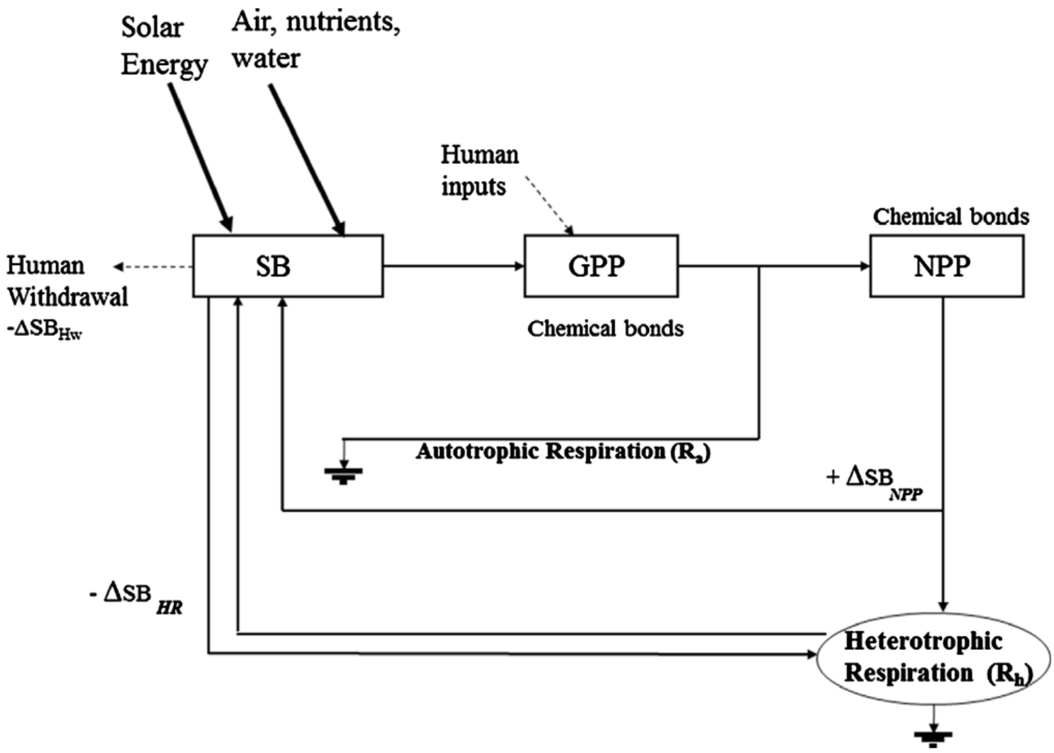



Figure 2.4: A general representation of a terrestrial ecosystem in terms of standing biomass (source: Lomas and Giampietro, 2017: pp. 14)

The initial fund of biomass *SB* has the ability to use various inputs such as $CO_2$, water and nutrients to reproduce itself. This reproduction goes hand in hand with the initial amount of solar energy captured through photosynthesis. The autotrophic compartment of *SB* generates a supply of energy that is stored in the form of chemical bonds and the amount of energy is measured by general primary productivity ($GPP$). A fraction of $GPP$ is used by the plants which constitute $SB$ for the purpose of autotrophic respiration $(R_a)$. The remaining part of $GPP$ is available for the synthesis of plant tissue such as foliage, wood and roots $(NPP)$. If the ecosystem is not mature enough, a part of $NPP$ is used to increase $SB$ and this is denoted with $+\Delta SB_{NPP}$. The other part of $NPP$ is used for heterotrophic respiration $(R_h)$ and this fuels the activity of other compartments in the ecosystem; this mostly happens in mature ecosystems.

The treatment of this terrestrial ecosystem as a CAS bound by thermodynamic principles supposes that the undisturbed state of a terrestrial ecosystem encompasses the minimization of negentropic costs and maximization of energy dissipation (Aoki, 2008; Jørgensen et al., 2000). Such an undisturbed state exhibits characteristic metabolic patterns such that one is able to detect alterations as a result of dynamics in the societal metabolism. One specific intensive variable which can be used to express the alteration of terrestrial ecosystems is the negentropic cost $(\Phi)$, a flow-fund ratio. This is represents the amount of energy required to support the metabolic processes per unit of $SB$. Of course, one can also use an extensive variable to express human alteration, namely the absolute reduction of the $SB$ fund.

The maintenance of $SB$ is highly dependent on water. It is a direct input for photosynthesis, necessary to maintain tissue functionality, plays an important role in nutrient transportation from the roots to the leaves and cools and maintains the turgidity of vegetative structures. For this reason, the required flow of water evapotranspiration or thermal dissipation of water, $ET$, is another key flow-fund ratio. However, $ET$ entails both physical (evaporation) and biochemical (transpiration) processes which are generally difficult to separate. This is why the amount of water lost during the production of biomass, as the result of $CO_2$ fixation during photosynthesis, is taken into account instead. In other words, transpiration efficiency $(TE)$ or water-use efficiency $(WUE)$ is used for the calculation of energy dissipation (W/m$^2$)[5] per unit of $SB$ (kg of biomass/m$^2$) for both intact and altered terrestrial ecosystems:

$$\Phi = \frac{PAWF}{SB} = \frac{GPP \times TE}{SB} = \frac{GPP \times \dfrac{1}{WUE}}{SB} \qquad [2.1]$$

Where $\Phi$ is the negentropic cost in W/kg, $PAWF$[6] is the energy dissipation of transpiration associated to production in W/m$^2$, $SB$ is the standing biomass in kg of biomass/m$^2$, $GPP$ is the Gross Primary Production in kg of biomass/m$^2$ on a yearly basis, $WUE$ is the water-use efficiency in kg of biomass/kg of water transpired and $TE = (WUE)^{-1}$ in kg of water transpired/kg of biomass. The usefulness of negentropic cost, $(\Phi)$, as a intensive variable which describes the metabolic state of an ecosystem and how it is altered by agriculture, is best explained by taking into account Figure 2.5.

[5] Note that the energetic unit used in this case is Watt. 1 W is equal to 1 Joule per second.
[6] PAWF stands for plant active water flow and essentially captures how much energy is required for the evaporation of the amount of water which is necessary for the production of $GPP$.

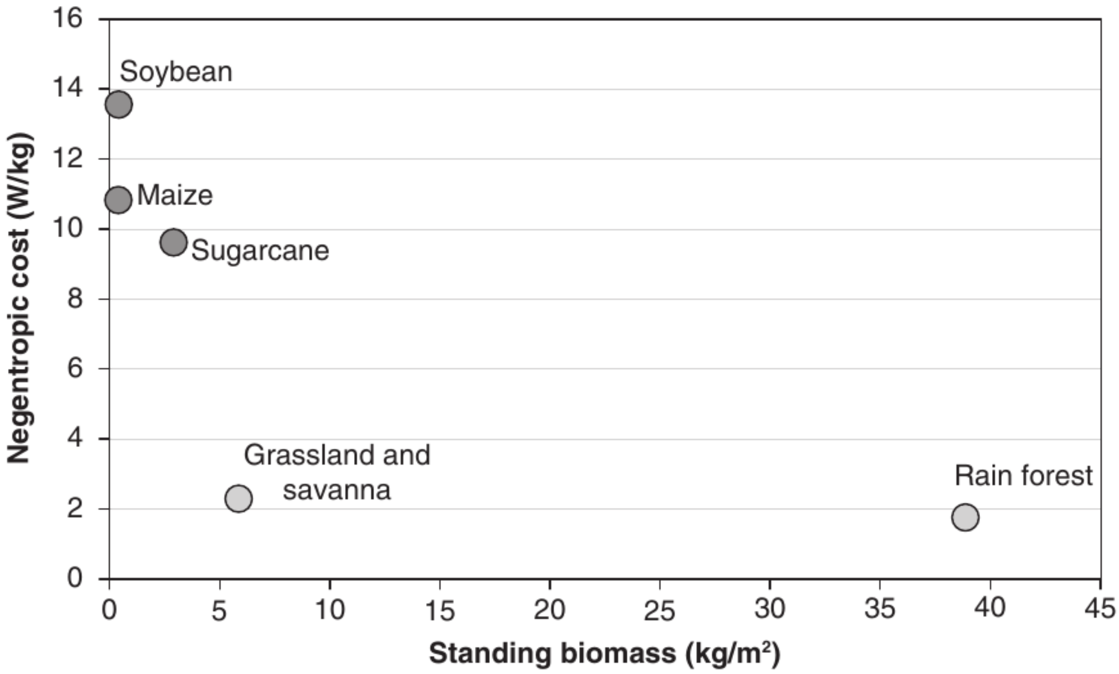



Figure 2.5: The standing biomass of unaltered tropical ecosystems (light gray) vs. crop cultivation under tropical conditions (dark gray) (source: Giampietro et al., 2016: pp. 41)

The figure shows that human alteration for the purpose of crop cultivation tends to decrease the absolute size of the $(SB)$ fund while increasing the flow/fund ratio $(\Phi)$ of terrestrial ecosystems. Giampietro et al. (2016) argues that the extent to which the negentropic cost is increased as a result of agriculture depends on the openness of nutrient cycles sustained by respective agricultural practices.

A distinction is made between high-external-input agriculture (HEIA) and low-external-input agriculture (LEIA). HEIA is characterized by high productivity as the result of i) a complete modification of native ecosystem, which means that the natural vegetation is entirely replaced with monoculture crops and that pesticides are used to prevent other species from feeding themselves with $NPP$, ii) a complete linearizion of nutrient flows where crops are often excessively subject to fertilizers in concentrated mineral form. Furthermore, monocultures as a form of HEIA are often subject to a large $GPP$ despite a small $SB$ and this is mainly the result of external inputs ($GPP$ in this case does not reflect an abundance of unaltered ecological funds). Finally, the flow of $NPP$ arising from HEIA barely contributes to the reproduction of ecological funds is instead appropriated as an input for the socio-economic system. This is also referred to as the human appropriation of net primary productivity (Haberl, 1997).

LEIA or sometimes referred to as conservation agriculture (CA) is based on minimal soil disturbance, continuous soil cover and crop rotation — maintaining a rich diversity in ecological funds (FAO, 2017). Research seems to suggest, however, that the homogeneous application of CA across every single mode of crop production system is ineffective (Giller et al., 2015). Instead it should be pragmatically adopted by large mechanized farms, while smallholder farmers in developing countries should still be granted the opportunity to engage in the use of tillage and herbicide use. This automatically calls into question the extent to which rural communities in developing countries are dependent on the sale of their yields to urban and/or international markets. Indeed, Giampietro et al. (2016) mentions that the most extreme form of LEIA is subsistence agriculture, indicating that the openness of the socio-ecological system is limited and that international import/export relationships are near-absent. Hence, the adoption of HEIA and LEIA is very much dependent on the degree of openness and the consequences thereof. The main difference between LEIA and HEIA with regard to the aforementioned is related to the higher intensity of exports and imports under HEIA and how this results in an increase of environmental stress on ecosystems all whilst agricultural production relies less on the ecosystem functions. Apart from that, there is also a larger dependence on the urban part of the society said rural communities take part of. For example, it is common knowledge that many rural households often consist of a member (mostly male) who is entitled to manage the farm because of the income they provide through labour in urban areas (Ramisch, 2016).

The above discussion of LEIA and HEIA aimed to show how the framework incorporates agriculture and its impact on ecosystems. Even if the discussion is rather general and a-specific, we hope that it is enough of an introduction to finally analyse the compatibility between eco-Marxism and MuSIASEM in the final section of this paper.

## 2.5. A conceptual integration between eco-Marxism and MuSIASEM

This section will provide an exploratory analysis of the potential compatibility between eco-Marxism and the MuSIASEM framework. One way to kick-start this discussion is by reiterating the fact that eco-Marxism, as presented through the metabolic rift theory and the world-ecology, are thus far limited to the field of environmental sociology. MuSIASEM on the other hand is a method built on various disciplines ranging from bioeconomics to complexity science. Hence, perhaps the most apparent difference between the two fields is related to the fact that MuSIASEM is already seen as a specific articulation of quantitative analyses while eco-Marxism provides a qualitative description of the role of nature in the development of capitalism.

Indeed, the equations of congruence found in Giampietro and Mayumi (2000) and Giampietro et al. (2001) treat social metabolism in terms of energy throughput and provide both a biophysical and economic reading of the dynamic equilibrium between energy supply and requirement (demand). In our opinion, it is particularly the economic reading of this dynamic equilibrium which could be expanded in a way that reflects an Ecological Marxist interpretation. In order to provide a more in-depth exploration of compatibilities and incompatibilities between the two scientific fields we will introduce a trivial example of an economy and evaluate it from a MuSIASEM and eco-Marxist perspective.

### 2.5.1. A fictional 3-sector closed economy

The economy we aim to introduce consists of three sectors; agriculture, energy & extraction and industry. The population is divided into workers and capitalists operating in each of the sectors. For the sake of simplicity, we abstract away from fixed capital. Thus, variable and constant capital in each of these sectors and the resulting marketable output is schematically presented in the following table:

| Sector | Input | Output | Composition of Demand |
|---|---|---|---|
| Agriculture | • Labour<br>• Energy<br>• External input | • Crop | • Worker consumption<br>• Capitalist consumption |
| Industry | • Labour<br>• Energy | • Intermediate good<br>• Consumption good | • Crop demand<br>• Worker consumption<br>• Capitalist consumption |
| Energy & Extraction | • Labour<br>• Energy | • Energy | • Crop demand<br>• Consumption good demand<br>• Worker HH consumption<br>• Capitalist HH consumption |

Table 2.2: Input, Output and Demand in the fictional 3-sector closed economy

If we consider the above to be a closed economy and take a post-Keynesian demand-led perspective, the information in Table 2.5.1 can be described as follows.

The agricultural sector uses a combination of inputs to produce an agricultural crop, it produces according to the expected demand for the crop which is a function of worker and capitalist consumption of crop, for example corn. Of course, seed is also an input, but we assume that it is automatically retrieved from the crop and used for the next production period. The industry sector uses its combination of inputs to produce an intermediate good and a consumption good. We assume that these intermediate goods are those which the agricultural sector needs for the purpose of artificially increasing the productivity of the land. The intermediate good is used by the agricultural sector and industrial production is therefore a function of the expected demand for the agricultural crop while the production of the consumption good is a function of the industrial sector's expected demand based on worker and capitalist consumption. Finally we combine the energy and extraction sector into one, which means that the production process of this sector is two-fold. On the one hand it uses labour and energy to extract the raw material, on the other hand it combusts the fossil fuel e.g. oil in order to provide energy to the rest of the economy. In this case, we assume that the extraction and combustion directly meet aggregate demand, which is a function of worker and capitalist household consumption as well as industry and agriculture consumption. We also adopt the following general assumptions:

- We abstract away from competition, thus actually each of the sectors represent interdependent price-setting firms.

- Since we disregard fixed capital, we abstract from investment and savings as well as the government sector. Put differently, we assume that increases in demand can be met without increases in fixed capital because of a low capacity utilization rate.

- Energy is an input for each of the sectors and we postulate that in a closed economy, the scarcer the resource, the more inputs are necessary to produce one unit of energy. As a result, under a price-setting situation and if capitalist consumption out of profit remains constant; the price of the fossil fuel increases with its scarcity. We will revisit this assumption further along this section.

### 2.5.2. A MuSIASEM interpretation of the 3-sector closed economy

Summarizing Section 2.4, a MuSIASEM intepretation of our fictionally set-up economy must necessarily take into account this society's social metabolism. In our case, it is relevant to consider energy throughput flows, food throughput flows and the land-fund. Following Figure 2.2, a hierarchical representation in terms of energy throughput would look like Figure 2.6 below:

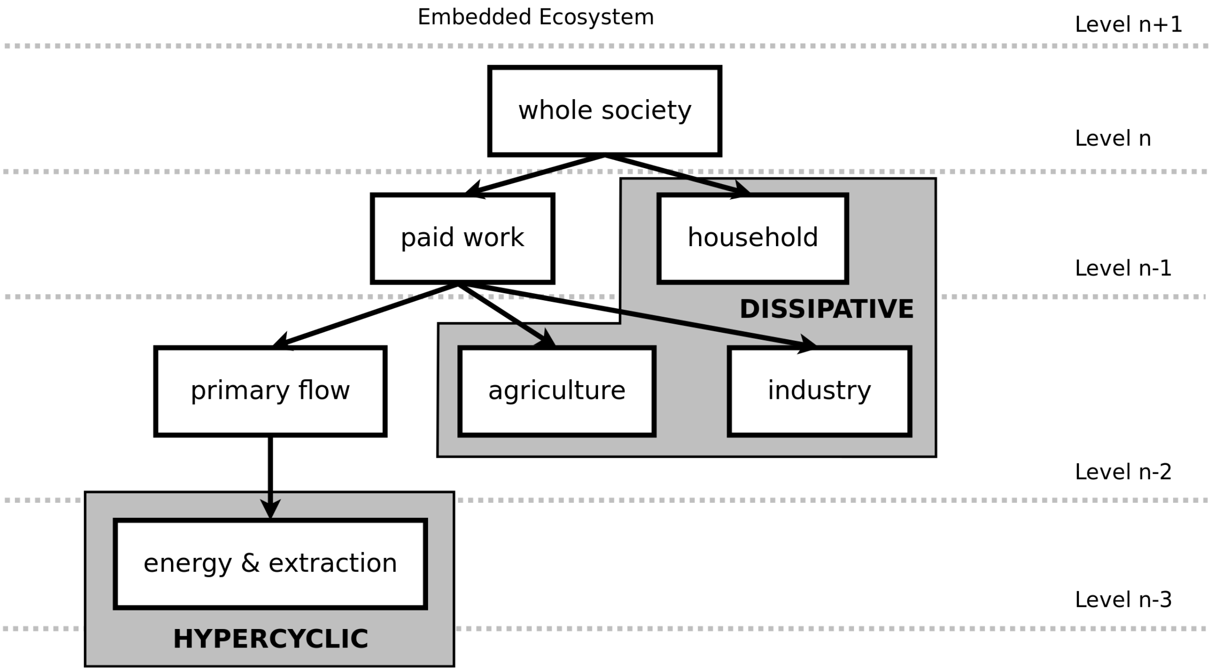



Figure 2.6: Social Metabolism for a 3-sector closed economy based on energy throughput

The figure above represents the allocation of human activity according to the hierarchical scales of energy throughput. We can discern that the household, industry and agricultural sector are the dissipative part of the system while the energy & extraction sector are the net hypercyclic part of the system. Thus the biophysical intensity of the dissipative sector can be calculated in each compartment by analysing the energy throughput per unit of human activity allocated in each compartment. Furthermore, the hypercyclic part, the energy and extraction sector, is also subject to a biophysical intensity in terms of the fossil fuel extracted per unit of energy (e.g. liters per J or Watt) delivered to the grid. Since we assume that the energy and extraction sector is the only sector consuming fossil fuel, it is redundant to represent Figure 2.6 in terms of the physical quantity of fossil fuels. In essence, this would mean that the energy and extraction sector is the dissipative compartment while the ecosystem is the hypercyclic compartment. The same reasoning applies to food throughput: the household sector represents the dissipative compartment while the agricultural sector in conjunction with the ecosystem represents the hypercyclic compartment.

When it comes to the allocation of land, the distinction between the hypercyclic and dissipative compartment is not as adequate since land is treated as a fund, not a flow. Hence, a representation in line with the dendogram representation in Figure 2.4 is in place:

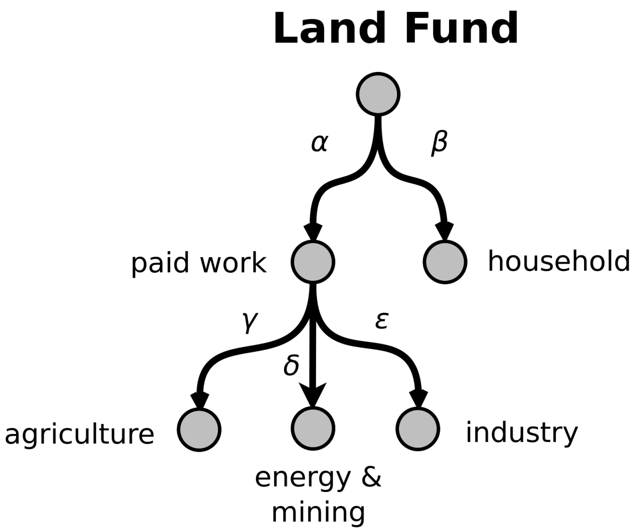



Figure 2.7: The allocation of the land fund in a 3-sector closed economy

Changes in land-use are driven by expansionary processes, either in terms of population growth or sectoral growth in the agricultural and energy & extraction sectors. These changes are relevant when we assess the sink of carbon emissions.

The second factor a MuSIASEM assessment takes into account is related to the ecosystem metabolism. This is primarily affected by the type of agriculture, which in the most trivial case can be either Low External Input Agriculture (LEIA) or High External Input Agriculture (HEIA). A distinction which essentially depends on the intensity of deforestation, the closure of nutrient cycles affected by the foodwaste returned to the land and external inputs used. These factors not only affect the ecosystem stability/health, evaluated through the negentropic cost, but also potential net primary productivity and thereby further appropriation of land; a process which feeds back into the utilization of the land fund affecting the carbon emission sink. Finally, as seen in Giampietro and Mayumi (2000); Giampietro et al. (2001), MuSIASEM also provides a narrow assessment of monetary flows by taking into account GDP for society as a whole and for each of the sectors in terms of Total Value Added per unit of human activity allocated (closely reflecting social productivity/labour productivity). An equilibrium between the supply and demand is posited both in terms of energy throughput per unit of human activity and monetary throughput per unit of human activity.

While the economic productivity of a given society and across its different sectors (GDP/HA) is useful, it does not divulge any information on the *relations of production* which give rise to the monetary flow of economic value. That is to say, it does not disclose the role of distribution (the relationship between wages and profits) which is essential for an analysis of a capitalist economy. Furthermore, an economic analysis limited to GDP takes the process of price-formation in each of the sectors for granted. We contend that distribution is relevant in order to arrive at clearer depictions of economy-ecology configurations. But before we discuss the implication hereof, let's return to our 3-sector economy and deliberate its noteworthy components from an eco-Marxist perspective.

### 2.5.3. An eco-Marxist interpretation of the 3-sector closed economy

If we take into consideration the synthesis between Marx & Ecology presented in 2.3, an analysis of our fictional economy must necessarily take into account class composition the impact thereof on the ecological system. A useful metric to consider in this case is the world-ecological surplus defined as the ratio between unpaid and paid work or appropriation and capitalization. Having said this, the two key sectors in the determination of our fictional society's ecological surplus are the agricultural sector and the energy & extraction sector. Table 2.5.3 aims to display an eco-Marxist demarcation of society and the elements which are relevant for analysis:

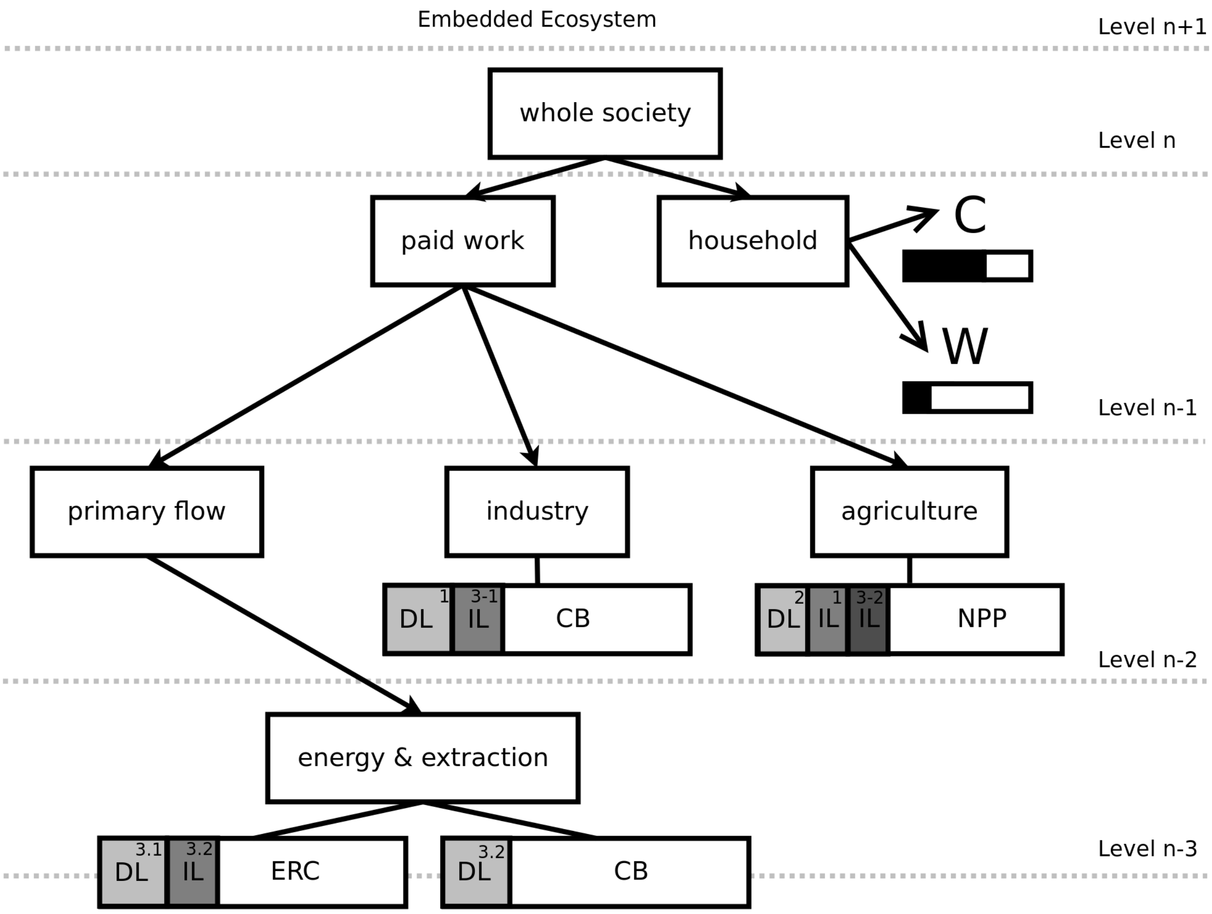
| Sector | Capitalization | Appropriation | Ecological Surplus |
|---|---|---|---|
| Agriculture | • Direct labour time<br>• Indirect labour content in external input<br>• Indirect labour time content in energy | "Tap" appropriation:<br>• Land<br>• Crop | $\frac{Appropriation}{Capitalization}$ |
| Industry | • Direct labour time<br>• Indirect labour time embodied in energy | "Sink" appropriation:<br>• Waste<br>• Carbon Emissions | $\frac{Appropriation}{Capitalization}$ |
| Energy & Extraction | • Direct labour time | "Tap" appropriation:<br>• Land<br>• Fossil Fuel Resource | $\frac{Appropriation}{Capitalization}$ |

Table 2.4: Capitalization, Appropriation and the Ecological Surplus in the fictional 3-sector closed economy

What is immediately clear in this table, is that a cross-sectoral analysis of the ecological surplus requires a contemplation on its measurement. More specifically, a measure for appropriation/expropriation of non-paid work and a measure for capitalization of paid work are key components. When it comes to the latter, a classical Marxist term which can be deployed is the direct and indirect labour content per unit of output or for total output. Or in other words, the sum of variable and constant capital in measures of labour time. When it comes to the former, quantification becomes a bit more complex and the literature on metabolic rift and world-ecology either lacks or fails to provide what such a quantification could look like. This is a void is which MuSIASEM could potentially fill.

### 2.5.4. On the complementarity between eco-Marxism and MuSIASEM

The foregoing section provided a MuSIASEM and eco-Marxist evaluation of an arbitrarily set-up economy. Even if this exercise was trivial and rather hasty, we content that it nevertheless allows us to draw two rather apparent conclusions on the compatibility between the two fields. In sum, the economic representation in the MuSIASEM framework avoids an account of distribution by limiting its focus to GDP while the ecological considerations from an eco-Marxist perspective lack an idea concerning the quantitative assessment of extra-human work. Hence, the classical Marxist component of eco-Marxism is able to add a distributive layer to the analysis in the MuSIASEM framework while thermodynamic principles and considerations on biophysical social metabolism and ecosystem metabolism can be useful for the assessment of appropriation as a component of the ecological surplus.




*Note: Numerical indicators in the corners of the boxes are referred to with subscripts in the text*

Figure 2.8: A conceptual integration of MuSIASEM and eco-Marxism from a biophysical perspective

Having identified the points of complementarity between MuSIASEM and eco-Marxism an attempt to conceptually integrate them from a biophysical point of view is provided in Figure 2.8. The figure captures a kind of static benchmark representation of a given amount of demand-driven energy throughput. We refer to a benchmark situation as one in which ecological disruptions have not yet manifested themselves. Or, in other words, there exists a "sustainable" circulation of matter between society and the ecological system. Figure 2.8 is similar to Figure 2.6 but shows 2 main differences:

1. When it comes to level $n-1$, where the distinction is made between the paid work compartment and the household compartment, the latter is further divided into a worker and capitalist compartment. The household compartment as a whole analyses the flow of energy throughput per unit of allocated fund of human activity. While human activity which takes place in the household can be subdivided into various activities, our interest with respect to Figure 2.8 only emphasizes the consumption activity (of energy).

   The figure clearly shows that a difference exists between energy throughput per unit of worker household activity and energy throughput per unit of capitalist household activity. This is indicated by the bar below the W and C where the black fraction of the bar aims to indicate how much of the household activity is dedicated to the consumption of energy. Note that even though in the figure it seems that workers and capitalists are subject to an equal quantity of household activity, this need not be the case. The reason why we assume that the energy consumption of workers is higher than that of capitalists is related to an assumption of profits being higher than wages. Hence, if capitalists purchase more electricity-based consumption goods, their demand for energy throughput will be higher. Other factors that play a role in this distinction could be related to longer working days by workers resulting in a lower amount of time to engage in the consumption of energy within their households (compared to capitalists).

   The introduction of this distinction equips MuSIASEM with a, be it fairly simple, distributional aspect. MuSIASEM's distinction between development and growth can be complemented with an analysis of which class benefits most from the more useful flows of energy due to development. Or in the case of growth, it would be interesting to disentangle whether it was growth in worker consumption or capitalist consumption (directly related to the respective social metabolisms) which dominated the overall increase in the dissipative sector.

2. The second main difference with respect to Figure 2.6 is related to the "bars" beneath the industrial and agricultural sector on level $n-2$ and the energy & extraction sector on level $n-3$. These elements essentially aim to provide an additional descriptive layer to each of the sectors, from which one can discern the ecological surplus as discussed

in Table 2.5.3. These bars represent the composition of one unit of output in each of the sectors, given the energy throughput in that sector.

In the benchmark/initial representation, we impose that each of the sectors is subject to an opportune ecological surplus. The ecological surplus can increase with an increase of appropriation, graphically depicted by the white part of the bar, or with a decrease of capitalization, indicated with parts that are shades of gray. While Table 2.5.3 depicts an eco-Marxist representation of our fictional economy without a quantifiable measure of appropriation, Figure 2.8 conceptually integrates variables from the MuSIASEM framework in the calculation of the appropriation component of the ecological surplus. The following subsections will treat this integration for each of the 3 sectors seen in Figure 2.8.

**Industry**

When it comes to the industrial sector, one unit of output embeds a direct labour time component $(DL_1)$ and an indirect labour time component. The first component is a function of the human activity fund allocated in the industrial sector per unit of output, $DL_1 = HA_1/Y_1$. The second component is a function of the energy throughput and the labour expended in the provision of that energy throughput per unit of output, $IL_{3-1} = \frac{(ET_1/EMR_3)}{Y_1}$.[7] Together these 2 components make up the capitalized portion of a unit of output in the industrial sector (shades of gray). Table 2.5.1 states that the output in the industrial sector is either an intermediate good or a consumption good. For the sake of simplicity we assume that the production technique of each good is the same and that the division of total output in intermediate and consumption goods is simply a function of demand for each of the goods.
The white component of the bar beneath the industrial sector represents the appropriation of unpaid work, or in our limiting case, the extent to which the ecological system participates in the production of one unit of output. As mentioned in Table 2.5.3, the most palpable description of this appropriation by the industrial sector is by means of its emissions and waste disposal. In terms of MuSIASEM jargon, we can think of the ecological sink capacity as an atmospheric stock related to a carbon budget beyond which serious ecological disruptions occur. The depletion of this stock is a positive function of industrial activity and therefore of output. Without regard for technological change, an increase in the demand for output depletes the carbon budget stock to an extent which can be indicated by a parameter, $CB = CB - \alpha Y_1$. As mentioned before, the ecological surplus in this case is simply: $ES_1 = \frac{CB}{DL_1 + IL_{3-1}}$ in tonnes $CO_2$/labour content per unit of output.

[7] $EMR_3$ is the exosomatic metabolic rate of the energy & extraction which represents the energy throughput per unit of human activity allocated in the subsystem (see Giampietro and Mayumi, 2000).

**Agriculture**

In the agricultural sector, the same distinction is made between the amount of capitalization (white) and appropriation (shades of gray) embedded in one unit of output. According to Table 2.5.3, the amount of capitalization embodies i) direct labour time expended in the agricultural sector per unit of output, $DL_2 = HA_2/Y_2$ ii) indirect labour time expended in the production of the industrial intermediate good, $IL_{1-2} = a_{12}\frac{HA_1}{Y_1}$ where $a_{12}$ is the intermediate good input coefficient for the agricultural sector and iii) indirect labour time expended in the energy throughput produced in the energy & extraction sector, $IL_{3-2} = \frac{(ET_2/EMR_3)}{Y_2}$.

On the other hand, the amount of appropriation embedded in one unit of agricultural output can be represented in terms of the land fund and the related flow of Net Primary Productivity ($NPP$) per hectare of the land fund. The analysis of ecosystem metabolism found in Section 2.4.2 allows us to provide a general discussion on the relationship between $NPP$ and further appropriation of the land-fund. In light of our hypothetical 3-sector economy, it is sufficient to make a simple distinction between Low External Input Agriculture (LEIA) and High External Input Agriculture (HEIA) in terms of nutrient cycles. At the beginning of this discussion we posited a benchmark situation in which we assumed that no serious ecological disruption is taking place. In other words, we assume that agricultural production is more or less in sync with agro-ecological cycles. This means that an increased demand in the agricultural sector was mostly met through further appropriation of the land-fund. Therefore, agricultural production mainly depended on the land's unaltered $NPP$ (post-deforestation) and thus required a limited amount of external inputs (fertilizer as intermediate good and energy). In other words, in this benchmark situation, the sector is situated more to the side of LEIA which is subject to a favourable and constant ecological surplus.

However, it is not only the increase in demand which further induces appropriation of the land-fund. We assume that the $NPP$ of a freshly appropriated plot of land (baseline $NPP$) is potentially higher than that of a frequently used plots of land. This potential is related to the organic closure of nutrient cycles, also known as the return of food-waste to the field. If this is optimal, each hectare of land is subject to a maximum $NPP$ under natural conditions. But if this component falls short of what is necessary (low closure of nutrient cycles) then the $NPP$ of the plot of land which is already in use is below its maximum. In reaction to this, agricultural capitalists can either choose to intensify (increasing dependency on external inputs) or further appropriate other land-funds. In both of these cases, the ecological surplus decreases, though the decrease in the second case is usually temporary (see Section 2.3.2). Of course, in a closed economy, land is limited which means that as demand-led growth intensifies, the agricultural sector is bound to experience a decrease in the ecological surplus as more capitalized inputs are used to meet demand — transitioning from LEIA to HEIA.

Note that both the further appropriation of the land-fund as well as the increasing use of external inputs feeds back into the ecological sink capacity related to the previously mentioned carbon budget. On the other hand, we abstract from the fact agricultural production also emits carbon and uses up the carbon budget. In any case, in this benchmark situation the ecological surplus per unit of agricultural output can be defined as $ES_2 = \frac{(NPP_b L_1)/Y_2}{DL_2 + IL_1 + IL_{3-2}}$ in tonnes of crop/labour content. Where $NPP_b$ stands for the baseline $NPP$ under a natural/circular closure of nutrient cycles and $L_1$ refers to the amount of land appropriated in hectares.[8]

**Energy & Extraction**

Finally, for the sake of simplicity we assume that the energy & extraction sector only uses direct labour and a part of the energy it produces in order i) extract fossil fuels and ii) produce energy for society as a whole. As a result, the capitalized component of one unit of energy is given by $DL_3 = HA_3/TET$, where $TET$ stands for total energy throughput. However, this is still too much of a simplification. Even if we merged the energy sector with the extraction sector it is necessary to take into account two distinct/non-equivalent measures of the ecological surplus because there are two different processes occurring.

The first is related to the activity of extraction and refers to stock of fossil fuel. While not explicitly mentioned in the MuSIASEM framework itself, we propose thermodynamic rarity as a measurement of the appropriation embodied in one unit of fossil fuel. This concept was introduced in (Valero and Valero, 2015b) and it incorporates two types of costs: i) the embodied exergy cost which refers to the amount of exergy it takes to convert the fossil fuel into a commodity and ii) a hidden cost understood as the free natural benefit provided by nature. The hidden cost refers to the extent to which the fossil fuel is concentrated in one place instead of dispersed throughout the earth's crust. It is represented by the exergy replacement cost ($ERC$), which, given a certain condition of technology, is the exergy necessary to extract fossil fuels from a dead state[9] to the conditions related to concentration and composition found in the fossil fuel deposit; for example, a set of concentrated crude oil wells on a given plot of land (Calvo et al., 2018).

A thorough exploration of thermodynamic rarity falls beyond the scope of the current considerations, but an exploratory incorporation of the concept into our fictionally set-up economy allows us to introduce a possible quantification of appropriation in terms of the $ERC$ found for each unit of fossil fuels. The higher the $ERC$, the higher the "free" natural benefit due to the high concentration of fossil fuels in one place and their high chemical quality. The simplified presentation of our 3-sector economy deems the consideration of the embodied

[8] The implicit assumption here is that external inputs which increase the $NPP$ beyond the $NPP_b$ do not count as appropriation even if it contributes to an increase in output. Thus it may be the case that $NPP_b < Y_2$. The reasoning behind this assumption is explained in Section 2.4.2: gains in $GPP$ (and therefore $NPP$ as the result of external inputs do not contribute to the ecological fund)

[9] This dead state is referred to as Thanatia — a hypothetical state in which all mineral deposits have been extracted and all chemical elements have been oxidized. This means that both mineral deposits and chemical elements are highly dispersed throughout the crust (see Valero and Valero, 2015a).

exergy costs (from crude to refined oil) redundant but is certainly crucial for realistic analyses. Either way, our first ecological surplus can be defined as $ES_{3.1} = \frac{ERC_{avg}}{DL_{3.1} + IL_{3.2}}$ in GJ/labour content per unit of fossil fuel. For simplicity we assume an average measure of appropriation for each litre of fossil fuel on the already appropriated field, $ERC_{avg}$. Where $DL_{3.1} = HA_{3.1}/Y_{3.1}$ represents the human activity allocated to the extraction process divided by the output of extracted material, in this case fossil fuel/oil. $IL_{3.2} = a_{3e}\frac{HA_{3.2}}{Y_{3.1}}$ represents the indirect human activity expended in the energy required for extraction, where $a_{3e}$ refers to the energy input coefficient for the extraction process.

In the imposed benchmark situation we subject the energy & extraction sector to a high ecological surplus which means that because of a high average $ERC$, low amounts of external inputs (labour and energy) are necessary to extract one unit of fossil fuel. However, as the fossil fuel stock depletes the $ERC$ of a specific field decreases. To compensate for this decrease either the external inputs used for extraction must increase or another potential field must be prepared for extraction. Evidently, the increase of external inputs for the purpose of extracting one unit of fossil fuel is limited — at some point the stock is simply depleted.

Further appropriation of land by the energy & extraction sector is a certainty if demand-led growth intensifies and requires more fossil fuels which cannot be found in the current oil field. Much like Ricardo's theory of decreasing land fertility, in our closed-economy example, we can easily assume that the first set of oil wells extracted from had the highest $ERC$. This means that $ERC$ is a decreasing function of the land-fund appropriated for extraction purposes. This allows us to reformulate the previously defined ecological surplus as follows: $ES_{3.1} = \frac{ERC_{avg}(L_3)}{DL_{3.1} + IL_{3.2}}$ with $\frac{dERC_{avg}}{dL_3} < 0$. Of course this assumption takes a different character if the same analysis would be made for an open economy.

For the second ecological surplus, our consideration is related to the combustion of the extracted fossil fuel for the purpose of energy provision. Similar to the industrial sector, this is can be defined as: $ES_{3.2} = \frac{CB}{DL_{3.2}}$ in tonnes $CO_2$/labour content per unit of output. The denominator refers to the amount of human activity allocated to the second process per unit of energy production $DL_{3.2} = HA_{3.2}/Y_{3.2}$. Note that $CB$ is a function of the emissions in the industrial sector as well, leading to a following reformulation of $CB$; $CB = CB - \alpha Y_1 - \beta Y_3$.

**Appropriation and allocation of the land-fund**

Ultimately, the allocation of the land-fund for the sectors in our benchmark situation means that the parameters $(\alpha, \beta, \delta, \epsilon)$ in Figure 2.7 are subject to certain values. Since we assumed that the benchmark situation implied a healthy interaction between social and ecosystem metabolism the sum of each fractions amounts to a non-threatening change in land-use. Evidently, this is subject to change as the ecological surplus for the initial amount of appropriated land decreases. When it comes to each of the sector's ecological surplus, it is worth mentioning that, particularly from a closed economy perspective, the process of appropriation with respect to the carbon budget is much slower than that with respect to Net Primary Productivity and the Exergy Replacement Cost. Climate change and global warming are long-term phenomena of which the impacts manifest themselves on a broader time-scale. Notwithstanding, increased appropriation of the land-fund accelerates this process by affecting the carbon sink potential. This is why it is more accurate to redefine the previously introduced carbon budget, $CB$ in terms of the land-fund appropriation, e.g. $CB(L)$.

### 2.5.5. Economic reflections

The previous sections conclude a potential integration between MuSIASEM and eco-Marxism for a 3-sector closed economy and from a biophysical perspective. This mental exercise would be incomplete if we were not to consider how economic components drive changes in the aforementioned biophysical components. While much of the above discussion already divulged that changes in production and the ecological consequences thereof are demand-driven, distributional aspects were only apparent in mentioning a difference between worker and capitalist social metabolism. Hence, a few additional, but still preliminary, insights are in order.

Our first point of departure is closely related to Marx's introduction of the metabolic rift as the result of capitalist industrialization. The combination of industrial development and a growing population eventually led to a growing discrepancy between town and country-side, disrupting the circular flow of nutrients. Sticking to a closed-economy perspective, if we assume that the food waste is only returned to the field by agricultural workers then there is a direct relationship between the $NPP$ and the allocation of workers among the industries. Furthermore, introducing a wage determined by class-struggle allows us to posit that such a class-struggle differs across sectors — resulting in wage differentials. Let's analyse a situation where: $w_{AG} < w_I \leq w_{E\&E}$. If we assume a positive degree of labour mobility this would incentivize workers to migrate from the town to countryside, thereby decreasing the extent to which the nutrient cycle remains open and feeds back into the $NPP_b$ of appropriated land. If in the consecutive period, the agricultural sector is faced with an increase in demand (or even constant demand) the possibility exists that the prevailing combination of non-paid and paid work fails to meet expected demand.

In order to nonetheless meet this demand, either the amount of external inputs or the amount of appropriated land must increase. If the price of the intermediate good, $p_I$ and the wage, $w_{AG}$ remain constant, a constant rate of profit, $r_{AG}$, requires a an increase in the price per unit of agricultural output which could possibly lead to overproduction if wages are too low. As far as the land-fund is not completely exhausted, it is possible to meet demand through further appropriation. This would require either an increase in the working time or labour intensity of the employed or additional employment in the sector (assuming a reserve army of labour). Another possibility, shifting away from the closed-economy perspective is to

outsource agricultural production to another country or region which is subject to a higher baseline Net Primary Productivity, $(NPP_b)$. This scenario falls in line with what world-ecology refers to as the expansion of commodity frontiers as the result of domestic metabolic rifts; ultimately *shifting* the occurrence of the metabolic rift across geographical scales.
The situation for the energy & extraction sector is similar, except that a fossil fuel stock is completely exhaustible while $NPP$ (almost) never reaches 0. In our simplified analysis of a closed economy, capitalists in the energy & extraction sector are naturally faced with increasing external inputs once the prevailing oil field is depleted since we assumed that the best oil mine is found first. This means that without taking into consideration R& D-driven increases in efficiency, the price per unit of energy is an increasing function of the additional amount of oil fields if the rate of profit, $r_{E\&E}$ is to remain constant. Unless, of course we shift from from a closed to open economy, allowing the extraction process to take place on different geographical scales subject to an equal or higher $ERC$. The determinants of this process are driven by the energy requirements and respective demands of both the productive sector and household sectors.
All in all, these preliminary reflections aim to show that a complex but relevant relationship exists between distribution and appropriation of the ecological components in a given society. It is precisely this interaction which takes up the central topic in subsequent research.

## 2.6. Conclusion

This paper set out to explore the compatibility between eco-Marxism and Multi-Scale Integrated Assessment of Social and Ecosystem Metabolism (MuSIASEM). The motivation behind such an exploration lay with the fact that contemporary analyses of economy-ecology configurations limit their considerations to output-based emissions. This, in the face of advancements in the natural sciences which point out that our current ecological crises is a complex whole of ecological feedbacks and loops.
In the second section of this paper we strengthened this argument by shortly addressing the representation of ecology in post-Keynesian Ecological Macroeconomics and concluding that they may benefit from a secondary ecological vantage point related to agriculture. Thereafter we singled out two particular scientific fields which *do* consider agriculture in their treatment of our ecological crises. While eco-Marxism is rooted in environmental sociology, anthropology and historiography, it draws on the ecological insights provided in the economic texts of political economist Marx. These reflections are mainly based on the discrepancy between industrial and agricultural development occurring under mid nineteenth century capitalism. Perhaps archaic, but nonetheless relevant given the fact that technological development under capitalism has not dramatically altered the subsistence base of society. Put differently, we still heavily depend on the soil and its provision of essential nutrients for the proper functioning of humanity as a whole.

Hence, in the third section of this paper we aimed to provide the reader with an understanding of Marx's often neglected conception of the relation between humanity and nature. The revival of this understanding by scholars in the late twentieth century led to what is now perceived as the metabolic rift theory, an explicit formulation of ecological crises as the result of capital accumulation and expansion. But the second section also provides a more recent adaptation of the metabolic rift theory, world-ecology and introduces the concept of the ecological surplus. Reiterating the fact that both metabolic rift and world-ecology are rooted in qualitative analyses, their usefulness for analytical analysis is limited. This is why the MuSIASEM was additionally taken into consideration; a framework grounded in bioeconomics, thermodynamics, ecology and complexity science. As such, the fourth section was dedicated to a lengthy introduction to MuSIASEM and its treatment of both social metabolism and ecosystem metabolism.

Finally, the last section provided a discussion on the compatibility between eco-Marxism and MuSIASEM by engaging in a trivial exercise based on a 3-sector closed economy. While our analysis is certainly limited to many extents, we can carefully conclude that at least on a conceptual level an integration between eco-Marxism and MuSIASEM is possible from a biophysical perspective (see Figure 2.8). In essence, eco-Marxism complements the MuSIASEM approach by introducing the question of distribution while MuSIASEM complements eco-Marxism by offering the ability to quantify ecological components. This exercise is far from complete, particularly from an economic perspective it is underdeveloped for a couple of reasons. Firstly, in our fictionally set-up economy we consciously omitted a large set of relevant economic variables. For example, in conjunction with our accentuation of the land-fund as an essential ecological component we completely dismissed the role of land rents, their impact on cultivation, resource and surplus value extraction (see Basu, 2018). But apart from that we also left out key considerations on price, competition, investment, government, international trade, money creation, credit/debt relationships, domestic and foreign policy and foreign currency exchange. Certainly, these components demand attention when it comes to accurate representations of capitalism. Notwithstanding, our short-term aim is to analytically study a limited set of interactions between distribution and appropriation of key ecological components: net primary productivity, the extraction of minerals and greenhouse gas emissions. Finally, we wish to conclude with a well-known statement made by George Box: "all models are wrong but some models are useful" (Box and Draper, 1987: pp. 424). Indeed, a desired outcome of future research is yet another model in the ocean of prevailing economic models. Our hope lies with the potential to disclose analytical conclusions which are capable of informing a more radical agenda. This, as the result of an enhanced understanding of the capitalist social relations of production — the crux of ecological disruptions and the iron gate preventing society from a just reconciliation with nature.

## Chapter 3

# An eco-Marxist reinterpretation of formal abstraction in Ecological Economics*


### Abstract

The popularization of natural capital among economists in the 1990s led to divergent views concerning the relationship between natural and human-made capital in production functions. Where *weak* sustainability advocates for substitutability, *strong* sustainability calls for complementarity. This distinction is also one of the many lines along which one is able to distinguish Environmental & Resource Economics (ERE) from Ecological Economics (EE). This paper addresses the triumph of *strong* sustainability in terms of scientific assessments which highlight the necessity of natural capital conservation and the fomentation of conservation efforts that rely on monetary valuation. While research on the various pitfalls related to monetary valuation are more than present in EE, this paper's contribution is unique in that it reinterprets the exchange value assessment of natural capital from an ecological Marxist perspective. By drawing on world-ecology and Marx's labour process theory, the paper is able to amend the existing literature on commodification with considerations that are specifically aimed at the formal representation of natural capital in the field of economics. This leads to the following insights: i) the formal representation of economy-ecology interactions through the production function only captures the contribution of *capitalized* nature and fails to consider *appropriated* nature ii) the monetary valuation of critical natural capital represents a capitalization-based accumulation strategy and iii) ecological sustained accumulation alters 'material metabolism' while 'purpose realisation' is unchanged. This last insight is interpreted as *capital bargaining on behalf of nature*. We argue that an ecological sustainability which aims to avoid the illusion of green capitalism requires *labours to bargain on behalf of nature*. This argument is strengthened by drawing on literature which addresses labour environmentalism. and treating the job blackmail as a *fabricated trade-off*. Finally, our reinterpretation is translated into recommendations for alternative formalisms in the field of EE.



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## 3.1. Introduction

In the field of economics, Environmental and Resource Economics (ERE) and Ecological Economics (EE) are the two main branches that have dealt with the abstraction of the interrelation between economic production and ecological processes. EE is typically characterized as being fundamentally at odds with ERE's negligence of biophysical constraints (Beder, 2011; Gowdy and Erickson, 2005; Venkatachalam, 2007). As such, EE developed into a pluralist and trans-disciplinary field whose literature engages in both critiques and the introduction of previously overlooked considerations. Some authors argue that pluralism represents the biggest strength of the field (Goddard et al., 2019). Others like Spash (2020), argue that pluralism in EE has not sufficiently dealt with neoclassical economic epistomologies and formalisms.

This paper builds on the above argument by carefully considering the mathematical formalization and abstraction of economy-ecology configurations in EE. In other words, we take interest in EE's method of analysis by means of models or "the mental constructs based on assumptions, abstract concepts and relations among variables" (Katzner, 2001: pp. 49). In our view, natural capital is a fundamental variable in many of the economic models which try to analyze economy-ecology configurations. In the first section, we introduce the natural capital concept and discuss how its treatment differs across ERE and EE. We then isolate strong sustainability as one of the main attributes of EE when it comes to the assumed relationship between ecological processes and economic production. Strong sustainability's prescription to treat natural capital as a complementary input in economic production functions has led to the implementation of various strategies concerning natural capital conservation. The bulk of these strategies has subsequently relied on monetary valuation for the purpose of embedding conservation strategies within the broader rationale of the market. Critical studies have identified this phenomenon as commodification and we address some of the experienced and theorized contradictions it is associated with.

In section 2 we discuss Marx's ecological insights and the concept of dualism in eco-Marxism and economics. Our focus on mathematical formalization forecloses a complete rejection of conceptual distinctions inherent to dualism. This is why we argue for duality instead. Section 2 also reviews Marx's labour process theory and Moore's world-ecology in order to examine the underlying assumptions concerning natural capital, strong sustainability and monetary valuation.

In section 3 we argue that Marx's labour process theory and the two elements that constitute it, 'material metabolism' and 'purpose realisation', reveal that the isolated treatment of natural capital obfuscates the relationship between labour and ecological process(es). World-ecology allows us to reconsider the commodification of natural capital as the transition of an ecological process from an appropriated to a capitalized state. Such a transition squares with the overarching rationale of capitalism in that it safeguards production processes against future constraints to accumulation and/or is expected to increase accumulation in the future. Given the above, EE's mathematical formalization of economy-ecology configurations by means of natural capital can be seen as a method of analysis which only accounts for ecological processes which are, or are promoted to become, capitalized. From an eco-Marxist perspective, the advantage of a strong sustainability approach over a weak sustainability approach is limited given the centrality of natural capital. Our reinterpretation also suggests that the underlying assumption behind the aforementioned centrality is one which suggests that ecological degradations are best mitigated when capital bargains on behalf of nature.

An alternative to capital bargaining on behalf of nature, could be for *labour* to bargain on behalf of nature. In Section 4 we draw on environmental historian Stefania Barca and her research on labour environmentalism, the job blackmail and working class ecology to discuss historical instances of labour bargaining on behalf of nature as well as theoretical iterations thereof.

Finally, we conclude with recommendations for an alternative formalization practice which are based on the concept of *duality* instead of dualism and the deliberation on the configuration between *appropriated* ecological processes and waged-labour.

## 3.2. Natural capital and the advances of strong sustainability: monetary valuation and commodification

The natural capital concept was popularized among economists in an important contribution by David Pearce in 1988 (Åkerman, 2005; Pearce, 1988). It is used to describe the exchange value of natural resources and formally appears as an input in production functions for goods and services (Howitt and Weil, 2018). Since natural resources are diverse, natural capital is broken down into various sub-components; i) non-renewable resources, ii) renewable resources and iii) regulating ecosystem services (Berkes and Folke, 1992). We maintain the following economic definition of natural capital: any natural resource, both renewable and non-renewable, which enters a formally defined production function (a mathematical equation) as an input. In discussing 'ecological processes' however, we refer to renewable resources.

One of the distinctions between ERE and EE regards the *weak* and *strong* sustainability[1] paradigms (Gowdy and Erickson, 2005). When it comes to mathematical formalization, the difference between the two paradigms is based on the degree of substitutability between natural capital $(N)$ and human-made capital $(K)$ in production functions $(Y = f(K, L, N))$. Treating the two inputs as full substitutes follows *weak* sustainability while treating them as partial substitutes or complements follows *strong* sustainability (Ayres et al., 1998; Neumayer, 2013). The main implication of *weak* sustainability in economic models is that reductions in $N$ (ecological degradation) are permitted as long as they are compensated with an increase

[1] While a precise definition of sustainability is highly contested, its basic principle is that an economic, social or ecological ecosystem be managed such that it exhibits continuity in output or value (Mabee et al., 2020).

in $K$ (Common and Perrings, 1992). *Strong* sustainability rejects the above compensation mechanism on the basis of i) the inability to fully account for nature's complex characteristics (Turner, 1993) and ii) finite natural resources which are necessarily subject economy activity to constraints (Costanza and Daly, 1992; Daly, 2008; Spash, 2008). For a more in-depth explanation of modelling approaches under *weak* and *strong* sustainability, the reader is suggested to read Appendix B. As an alternative to the aggregated treatment of $N$, ecological economists have additionally introduced a distinction between *critical* and *non-critical* stock-flow and fund-service natural capital.[2] The criticality of natural capital depends on whether i) the flows or services can be substituted for, ii) their depletion or degradation is irreversible and/or iii) their depletion or degradation is immoderate (Ekins et al., 2003). One trivial way to review the ensuing research on criticality and conservation is to discuss planetary boundaries and ecosystem services.

The planetary boundaries concept assesses earth's system processes and proposes preconditions for further human development. It was introduced by a group of scholars at the Stockholm Resilience Centre in a publication which identifies ten macro-determined earth system processes, their proposed boundary, current status and pre-industrial value (Rockström et al., 2009a,b). Together these boundaries delimit an expert-estimated 'safe operating space' outside of which the Earth's capacity to maintain agriculture and complex human societies is compromised (Lade et al., 2020). Since each separate planetary boundary is approximated with control variables, it is easy to recognize these variables as natural capital types and the distance between their current value and boundary as a measure of criticality.

Ecosystem services (ESs) were academically popularized by Daily (1997) and ever since, the concept has undergone various adaptations and classifications such as to provide a clear-cut accounting system for decision-making processes that guide ecosystem management practices. Following the *Millennium Ecosystem Assessment Report* from 2005; the most common way to categorize ESs is by distinguishing between i) provisioning, ii) regulating, iii) cultural and iv) supporting services (World Resources Institute, 2005). This has led to a widespread literature on the historical development of the concept, recommendations for improving the methodology and local or regional assessments of ESs (see Boerema et al., 2017; Cabral et al., 2017; Costanza et al., 2017; Greenway, 2017; Harrison et al., 2014).

The bulk of critical natural capital conservation policies are based on monetary valuation which is rooted in the treatment of pollution under welfare economics. Following Perman et al. (2003: pp. 34), pollution as a by-product of production indicates the presence of a negative externality which remains unaccounted for as long as the externality is not reflected in the price of the produced commodity. Economic instruments such as Pigouvian taxes, subsidies and tradeable

[2] Stock-flow natural capital is materially transformed into what it produces and can be used at a desired rate while fund-service natural capital is not materially transformed and only available at a fixed rate (Daly and Farley, 2011: pp. 72; Georgescu-Roegen, 1971).

permits are implemented to correct for these market failures and subsequently achieve an optimal allocation of resources. While taxes and subsidies require monetary valuation for the purpose of conveying a correct price signal, trading systems are based on the idea that the dynamic between supply and demand can derive an autonomous price/monetary value of for example, a ton of CO2 (Pirard, 2012).

In terms of planetary boundaries, the bulk of monetary incentives have been developed to either foster the conservation or creation of atmospheric carbon sink services. One example is the Clean Development Mechanism (CDM) defined as one of the flexible mechanisms under the Kyoto Protocol. It allows Annex I (those subject to an emission reduction commitment) to implement emission reduction projects in developing countries (UNFCCC, 2020a,b). Accredited projects are subject to the issuance of temporary or long-term certified emission reductions (CERs) which are based on the estimated amount of greenhouse gas removals both during and at the end of the project implementation period (UNFCCC, 2013). These CER's are then purchasable by Annex I countries as a means to abide by their emission reduction targets (UNFCCC, 2020a). The economic value or price of CER's, expressed in units of currency per tonne of CO2 reduction, is said to be a function of various market conditions: offset import limits[3], the cost of abatement, the penalty rate, the emission cap and baseline emissions (Fearnehough et al., 2018; Yu and Mallory, 2020).

Touching upon the monetary valuation of ecosystem services (ESs) brings us to payment for ecosystems schemes (PES) and "green"/"sustainable" financial instruments. The aim of PES schemes is to provide the stewards of ecosystem services with financial compensation so as to incentivize conservation efforts. Salzman et al. (2018) record approximately five hundred fifty active programmes exposed to thirty six to fourty two billion dollars in annual transactions. According to Arriagada and Perrings (2013), i) carbon sequestration in biomass and soils, ii) habitat provision for endangered species and iii) the protection of landscapes and hydrological functions constitute the main services included in such programmes.

There are different ways to derive the monetary value of ESs, following Victor (2020) these methods are mostly drawn from benefit-cost analyses which aim to retrieve the competitive market price of a conservation project. Travel cost estimates take the cost of traveling to an area with ESs, multiply it by the yearly visitors and use this measure as a proxy for the ES's monetary value. Another method is contingent valuation, which estimates monetary values on the basis of participants' willingness to pay for an ES or willingness to accept the loss of an ES (Arias-Arévalo et al., 2018).

ESs are also related to the development of "green" financial instruments such as green bonds and biodiversity credits. Green bonds raise funds from fixed income investors which are

[3] A mechanism designed to prevent CER's from flooding into the market and driving the price of emission allowances to zero (EC, 2016)

then loaned to eligible projects (stewards) that seek to mitigate climate change and/or sustain critical ESs (World Bank, 2019a). This provides private investors, pension funds, insurance companies or sovereign wealth funds (polluters) with triple A rated bonds which they can use to showcase their green financial portfolios as proof for their commitment to environmental improvement (Sullivan, 2018b). Biodiversity banking allows firms or entities to compensate for biodiversity losses that occur due to current or projected economic activity (Coralie et al., 2015). The issuance of credits is delegated to mitigation banks which are established by acquiring or managing land for the purpose of habitat, resource or particular wildlife species conservation. The monetary valuation of the site results in an amount of credits which are purchasable by entities who have incurred or are expected to incur biodiversity losses (Latimer and Hill, 2007: pp. 157).

In theory, each of the above examples capture what can be referred to as the commodification of nature[4]: the renunciation of nature's systemic character since monetary valuation transforms an ecosystemic entity into a succession of privatised units which are consequently subject to the capitalist logic of profit maximization (Bermejo, 2014: pp. 22-23). Following Castree (2003), one can distinguish between two types of commodification processes. The first is referred to as *real* commodification and points out the treatment of nature as if it were a real commodity, completely privatizable and separable. The markets for these (or similar) entities and processes exist prior to the commodification of new repositories. By contrast, the second type of commodification involves the commodification of previously non-commodified entities as a means to account for "missing markets"; it is therefore referred to as *proxy* commodification. According to Gunderson (2017: pp. 11-17), the subjection of ecological processes to an economic system organized around the market mechanism is ridden with contradictions. Literature on the proxy commodification of atmospheric sink capacities points out how forest conservation projects intensify the struggle over land, offer the biggest polluters a cheap means to comply to emission targets and inadequately address the social and ecological effects of the project (see Bayrak and Marafa, 2016; Bumpus and Liverman, 2008).

The literature on the proxy commodification of ESs reveals that PES schemes frequently exclude small landowners and indigenous community forests; neglect the issue of additionality[5]; clash with poverty reduction priorities and bear insufficient consideration for the feedback loop between equity and ecological outcomes (Börner et al., 2017; Calvet-Mir et al., 2015; Corbera, 2012). Finally, "green" financial instruments are innovative financing mechanisms that blur the line between pure financial returns and positive social and environmental impacts (Lohmann, 2012). In the neoliberal age of public-private sector substitution, this kind of 'impact investing'

[4] Much of this stream of literature borrows insights from Karl Polanyi and his treatment of land as a fictitious commodity (Polanyi, 2001: pp. 76). Smessaert et al. (2020) provide an excellent review of commodification in the field of social sciences.

[5] Additionality is meant to capture to what extent the improvement of an ecosystem service is additional to what would have occurred in absence of the PES.

presents a low-risk opportunity for the private sector to fill the social and environmental funding gap (Sullivan, 2018a). The literature evaluating wetland mitigation banking in the USA indicates that these mechanisms often fail to consider geographically differentiated ecosystem functions and allow significant dissonance between the issuance of offset credits and the establishment of ecological criteria for the respective wetlands (Driesen, 2005; Robertson and Hayden, 2008).

This section introduced the reader to the concept of natural capital and the difference between EE and ERE with respect to its mathematical treatment in economic models. Where strong sustainability can be seen as a unifying principle in EE, the monetary valuation of critical natural capital remains a contested subject (see Costanza et al., 1997; Gómez-Baggethun and Martín-López, 2015; Spash, 2008). Some *strong* sustainability proponents argue that monetary valuation is necessary to communicate the obligation and urgency to protect critical natural capital while others argue for an expansion of valuation methods into spheres that stretch beyond exchange value[6] (Arias-Arévalo et al., 2018; Lo and Spash, 2013).

The aim of this paper, however, is geared towards a deeper understanding of mathematical formalization. In our view, the abstract representation of ecological processes by means of complementary natural capital embodies incomplete assumptions concerning economy-ecology configurations. In an attempt to unveil this incompleteness we now turn to eco-Marxism.

## 3.3. Eco-Marxism: dualism, labour process theory and the ecological surplus

n this section the reader is introduced to eco-Marxism and some of the elements we deem crucial for a reinterpretation of formal abstraction in EE. The reinterpretation itself will be left for the subsequent section. Here, we discuss Marx's ecological insights, the debate on dualism in eco-Marxism, Marx's labour process theory and the ecological surplus concept.

Emanating from geography, history, environmental sociology and critical environmental studies, eco-Marxism is a field of thought which places capitalism's specificity in the foreground when it comes to the assessment of ecology-economy configurations. One of the most acclaimed eco-Marxist concepts is the metabolic rift which captures a break in the metabolism "on which life is sustained and growth and reproduction become possible" (Foster, 1999: pp. 383). The metabolic rift is derived from Marx's insights regarding the metabolic exchange between humans and ecological processes under capitalist industrialization. By drawing of agro-chemistry, Marx was able to develop a systematic critique of capitalist exploitation; not only in terms of labour exploitation but also in terms of soil degradation.

[6] For example, Jacobs et al. (2016) argue that value pluralism or integrated valuation methods extend the scope of valuation from instrumental values to non-anthropocentric values (for example ecosystem integrity) and relational values (social well-being as the result of ES's).

Marx noticed that as industrialization mobilized labour from the fields to the factories, natural nutrient cycles became disturbed. In order to restore agricultural output the agricultural sector became increasingly dependent on fertilizers. This development captured the "progress toward ruining the more long-lasting sources of fertility" (Marx, 1887b: pp. 330).

### 3.3.1. Dualism and duality in eco-Marxism and economics

While the contemporary emphasis on Marx's ecological and metabolic insights is consolidated under eco-Marxism, it is important to mention the debate between the metabolic rift school and world-ecology concerning the binary treatment of society and nature.

Dualism is one of the key issues world-ecologist Jason W. Moore attempts to overcome in *Capitalism in the Web of Life*. In it, Moore discusses the limitations of the metabolic rift school with respect to its binary treatment of society and nature. Such a treatment restricts analysis to the *interaction* between social and natural metabolisms and fails to consider how the two are *unified* across space and time (Moore, 2015a: pp. 89). Treating society and nature as two independent units leads to analyses in which the ecological externality of capital accumulation is elucidated. Instead, the world-ecology perspective draws attention to the interdependent flows, forces, conditions and relations that manifest themselves in the web of life. Capital accumulation is a seen as human activity which "makes" the environment in both an ideal (the way we think about, quantifiy, measure the environment) and material (agricultural, mining, urbanization) sense.

While we are sympathetic to Moore's world-ecology, it is important to reiterate that our aim is to revisit and critique the status-quo of *mathematical formalization* in EE. In economics, dualism is said to be the dominant mode of thought used to order observations and ideas for the purpose of theorizing (Dow, 2012: pp. 56). This is apparent in models where categories, such as labour, capital, in/out of equilibrium are used as comprehensive and mutually exclusive units or states of analysis. The neoclassical application of dualism between individual agency and the social structure has resulted in the admired modeling of extreme cases such as perfect competition, complete preference sets and the maximization of utility under conditions of pure rationality (Jackson, 1999; Hamilton, 2002: pp. 94-95).

A compelling alternative to dualism is expressed in the field of social theory by Anthony Giddens in *Central Problems in Social Theory*. Giddens argues for a duality of structure, where the social structures should be seen as both the medium and outcome of individual actions (Giddens, 1979: pp. 5). Duality implies that two essential elements are retained but their separation and opposition is replaced by interdependence (Jackson, 1999: pp. 549).

In our view, duality, as opposed to dualism, also resonates with Moore's idea of the web of life or *oikeios*: the bundle of co-produced configurations (or relations) consisting of both human and extra-human natures (Moore, 2015a: pp. 46-47). This argument can be clarified by drawing on a trivial example based on the production of wood: Instead of treating a forest as an object which is entirely separate from the capitalist society which destroys it for the purpose of exchange value accumulation, the notion of an *oikeios* allows us to treat both the forest ecosystem and the production of wood as a specific configuration which is centered around a shared substance. In doing so, it is possible to conceive of both the forest and the piece of processed wood as a result of the co-production of two ontologically interdependent units, continuously flowing in and out of each other. Having said that, the delineation of the forest ecosystem and production of wood as two analytically distinct elements grants us the possibility to conceive of the forest ecosystem as an entity subject to a non-conscious autonomy, or an autonomy without agency. Interdependency and relationality dictate and shape the set of conditions under which natural processes in the forest ecosystem are able to unfold. However, it is difficult to conceive that the way natural processes unfold with respect to the production of wood is a conscious response such as "Let's teach IKEA a lesson!".

In sum, adherence to *duality* allows us to provide a world-ecology informed critique of the formal abstraction in EE which is based on an assumed dualism between nature (natural capital) and society (labour and human-made capital). At the same time, *duality* permits the conservation of mathematical formalization practices which are *de facto* based on conceptual and analytical distinctions between specified variables.

### 3.3.2. Marx's labour process theory

Following Han (2010), a Marxist discussion of the ecological issue will inevitably be focused on the concept of labour since Marx's labour process theory incontestably addresses the interdependence between humanity and nature. In Marx's description of the labour process in Chapter 7 of *Capital I* (Marx, 1887b: pp. 127), one can identify two elements: 'purpose realisation' and 'material metabolism' (Shimazaki, 1997 in: Han, 2010). 'Purpose realisation' describes labour as the imposition of human intention on nature from the outside which then causes nature to capitulate to the humanity's will. In other words, natural objects are endowed with humanistic forms for the purpose of use value creation. 'Material metabolism' focuses on the labour as a metabolic process, an exchange or a mediation between itself and nature. This metabolic process is subject to a two-fold meaning; on the one hand it represents a physiological meaning grounded in natural sciences and therefore concerned with the functioning of as well as the interlinkages between organisms, ecosystems and biophysical processes (Schmidt, 2014: pp. 86-87). At the same time, 'material metabolism' is also subject to a broader philosophical meaning which refers to the process of interchange and transformation of both substance/material between two entities — humanity and nature. Han (2010) goes on to state that Marx envisioned labour as a process of 'matter interchanging', where the endowment of a humanistic form is merely temporal and accidental compared to the natural substance itself. As soon as the imposed form no longer suits human will, the matter of the natural substance returns to nature. For example, wood that has been filtered by the labour process experiences a shift in its form: from the trunk of a tree to a table. But if the table breaks or decays, an unaltered amount of matter (wood) returns to nature (Marx, 1887b: pp. 42). Seen in this way, the philosophical meaning behind Marx's 'material metabolism' can be considered as the imposition of a *duality* between humanity and nature and the characterization of nature as an independent force which cannot be fully dominated by humanity and its labour subjects.

### 3.3.3. World-ecology and the ecological surplus

Apart from the negation of *dualism*, world-ecology additionally accentuates the specific transition of nature's contribution to capital accumulation over the course of history. Instead of locating the emergence of this contribution in the late 19$^{th}$ century, Moore (2017) locates the radical shift in scale, speed and scope of landscape change in the long 16$^{th}$ century — characterized by the conquest of the Americas and the English and Dutch agricultural revolutions. In Moore's account of world-ecological regimes[7], he introduces a concept called the ecological surplus, a ratio between appropriation and capitalization. Capitalization entails the use of a broad array of elements or inputs; fixed capital, circulating capital (raw materials) as well as *paid* human (labour power or variable capital) and extra-human reproduction (for example tree plantations and farm animals). These inputs are already subject to the market logic and are therefore competitively priced. Appropriation on the other hand, represents the process by which capital gains access to minimally or non-commodified human and extra-human inputs such as *unpaid* domestic labour, soil fertility and atmospheric sink capacities (Moore, 2015a: pp. 71). Minimally commodified inputs are human and extra-human labour processes which are available at a cost which is significantly lower than their average market price (Walker and Moore, 2019). This is also referred to as "cheapness": a reduced value composition with respect to the system-wide average for all commodities (Moore, 2015b: pp. 3). In the rest of this paper, we use appropriation in its incomplete sense and hence as a way to refer to *unpaid* and *non-commodified* inputs. Appropriated labours and processes are said to constitute the basis on which waged labour can be built and exploited (Mies, 1998; Moore, 2015a: pp. 223-224;237-238). Human unpaid labour is also referred to as meta-industrial: non-monetized labour which is regenerative and therefore essential to the sustenance of everyday life and livelihoods as well as capitalist production (Salleh, 2010). Meta-industrial labour sustains metabolic value[8], which captures the material and energetic integrity of living processes in both nature and human bodies.

Coming back to the ecological surplus, a high ratio between appropriation and capitalization generally indicates that capital accumulation is comfortably proceeding by means of

[7] These are characterized by a fundamental reorganization of nature-society relations in comparison to a previous regime (Moore, 2011b)

[8] An interesting discussion though outside the scope of this paper would be on the relationship between the concept of *negative value* (Moore, 2015b) and metabolic value. We presume that metabolic value co-constitutes the inverse of *negative value*.

labour productivity gains — secured by the high quality of appropriated labours, entities and processes. A low ratio triggers metabolic *shifts* in search of i) new sources for appropriation, ii) cheaper sources of capitalized inputs or iii) investment in technologies that increase efficiency/productivity or the localization of new appropriation sources - eventually establishing a new world-ecological regime. According to Moore, every long wave of accumulation is characterized by a high ecological surplus created through the combination of capital, science and power which allows the comfortable appropriation of non-commodified human and extra-human entities and processes. After reaching a certain peak or maximum, the ecological surplus tends to fall which increases costs and decreases the rate of profit; opening up the necessity for the establishment of a new world-ecological regime. In essence this represents a cyclical interplay between commodified and non-commodified inputs characteristic of capitalism as an ecological regime. The hypothesis being that accumulation proceeds faster with a higher access to non-commodified inputs.

## 3.4. Reconsidering the underlying assumptions of formal abstraction in EE

Our starting point is the reinterpretation of the advances under the *strong* sustainability paradigm as ignitions of capitalization as defined under world-ecology. Prior to the monetary valuation of for example carbon emissions or ecosystem services, one can regard the respective processes to be in a state of appropriation. Even if capitalistically organized production processes constitute an interdependency with appropriated ecological processes, the latter are not considered to enter the production function as an input. Advocacy for the conservation of these ecological processes calls monetary valuation into being as a means to achieve the internalization of an externality. As soon as valuation techniques are able to expound the benefit of conservation in terms of exchange value, an optimal amount of conservation is expected to establish itself. This is comparable to the purchase of exhaustible resources for the purpose of capitalist production.

Recalling Moore's concept of the ecological surplus, both a decrease in appropriation in favour of capitalization and an increase in capitalization result in a lower ecological surplus. This begs us to question why the capitalization of nature is a dominant response to ecological degradation if it serves to hamper accumulation. Our concern with respect to accumulation strategies abstracts away from the long-run entry into new world-ecological regimes. We do so on the basis of Moore's contention that the accumulation strategy based on increased capitalization for the purpose of localizing new sources of appropriation is slowly wearing out on a finite planet (Moore, 2014). Instead, our aim is to elucidate the short-term raison d'être behind capitalization.

The first justification[9] for capitalization-based accumulation strategies is related to the realization that continued appropriation decreases or is expected to decrease the productivity of inputs which are already capitalized. In this case, the expected costs of both setting up the facilitating infrastructure and capitalization itself are lower than the expected costs of less productive capitalized inputs. This can be seen as the capitalist awareness of what eco-Marxist James O'Connor calls the second contradiction: nature undermining productive forces resulting in underproduction due to declines in productivity (O'Connor, 1991). This also resonates with the current practice of monetary cost-benefit analyses; where foreseeing the future sabotage of productive assets allows the protection of a higher ecological surplus than what is expected to manifest itself in the absence of additional capitalization. The main difference here, is that we are not evaluating these adjustments in terms of the rational optimization of utility or welfare by means of an efficient allocation of capitalized nature. Instead, we present a trivial consideration based on the extent to which capital accumulation can proceed. A small constraint to accumulation for the prevention of a bigger constraint in the future is obviously preferable. Clear examples of this logic are best captured by the economic instruments designed to mitigate the pollution which negatively impacts human health and thereby labour productivity. But since climate change is also expected to heavily impact labour productivity through health consequences, it is reasonable to count forest conservation projects under CDM towards this logic as well.

The second justification can be seen as the inverse of the first, namely the expectation that the inclusion of capitalized nature as an input will increase the productivity of other capitalized inputs as a whole. One way to envision such a logic is by considering examples where the capitalization of previously appropriated natures offers new means by which to increase competitiveness. Taking green bonds and voluntary carbon or biodiversity offsets projects as an example, it is possible to argue that the acquisition of capitalized nature polishes corporate appearance. In turn this may result in an increase of market-shares given that the entire corporation or firm abides by its duty to "protect the environment". Some scholars have characterized this phenomenon as greenwashing: the range of communications concerning corporate social responsibility initiatives which mislead the public into the adoption of positive beliefs about the firm's environmental performance, practice or products (Lyon and Montgomery, 2015).

These considerations and justifications are nothing new and probably under-elaborated. So far, the result of this eco-Marxist reinterpretation simply reiterates the "sustainable" capitalization *pays off* slogan as *sustains accumulation*; assessed by means of the ecological surplus and its two components. But if capitalizing critically delineated nature constitutes a capitalist

[9] In mentioning justifications we intend to convey the reasons behind the pursuit of capitalization *from a capitalist perspective*.

accumulation strategy in the age of looming ecological collapse it is not only crucial to identify the low efficacy of this strategy in terms of ecological performance, but also to call into discussion the implication of this strategy for the *other* capitalized input, wage-labour.

We argue that even in absence of considerations on the degree of substitutability between natural capital and human-made capital, the portrayal of ecological processes which enter a production function, assessed in terms of exchange value, automatically imposes its commensurability with both labour $(L)$ and human-made capital $(K)$. This is because each of the inputs are, or are assumed to be, subject to a compensation: labour receives a wage and human-made capital is subject to a price or rent. The magnitude of the wage is determined by social norms, the relative bargaining position of labour with respect to capitalists or in Marxist terms: class struggle. In turn, the price of human-made capital is determined by the cost of inputs that produced it (including labour and its wage) as well as the junction between capitalist competition, perspectives on expansion or growth and the appetite for positive profits. Each of these ultimately determine the mark-up on the costs of production and maintenance. Given that the price of human-made capital embodies the wage paid for the labour expended in its production, the price paid for both the direct labour input $(L)$ and human-made capital $(K)$ are essentially a function of distribution. In the end, both $K$ and $L$ are determined by the bargaining position of labour with respect to capital — a position which is of course differentiated across production spheres —.

Restricting ourselves to the confines of the assumptions underlying the mathematical formalization of production processes; one can wonder if the price of natural capital $(N)$ is a function of a similar kind of bargaining dynamic.[10] To answer this question one must first consider the fact that an ecological process, proxied by natural capital, is unable to bargain on its own behalf. Logged forests, eroded soils or coral reefs are unable to raise their fists, unite and strike for the purpose of a higher compensation. A third party is required to bargain on their behalf. Secondly, whatever the price of natural capital, the *last* entity to benefit from the derived compensation is nature or the ecosystem in and of itself. The sole function of this price is to increase/decrease the incentive to conserve/damage a natural entity. While it is assuredly the case that if such incentives work, the ecosystem is better off, the fact that it is subject to an exchange value is not the direct means by which it is improved. Unlike $L$ or $K$, which are at least able to use the wage/profit to purchase goods and improve material conditions, the improvement of $N$ depends on a reconfiguration between labour and nature.

Drawing on Marx's labour process theory, the incentives which the capitalization of ecological processes aim to foster can be seen as desired alterations to the 'material metabolism' element of the labour process — *without consideration for labour's entanglement with said ecological process*.

[10] Here we do not consider natural capital in terms of physical land which is subject to a rent and therefore includes rentiers as an additional class apart from labourers and capitalists.

For example, a decrease in the throughput of pollutants, an increase in the uptake of $CO_2$ emissions or an increase in the amount of species per hectare of land. If such aims are encapsulated by a capitalization strategy, we argue that they merely address the physiological character of 'material metabolism' without regard for its philosophical character and its related set of socially defined 'purpose realisations'. Capitalism continuously configures society's prevailing 'purpose realisation' in order to meet its inclination towards endless accumulation. Furthermore, the simple *a-priori* fact that a worker's labour is sold as labour-power to capitalists results in variegated oppressions which alienate the worker from their labour, the products thereof, their selves, others and nature. As such, 'purpose realisation' is no longer "the endowment of natural objects with humanistic forms for the purpose of use value creation" but "the endowment of natural objects with humanistic forms for the purpose of exchange value accumulation". When society is faced with ecological degradations, it is the confrontation with the ability to achieve said prevailing 'realisation purposes' that leads to redefined and/or novel but nonetheless primarily capitalistically orchestrated 'material metabolisms'.

## 3.5. The necessity of labour to bargain on behalf of nature

The previous section reiterated the monetary valuation of critical natural capital, as promoted by the *strong* sustainability paradigm, as a capitalization-based accumulation strategy in the world-ecological sense. We originate the aforementioned strategy in the economic and formal appearance of natural capital as an input which enters the production function. Such a representation we argue, represents an endorsement of the idea that ecological sustainability is attainable when capital, not labour, bargains on behalf nature.

In terms of Marx' labour process theory, when capital bargains on behalf of nature the aim is to adjust the 'material metabolism' element of the labour process while 'purpose realisation' remains intact. Scholars in the Degrowth tradition argue that such adjustments in 'material metabolism' do not rid the economic system of a continuous reinvestment of surplus into new production (D'Alisa et al., 2015b: pp. 248). As long as such a reinvestment takes place, the economic system is bound to grow; a process which goes hand in hand with increases in biophysical/material throughput and hence ecological degradation.[11]

In developing our position on the *necessity* of labour to bargain on behalf of nature we draw on a hypothesis formulated by Barca (2019a): the alienation of workers from the products of their labour is a fundamental component of the productive reinvestment of surplus. In light of our focus on the labour process, we treat the capitalist transformation of 'purpose realisation' into the endowment of natural objects with humanistic forms for the purpose of exchange value accumulation, as one of the characteristics of alienation. This brings us to a broader, but

[11] A recent publication by Hickel and Kallis (2020) compiles empirical data which demonstrates that even under optimistic technological efficiency scenarios, a decoupling of material throughput and GDP growth will only be temporary.

still preliminary, definition of what it could mean for labour to bargain on behalf of nature: *the orchestration of an ecologically sustainable 'material metabolism' by means of a return of 'purpose realisation' to its initial state: the endowment of nature with humanistic forms for the purpose of use-value extraction.* Given the above, it is crucial to question i) if similar proposals have been theoretically articulated before and ii) whether labour has historically been able to bargain on behalf of nature.

The primary tenet around which we assess the aforementioned questions is the job-blackmail - "the corporate practice of threatening employees with a choice between employment and health [...], making the public believe that there is no alternative to 'business as usual'" (Kazis and Grossman in: Barca and Leonardi, 2018: pp. 489). In line with the eco-marxist reinterpretation of natural capital presented in the previous section, we redefine the job blackmail as a *fabricated trade-off* between i) capitalization as a means for capital to bear responsibility for environmental and health damages and ii) the maintenance or promised strengthening of the prevailing bargaining position of labour vis-a-vis capital. The existence of this *fabricated trade-off* shows that increased capitalization, e.g. the investment in technologies which reduce pollution or the implementation of pollution taxes, can still take on its traditional role as a barrier to accumulation. Which is precisely why it can be instrumentalized as an instance which weakens the existing bargaining position of labour vis-a-vis capital through the threat of lay-offs or lower wages.[12] Evidently, one of the main entities which have been historically equipped with the task to strengthen the position of labour vis-a-vis capital are unions. In the following subsection, it will become clear that unions play an important, though not all-encompassing and homogeneous, role.

### 3.5.1. A brief overview of the historical junction between labour and environmental movements

**The U.S. experience**

Characteristic of the historical confluence between labour and environmental movements in the second half of the twentieth century is the expression of ecological consciousness, culminating in organized action. This is said to be the result of an encounter between micro-particles and the worker's bodies (Barca, 2014a: pp. 12). During the 1960s and 1970s for example, the US experienced a coalition between oil, chemical, atomic, steel and farm workers unions and environmental organizations (Ibid, 2012: pp. 67-69). Health professionals solicited reforms, aided labour movements and formed various Committees on Occupational Safety and Health. Such developments were the result of a medical science that developed around the observation of workers' bodies in their reaction towards the various hazards they were exposed to over the course of their labour hours (Ibid, 2014a: pp. 13). The vehement link between

[12] In other words, capitalization as a component of the *fabricated trade-off* has not taken its form as an accumulation strategy as it was previously articulated in relationship to the commodification of critical natural capital.

environmentalism and unionism at this time led to the enactment of important environmental regulations such as the Clean Air and Water Acts at the beginning of the 1970s. This alliance, however, was never fully consolidated as some environmental movements failed to internalize environmental workplace and social justice issues while unions remained restricted by the structure of decision-making occurring at the levels of industry.

Eventually the alliance withered with the political and economic turnover in the late 1970s and early 1980s; setting the stage for the *fabricated trade-off*. In sum, the US can be characterized by an initial absence of the *fabricated trade-off* and the presence of socio-political pressures emerging from a delicate unity between labour and environmental movements. The result of which was the enforcement of capitalization as a means to bear responsibility for environmental and health damages. One can postulate that such a trade-off was feasible at that time given that the bulk of Western countries were facing a post-WWII world-ecological regime characterized by an impressive ecological surplus due to increased access to cheap hydrocarbon and raw materials found in "the resource veins of ... colonial and semi-colonial" nations (Moore, 2015a: pp. 102-103).

Tightly linked to this development was an increased productive investment of surplus; generating economic growth and therefore a complacent bargaining position of labour vis-a-vis capital (Streeck, 2017: pp. 165). This is all to say that the absence of the *fabricated trade-off* can easily be seen in terms of the world-ecological circumstances that determine appropriation, capitalization, capital accumulation and economic growth. As soon as such circumstances falter, it makes sense for capital to inaugurate the *fabricated trade-off* since it is involuntary dealing with a decline in the ecological surpluses and aims to soften the blow. This not only deteriorates existing alliances between labour and environmental movements but also hampers the development of the necessity of labour to bargain on behalf of nature - a step beyond labour imposing capitalization as a means to bear responsibility.

**The Italian experience**

The Italian experience concerning the congruence between labour and environmental movements is similar to that of the US in its origins; "an alliance between workers' organizations and 'militant' scientists in the struggle for recognition and regulation of industrial hazards. This eventually produced social reforms such as the Labour Statute (1970) and the Public Health System (1978)" (Barca, 2012: pp. 70). The main difference however, is the development of a far stronger unity between labour and environment due to the cultural hegemony of the Left. This was visible both in the political sphere, through the Italian Communist Party (PCI), and strength/presence of union confederations. Barca further classifies the Italian experience as a *class ecology* variety of labour environmentalism (Ibid, 2012; 2014b; 2019b). Which signifies the concrete political engagement of trade unionists and workers with environmental issues (Stevis et al., 2018).

Born out of the accentuation of the human body as being situated within the configuration of power relationships Barca (2012), Laura Conti's[13] *class ecology* drew on Marx's theory of alienation from species-being, treated ecology as a science of biophysical interrelations and considered the strong urban/industrial working class as the sole political subject bearing the potential to lead society towards an eco-socialist horizon (Ibid, 2019b). Notwithstanding, Italian *class ecology* also succumbed to the *fabricated trade-off*. Even though it was proclaimed by working class itself; expressing an unwillingness to sacrifice comfortable material conditions in return for a healthier environment. This resulted in the false idea that without industrial growth, capable of granting high employment levels, high wages and the necessary bargaining power, it was impossible for workers to fulfil a role as defenders of the environment. Though different in its root-source, this too delayed the actualization of labour bargaining on behalf of nature in Italy.

**The Brazilian experience**

As the result of exchanges established between the Brazilian and Italian Left (Ibid, 2012), Brazil also experienced militant medicine and a union-led unity between labour and environmental movements. One remarkable difference however, is the formulation of ecological consciousness outside the typical industrial workplace. Instead, rural community struggles for land and livelihoods prompted alternative conceptions of nature/society relationships in the eighties. In the seventies the Amazonian rubber taper's movement advanced in its struggle against large-scale lumbering and ranching activities that were causing a significant loss of livelihoods in consequence of widespread deforestation as well as rural-urban migration (Schmink, 2011: pp. 145). As the rubber tapper's movement gained traction in response to various material contradictions over the course of the eighties, the extractive reserve bill was passed in 1990. This led to the formation of the Brazilian Extractive Reserve System under which the government holds title to the land while community-level associations hold resource-use (as opposed to land-use) permits (Vadjunec et al., 2009).

It can be argued that the idea of the extractive reserve represents a promising possibility at overcoming the Western dichotomy between work and nature. This is because it attempts to tie together i) collective use rights, ii) land-based cultural identity and livelihoods and iii) wild-fruit gathering and biodiversity conservation; each of which embody a defense of non-capitalist work forms (Barca, 2014a: pp. 19). In our opinion, the Brazilian experience exemplifies a far-reaching attempt at claiming the right for labour to bargain on behalf of nature, precisely because concepts such as the extractive reserve embody adaptations to 'material metabolism' as the result of a collectively redefined 'purpose realisation'.[14]

[13] Laura Conti was a prominent labour physician, ecologist and deputy of the PCI.

[14] One can also argue that this successful attempt was possible due to the near-absence of the *fabricated trade-off* given the collective pressure exerted by rubber tappers; an assumption which requires verification beyond the scope of the current paper.

### 3.5.2. Theoretical challenges to the centrality of production and waged-labour

One noticeable challenge to *class ecology* is based on a critique of the idea that industrial growth was a necessary condition for the full development of an ecological class consciousness. And example of such a critique was presented by political ecologist André Gorz and his call to liberate the labour movement from the conceptual categories that held it captive within the capitalist order. Gorz envisioned the alternative to capitalism as one in which wage-labour is eliminated and with that the ideology of productivism. Ecological sustainability required a society which was less work-dominated and operated according to autonomous producer and consumer collectives beyond the confinements of waged-labour (see Barca, 2019b; Bottazzi, 2019). In our view, Gorz's articulation of the liberation or refusal of work can be seen as a full rejection of the *fabricated trade-off*; a denial of the necessity to operate within its conceptual borders. As such, our call for the necessity of labour to bargain on behalf of nature is obsolete from a Gorzian perspective.

In contrast to both class ecology and Gorz's rejection thereof, stood cultural theorist Raymond Williams' re-articulation of the pillars around which to achieve a different unity between labour and environmental movements. Following an introduction to Williams' political ecological thought found in Barca 2019b: pp. 231-232, we know that in the eighties he advocated for a qualitative alteration to the existing types of socialism by means of two pre-requisites. The first was that the labour movement abandon productivism in favour of livelihood and the second was that the environmental movement recognize capitalism as an enemy of nature. Williams' anti-productivist stance was based on his experience with the British labour movement; exemplifying the spurious relationship between increased production and poverty reduction in the face of static *relations of production*. Livelihood meant, among other things, to redefine such relations according to the interest of all living beings involved. Unlike Gorz, Williams' rejection of the *fabricated trade-off* was aimed at what seemed to be the dominant goal of the working-class at that time: a limited focus on improving the bargaining position of labour vis-a-vis capital by means of increased wages instead of re-organized production and redefined *relations of production*.

So far, one is able to conclude that the living experience of Brazilian rural workers and Williams' call for a qualitative alteration to socialism fall closest in line with the necessity of labour to bargain on behalf of nature. Per contra, both of the aforementioned have predominantly focused on either the male industrial workforce or male waged employment in general. A material eco-feminist approach, as formulated by Maria Mies, Ariel Salleh and Moore's world-ecology analysis of appropriation, challenges such an outlook by considering how non-waged labour performed by for example domestic workers, rural peasants and informal workers constitute the basis on which waged-labour can be built and exploited. As mentioned in Section 3.3, this labour can be referred to as meta-industrial: non-monetized labour which is regenerative and therefore essential to the sustenance of everyday life and livelihoods as well as capitalist production. We argue that the capitalization of nature, as exemplified by natural capital which enters the production function, particularly the ecosystem services "shape" this has recently resulted in, is essentially an attempt to copy-paste the 'material metabolism' characteristics of meta-industrial labour into a mould which conforms to the market-logic. Seen in this light, such an operation not only represents a translation of use-values into exchange values but of metabolic value into exchange values.

Meeting each of the aforementioned challenges to class ecology is the recent formulation of *working class environmentalism*. It is articulated as a separate category of the broader definition known as environmentalism of the poor (Martínez-Alier, 2003); working class environmentalism represents a conjecture between labour and environmental justice which allows working class[15] communities to challenge the fabricated trade-off by means of mobilization around the primacy of reproduction or metabolic value (Barca, 2012; Barca and Leonardi, 2018). The concept stands in stark contrast to the contemporary alliance between labour and the environmental movement, known as *labour's eco-modernism* (Barca, 2019b). Of which the main characteristic is the formulation of optimistic win-win solutions in the face of the *fabricated trade-off*. Green technologies, incentivized by the market, are coupled with an increases of employment in the sectors which either produce/develop or operate with the aid of the aforementioned technologies. *Labour's eco-modernism* is closely associated to the green growth and green jobs narratives which fail to address accumulation and labour which is not bound to an official wage-contract (Littig, 2018).

With these insights in mind, we finally arrive at the amendment of our preliminary definition for labours[16] bargaining on behalf of nature:

- the development of an autonomous consciousness concerning the contradictions embedded in capitalistically orchestrated 'material metabolisms'
- the manifestation of a challenge towards the aforementioned by means of a struggle which aims to transform 'purpose realisation' into the endowment of natural objects with humanistic forms not only for the purpose of use value extraction but also for the purpose of maintaining and/or regenerating metabolic value.

Only then is the terrain opened for an adapted 'material metabolism' which does not fall victim to sustained alienation and the accumulation based reinvestment of surplus.

[15] When it comes to a definition of the working class, we adhere to the socio-ecological definition: people engaged in waged and non-waged labour across the industrial, agricultural and service sectors which are held captive by the imperatives of productivity, profit as well as gendered and racialized hierarchies (Barca, 2012: pp. 62; Barca and Leonardi, 2018: pp. 490)

[16] While the preliminary definition referred to "labour" as a singular noun, we now refer to its plural noun "labours" in order to capture that we are referring to both waged and non-waged labour.

## 3.6. Conclusion & Discussion

This paper set out to provide an eco-Marxist reinterpretation of mathematical formalization in EE. We isolated natural capital as a key concept when it comes to the formal abstraction of economy-ecology configurations in models. EE distinguishes itself from ERE by adopting the strong sustainability paradigm which imposes complementarity between human-made capital and natural capital. If natural capital is an irreplaceable input in production, it follows that it must be preserved if output is to remain constant. We then discussed the actual manifestation of this logic by highlighting the commodification of planetary boundaries and ecosystem services. In our view, the inability to foresee commodification as a self-evident outcome of EE's mathematical formalization *may* be the result of incomplete assumptions regarding economy-ecology configurations. In order to showcase the plausibility of this argument we draw on insights in the field of eco-Marxism.

We resort to world-ecology and regard the exchange value assessment of ecological processes as the transition of the respective process from a state of appropriation into a state of capitalization. By means of Marx' labour process theory we argue that dominant efforts directed towards the goal of ecological sustainability aim to achieve partial adjustments in 'material metabolism' while 'purpose realisation' still represents the endowment of natural objects with humanistic forms for the purpose of exchange value accumulation. In other words, the dominant interpretation of ecological sustainability, is one which presupposes that *capital bargain on behalf of nature*. Our suggested alternative to the aforementioned is to instead allow *labour to bargain on behalf of nature*. We explore this alternative by drawing on findings in the field of environmental history such as *labour environmentalism*, *class ecology*, *labour's eco-modernism* and *working class environmentalism*. Drawing on this field of literature allows us to provide an elementary definition of what it means for labours to bargain on behalf of nature.

What is the significance of these insights for the practice of mathematical formalization in the field of EE? On the one hand they allow us to classify the current abstraction of ecology-economy configurations as one which is incomplete. This is because the depiction of ecology-economy configurations by means of natural capital which *enters* the production process entirely neglects the role of appropriated ecological processes in the production of commodities. The fact that a given ecological process is treated as an input in the production function indicates that it *is* or *should be* capitalized. Furthermore, the negligence of appropriated ecological processes imposes *dualism* particularly when it comes to the configuration among ecological processes and labour. The creation of use value by means of a production process which is abstracted as the result of an isolated effort of labour and ecological processes is but one, idealized, configuration in the web of life. An alternative configuration is one of reciprocity and the unified management of interdependent flows; resulting in the reproduction of metabolic value. In our view, a mathematical formalization practice which is geared at delineating such a reciprocity, by taking into account the role of appropriated ecological processes, can improve EE's method of analysis. In order to clarify what an expanded mathematical formalization practice may look like we introduce Figure 3.1.

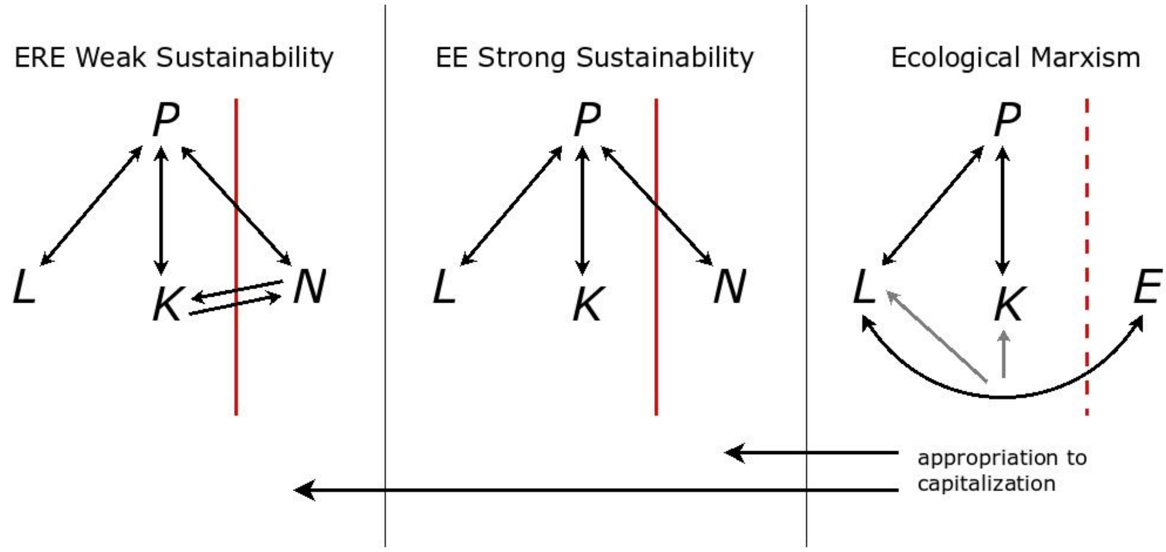


Figure 3.1: The formal representation of ecological processes under WS, SS and eco-Marxism (EM)

The first tile summarizes the assumptions under the weak sustainability paradigm or ERE. Assuming a set of technical coefficients (inputs required per unit of output), desired production $(P)$ determines the amount of labour $(L)$, human-made capital $(K)$ and natural capital $(N)$ entering the production function. At the same time, the specific characteristics[17] of $L, K$ and $N$ determine the amount of production which actually takes place. This is why the figure shows two-way arrows between $P$ and $L, K$ and $N$ respectively. According to our eco-Marxist reinterpretation, the fact that $N$ enters the production function indicates that the ecological process is either capitalized or proposed to be capitalized. Capitalization additionally implies a hypothesized *dualism* between ecological processes and societal elements of production — hence the solid red line between $P, K, L$ and $N$. Furthermore, since *weak* sustainability assumes substitutability, a pair of opposing arrows is introduced between $K$ and $N$ which implies the application of a production function which allows substitution between inputs.

The second tile summarizes the assumptions under the *strong* sustainability paradigm or EE. The only difference with respect to the first tile is that there are no arrows between $N$ and $K$. This implies the existence of complementarity and the application of a fixed proportions production function. It should be noted that the assumptions on substitutability and complementarity apply equally for the pairs $L, K$ and $L, N$ even if this is not explicitly pointed out in the figure.

The third tile summarizes what we consider to be an overlooked but fundamental aspect

[17] Formally, these specific characteristics take the shape of the real technical coefficients related to each input. When desired production is determined, this is done according to technical coefficients which need not coincide with the real technical coefficients.

of economy-ecology configurations. Firstly, $N$ is absent and therefore doesn't enter the production function. Instead we have an appropriated ecological process $(E)$ which forms an interdependent relationship with $L$: indicated by the two-way arrow between $E$ and $L$. This interdependent relationship also co-constitutes the specific characteristics of $K$ and $L$ which affect how production is determined by each input. This is indicated with the two grey arrows in the third tile. Interdependency between $E$ and $L$ also translates the *dualism* between 'societal' and 'natural' elements of production into a *duality*. Hence the dotted, instead of solid, red line. Finally, the arrows from tile three to tiles two and one elucidate the fact that the majority of responses to ecological degradation have led to the capitalization of ecological processes. The difference between *weak* and *strong* sustainability is simply a matter of substitution/complementarity. In both cases, the ecological process fully capitulates to production for the purpose of sustained accumulation.

It is important to emphasize that each of the configurations in Figure 3.1 portray a situation where the 'purpose realisation' element of the labour process serves the goal of exchange value accumulation. Hence, the contribution of eco-Marxism should not be seen as the mathematical formulation of an alternative to capitalization. Instead, it serves to stretch the confines of mathematical formalization in EE in order to allow for a more comprehensive portrayal of economy-ecology configurations.

Apart from the formal representation of appropriated ecological processes and given the importance attached to labour, it is essential for an alternative practice of mathematical formalization to shift away from the depiction of *relations of production* as a "cooperation of sacrifices". In other words, the reality of labour exploitation, alienation and the appropriation of surplus as necessary determinant of positive profits must be disclosed. Finally and perhaps most challenging, given the abstract nature of economic models; an alternative practice should reflect the relationship between ecological degradation and distribution throughout the transition from appropriation to capitalization. This could potentially reveal the theoretical conditions under which the *fabricated trade-off* manifests itself.

The result of pursuing the aforementioned recommendations may well be an elaborate fiction underpinned by hypothetical mathematical structures.[18] But such a fiction may nevertheless disclose the necessary avenues we must creatively explore for the achievement of radical ecological sustainability.

[18] Paraphrased from Levins and Lewontin (2009: pp. 31) and their description of evolutionary ecology as a highly mathematized scientific field which is argued to prescribe behaviour to variables on the basis of pre-existing ideological commitments.

# Appendix B

# On marginalism in weak and strong sustainability growth models

## B.1. Introduction

The aim of this Appendix is to provide the reader with further insights into the *weak* and *strong* sustainability paradigms in the field of economics. Much of the general discussion on the two paradigms is already found in Chapter 3 of the the dissertation, the Appendix on the other hand summarizes the mathematical of treatment of sustainability in economic growth models. It should be noted that the Appendix is limited to a discussion of exogenous and steady-state growth models. For a discussion of sustainability in endogenous growth models the reader is suggested to address Barbier (1999) and Smulders (2002).

## B.2. On the *weak* and *strong* sustainability paradigms

The debate concerning the substitutability between the economy and the environment, or rather - between *manufactured capital* and *natural capital* is also referred to as the debate on *weak* vs. *strong* sustainability[1].

According to Ayres et al. (1998), in neoclassical economics, sustainability in general concerns the maintenance of a nation's capital portfolio at a constant level over time (either as an aggregate or per capita). This measure of capital includes both natural capital and human-made capital. The former consists of renewable resources, non-renewable resources and environmental services (Berkes and Folke, 1994).

Common and Perrings (1992) originate the maintenance of capital for the purpose of not diminishing its availability for subsequent/future generations in the works of Hartwick and Solow. The "Hicks[2]-Hartwick-Solow" concept of *weak* sustainability can be reduced to the

[1] *Sustainability* concerns the specification of a set of actions which should be taken by the present generation. The key characteristic of these actions is that they do not diminish the prospects of future generations to enjoy a level of consumption, wealth, utility, or welfare comparable to those enjoyed by the present generation (Bomley, 2018: pp. 13367). In line with the above, *Sustainable development* is usually defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development and Brundtland, 1987)

[2] Hicksian sustainability concerns not the maintenance of capital but of consumption defined as gross output minus investment (Ayres et al., 1998)

following equation found in Pearce et al. (1996) and reiterated in Ayres et al. (1998):

$$Z = S/Y - d_M/Y - d_N/Y \quad \text{[B.1]}$$

Where $Z$ denotes the measure of sustainability, $Y$ is taken to be an arbitrary nation's Gross National Product and $S$ is that nation's national savings. Furthermore, $d_M$ is the rate of depreciation of human-made capital while $d_N$ is the rate of depreciation of natural capital. A country is said to be *weakly* sustainable if $Z > 0$. This means that investment in manufactured capital is then perfectly allowed to compensate for the decrease in natural capital.

In other words, *weak* sustainability requires keeping total net investment (net of depreciation) above zero. Because of the substitutability between natural and human-made capital, it is not necessary to question the destination of this investment (Neumayer, 2013). In order for $Z$ to be commensurate with investment, $d_N$ must take a monetary expression. In the past this estimation was limited to the resources which were already subject to a market price such as hydrocarbons, minerals, fish stocks etc. For example, the World Bank deploys a measure of net natural resource depletion which aggregates measures of net forest, fossil fuel and mineral depletion (Barbier, 2019). Hence, the estimation of $d_{N_i}$ is taken as the present value of the multiplication between the unit resource rent (its market price) and the net change of its natural capital stock $(i)$ (Common and Sanyal, 1998; World Bank, 2012):

$$d_{N_i} = PV_i\{(P_i - C_i)(R_i - N_i)\} \quad \text{[B.2]}$$

Where $P_i$ is the price of the extracted resource, $C_i$ is the average cost of extraction and $R_i - N_i$ is the physical amount extracted minus new discoveries. Evidently, a calculation of the present value $(PV_i)$ requires the consideration of a discount rate[3].

Recently, the estimation of depreciation has been extended to other more complex environmental assets such as wetlands, soil or recreational land. The most challenging aspect of this exercise is to estimate the price, $P_i$, of the respective ecosystem services[4]. But as mentioned in Costanza et al. (2017), the last 20 years have resulted in many deliberations on the definition, classification and monetary measurement of these ecosystem services.

One approach is to use revealed or stated preference and derive the monetary value of an ecosystem as a whole or of one of its services. The travel cost method is an example of the former while the contingent valuation method surveying an individual's willingness

[3] The implications of a discount rate for both economic modelling and policy development is another widely discussed topic in the fields of Environmental and Ecological Economics (see for example Stern and Great Britain Treasury, 2007 and Nordhaus, 2007). However, since the main consideration of this paper is the role of nature in economic production under the *weak* and *strong* sustainability paradigms, in-depth discussions of the discount rate are considered beyond its scope.

[4] Ecosystem services are the ecosystem-specific characteristics, functions and processes which positively affect well-being in either a direct or indirect fashion (Costanza et al., 1997)

to pay/accept is an example of the latter (see Chapter 12.2 in: Perman et al., 2003). The key assumption underlying these methods is that ecosystem services can be treated as the arguments in well-behaved utility functions.

Another approach is related to the derivation of an ecosystem's monetary value on the basis of what is already monetized. For example, a production process which deploys labour, capital and an ecosystem service will likely experience a change in production costs when the ecosystem providing the service degrades (and hence provides less or lower quality services). The change in production, leading to a loss in revenue, can then be taken as a proxy for the monetary value of the ecosystem service. An assessment of damages and the related cost of a "malfunctioning" ecosystem can also be taken as a proxy for the monetary value of a "healthy" ecosystem. For a detailed overview of such ecosystem valuation methods and techniques, the reader is suggested to read Grunewald and Bastian (2015).

Returning to the measure of sustainability introduced in eq. [B.1], once the proper price $P_i$ is found for natural capital; the *weak* sustainability paradigm imposes that natural capital is substitutable both as an input for the production process and as the provider of use-values (e.g. hydrocarbon energy sources vs. clean water provision). It should be noted that in eqs. [B.1] and [B.2] it is only the rate of change which matters and not the actual levels. This means that a nation which i) has *already* engaged in e.g. heavy deforestation, ii) engages in *additional* deforestation but iii) invests the rents of deforestation in the production of human-made capital is — in theory — sustainable.

On the other hand and according to Turner (1993), *strong* sustainability rejects the notion that human-made capital is substitutable for natural capital. This is due to the fact that natural capital is subject to complex characteristics such as irreversibility, uncertainty and criticality. Alternatively stated, natural capital is said to contribute to individual utility or societal welfare in an exclusive way.

In terms of economic terminology, Daly and Farley (2011) mention that instead of substitution, *strong* sustainability supports the idea of complementarity between natural capital and human-made capital. This means that natural capital is treated as a "unique entity" while a further distinction is made between its contribution to the production process (e.g as an input) and its contribution to utility/welfare (e.g. air/water quality) (Ekins et al., 2003). But even under the *strong* sustainability paradigm, it is necessary to disclose which particular natural capital type is either substitutable or complementary in a production function or utility/welfare function. Consequently, *weak* sustainability and its prescription to maintain the sum of natural and human-made capital above zero may still hold depending on the natural capital *type* and its *state*. Some types of natural capital may be indispensable for production and/or utility/welfare in which case the prescription is a strict non-reduction.

Returning to eq. [B.1], under *strong* sustainability $Z > 0$ is regarded as sustainability regardless

of whether $d_N > 0$ or $d_N = 0$. An example of the former ($d_N > 0$) could be the policy recommendation to continue the utilization of coal stocks for the societal provision of heat and energy while using the rents thereof for investment in renewable energy infrastructure (human-made capital).[5] When it comes to the latter ($d_N = 0$), a policy recommendation could be to entirely suspend the disposal of industrial run-off in a water body because the aquatic ecosystem is at the verge of collapse. This means that the aquatic ecosystem and the services it delivers to society have been characterized as critical natural capital; the *type* of natural capital which is deemed to be strictly complementary to not only human-made capital but also to *other* types of natural capital. In sum, under *strong* sustainability, the identification of critical natural capital is important in the determination of which stocks or services should be maintained and not allowed to depreciate (Ekins, 2003). For an extensive discussion on what exactly defines the "criticality" of natural capital, we suggest the reader to consult Chiesura and de Groot (2003).
A short summary of the difference between *weak* and *strong* sustainability is provided in the table below:

| **Weak sustainability** | **Strong sustainability** |
|---|---|
| Advocates the necessity to maintain the stock of total capital | Advocates the necessity to maintain the stock of (certain forms of) natural capital, since there is large uncertainty on the detrimental consequences of its depletion and the irreversibility thereof |
| The elasticity of substitution between human-made and natural capital is equal to or greater than unity, particularly when considering that technological progress[6] is able to decrease dependency on natural capital | Some forms of natural capital provide basic life-support functions that simply *cannot* be substituted for. |
| A rise in consumption can compensate future generations for a decline in natural capital | Individuals are highly adverse to losses in natural capital and they cannot be compensated for a decline in natural capital through increased consumption opportunities |

Table B.1: Key differences between *weak* and *strong* sustainability (Hediger, 2006; Neumayer, 2013)

In breadth of the short discussion on the *weak* and *strong* sustainability we contend that it is appropriate to shortly address the literature that contests the usefulness of such a distinction in the first place. That is, prior to the *economic* treatment of the two paradigms in growth models, the following paragraphs set out to disclose some critical considerations on weak vs. strong sustainability discussion.
As mentioned above, even the *strong* sustainability paradigm allows substitution to take place

[5] Note that in this case, $d_N > 0$ holds both in terms of the physical coal stock as well as the atmospheric sink capacity of carbon dioxide emissions after the combustion of coal has taken place.

between human-made capital and "uncritical" capital. This allows one to conceive that instead of being mutually exclusive, the two paradigms are likely to share an overlap. Hence, the fundamental question for both paradigms still remains an exploration of the extent to which human-made capital can substitute, compensate or off-set the loss of either natural capital as a whole or natural capital which is not deemed to be critical.

Holland (1997) offers an interesting perspective on this issue by discussing the assessment of substitution possibilities in terms of i) purpose, ii) degree and iii) cultivated capital. When it comes to *purpose*, prior to the substitution taking place it is important to reflect on the specific characteristic of natural capital one wishes to preserve. In the broadest sense this translates to an assessment of the kind of benefits society derives from natural capital. Having established the purpose, a consequent step is to specify the *degree* to which such a purpose should be preserved in the face of substitution. If for the sake of simplicity we assume that the sole purpose of natural capital is the provision of "clean air", then a human-made "pollution mask" can easily be regarded as a substitute. This ease of substitution is radically altered if one redefines the purpose of natural capital into "clean air and the ability of an individual to show their full face in public". Hence, once the purpose is defined, it is also crucial to determine the degree to which this purpose is met in the face of potential substitution for human-made capital.

Again, these kind of obfuscations and considerations hold equally across the *weak* and *strong* sustainability paradigm depending on what the latter defines as critical and uncritical capital. Note that the above-mentioned example completely disregarded the fact that our human-made substitute requires an input of natural capital as well. This brings us to another consideration; *cultivated capital*. This consideration truly complicates the discussion on substitution since it begs proponents of both paradigms to concretely define the distinction between human-made and natural capital. According to Holland (1997) both the *weak* and *strong* sustainability thrive on the absence of this distinction; if everything which is affected by human activity counts as human-made then natural capital is 99% obsolete, substitution can be seen as the historical engine of human progress[7]. Likewise, if everything consisting of natural materials is considered natural capital then this renders human-made capital and again, substitution obsolete.

Another perspective on the distinction between the *weak* and *strong* sustainability paradigms is given by Read and Scott Cato (2014). They claim that even if *strong* sustainability argues that critical natural capital cannot be substituted for with human-made capital, many of its proponents promote pricing as means through which one can advance critical natural capital's consideration and protection. This is because as long as trees, mountains or bees don't have

[7] Such reasoning can easily be applied to our elementary example taking natural capital to signify "clean air". If one considers the fact that industries and air planes introduce man-made pollutants to the atmosphere, even clean air is human-made.

a price-tag, their seat at a negotiation table is unwarranted. But monetary valuation in itself unknowingly establishes a homogenization of value across all *capitals*, easing the possibility to imagine substitution in the first place. Read and Scott Cato (2014) conclude that the "proper" price for critical or uncritical capital is inherently based on the presumption of commodity exchange. To express an object in terms of money embodies the assumption that it can be exchanged for another object (or set of objects) which is valued at an equal amount of money. Whether scholars favour *weak* or *strong* sustainability, as soon as natural capital falls victim to monetary valuation, an implicit assumption of substitution has already been made.

Finally, Burkett (2009b) argues that neither paradigms are capable of distinguishing sustainable development from sustainable capitalism. The argument is based on the issue of what to define as critical and non-critical capital and how the dominant criteria such as irreversibility, uncertainty and aversion to loss are not sufficient to establish concrete distinctions. As stated earlier, the result is often a differentiation between broadly defined life-support systems (critical) vis-a-vis natural resource deposits (non-critical) which fails to relate criticality to the economy's relations of production. In sum, both the *weak* and *strong* sustainability paradigms wholly overlook the role of wage-labour and its material requirements.

Having briefly introduced some critical perspectives on the division between *weak* and *strong* sustainability we will now direct the attention to the manifestation of both paradigms in economic growth models.

## B.3. Sustainability in economic growth models

The previous section provided the reader with a brief introduction to the concepts of *weak* and *strong* sustainability. The distinction has been crucial for the contemporary considerations on sustainable development and intergenerational equity. In this section we will try to convey the implications of both sustainability paradigms in economic growth models.

### B.3.1. Weak sustainability and the Solow-Hartwick model

The first model we will present as an example of *weak* sustainability is based on the works of the economists Robert M. Solow and John M. Hartwick. Their contributions focussed on economic growth and intergenerational equity whilst addressing non-renewable (Solow, 1974, 2016) and renewable resources (Hartwick, 1978). As a result, the economic growth model considering both non-renewable and renewable sources is coined as the "Solow-Hartwick" model.

The current exposition of this model is primarily based on its treatment found in Hediger, 2006: pp. 365. The model considers a closed economy which produces an output $Y_t$ that is divided into two components; aggregate consumption $C_t$ and investment into human-made capital $I_t$. It is assumed that output is produced with four factors of production, i) human-made capital $K_t$, ii) labour $L_t$ (assumed to be constant), iii) nonrewable resources $X_t$ and iv) renewable resources $H_t$. Hence in this case, natural capital consists of two heterogenous components each subject to

specific stocks; $N_t$ for non-renewable resources and $R_t$ for renewable resources.
Human-made capital is assumed to depreciate at a given constant rate $\delta \in (0, 1)$ whereas the stock of non-renewable resources $N_t$ declines as a function of extraction $X_t$. The dynamics of the renewable stock are governed by natural regeneration $g(R_t)$[8] and the harvest rate $H_t$. The dynamics of the system can be formally described by the following set of differential equations:

$$\dot{K}_t = Y_t - \delta K_t - C_t \qquad [B.3]$$

$$\dot{N}_t = -X_t \qquad [B.4]$$

$$\dot{R}_t = g(R_t) - H_t \qquad [B.5]$$

The model also assumes that a decrease in the stock of the resource increases the cost of extracting the resource which then implies a reduction of the potential output of the closed economy. As a result the production function takes the following functional form:

$$Y_t = f(K_t, L_t, X_t, H_t, N_t, R_t) \qquad [B.6]$$

With $f_v > 0$ and $f_{vv} < 0$ for $v = K_t, L_t, X_t, H_t, N_t, R_t$. Hence, the production function is assumed to be concave and twice continuously differential. Furthermore, the production function is said to be of the Cobb-Douglas with constant returns to scale type, e.g.:

$$f(v) = A \prod_{i=1}^{6} v_i^{\lambda_i}, \quad v = (K_t, L_t, X_t, H_t, N_t, R_t) \qquad [B.7]$$

Where $A$ is an efficiency parameter and $\lambda_i$ is an elasticity parameter for input $i$ (Brown, 2018). The Solow-Hartwick model further assumes that $\sum_{i=1}^{6} \lambda_i = 1$ and that $\lambda_1 > \lambda_3 \geq \lambda_4 \geq ... \geq \lambda_6$. The first assumption implies the constant returns to scale characteristic while the second assumption implies that with enough human-made capital, $K_t$, very high levels of output can be produced with very low levels of the renewable and nonrenewable resource inputs and stocks $(X_t, H_t, N_t, R_t)$.
When it comes to the evaluation of stocks $(N_t, R_t)$ the second assumption implies that the increase in extraction costs as the result of diminished stocks is sufficiently small. All of this is due to the fact that the elasticity parameter $\lambda_t^K$ is higher than that of natural capital $\lambda^{X_t, H_t, N_t, R_t}$. In lay-men terms this means that human-made capital is a "very good" substitute for natural capital. Each of the $\lambda$'s is assumed to remain constant over time, which implies that we are in fact dealing with the Cobb-Douglas variant of constant elasticity of substitution (CES) production functions.

[8] In environmental or bio-economics, it is common to assume that the renewable resource stock follows a logistic growth path. Initially, the growth rate increases with the stock of resources ($g_{R_t} > 0$ for $R < R'$) but decreases after the stock has reached a certain size ($g_{R_t} < 0$ for $R \geq R'$) (Neumayer, 2013: pp. 201)

Finally, it is important to add that *all* inputs in the Solow-Hartwick model are considered to be *essential*: output would be 0 if any of the inputs is 0. Formally; $f(v_i) = 0$ if $v_i = 0$ for all $i$. Thus even if substitution between natural capital and human-made capital is possible, natural capital cannot be *fully* substituted for by human-made capital.
Having introduced the assumptions related to the production function, the subsequent step is to find the maximum aggregate consumption that can be achieved in each subsequent period (held constant over time) all whilst taking into consideration the dynamics of the different capitals as presented in eqs.[B.3]-[B.5]. This is achieved by using the maximum principle as a technique to solve the constrained dynamic optimisation problem (see Perman et al., 2003: pp. 496). Given a social discount rate, $\rho > 0$, initial stocks of capital, $K_0, N_0$ and $R_0$ and the assumption of constant technology and population (and hence a constant labour force, $\bar{L}$) - one is able to derive the first-order conditions for intertemporal efficiency.
First we define the objective function which requires maximization: societal welfare expressed as aggregate utility as a function of consumption.

$$W = \int_{t=0}^{t=\infty} U(C_t)e^{-\rho t}dt \qquad [B.8]$$

Our state variables are $K_t, N_t$ and $R_t$. The control variables,for which we must find a time path such that the objective function is maximized, are $C_t$, $X_t$ and $H_t$. The current value Hamiltonian is then expressed as follows:

$$\begin{aligned} H_{C_t} &= U(C_t) + n_t(-X_t) + r_t(g(R_t) - H_t) + ... \\ &+ k_t(f(K_t, L_t, X_t, H_t, N_t, R_t) - C_t - \delta K_t) \end{aligned} \qquad [B.9]$$

Where $n_t, r_t$ and $k_t$ are the shadow prices of non-renewable, renewable and human-made capital respectively. They measure the value of a *marginal* unit of output (in units of utility or utils). The static efficiency conditions in this case are simply the first order conditions of the current value Hamiltonian with respect to the control variables:

$$\frac{\partial H_{C_t}}{\partial X_t} = -n_t + k_t f_{X_t} \stackrel{!}{=} 0 \Leftrightarrow n_t = k_t f_{X_t} \qquad [B.10]$$

$$\frac{\partial H_{C_t}}{\partial H_t} = -r_t + k_t f_{H_t} \stackrel{!}{=} 0 \Leftrightarrow r_t = k_t f_{H_t} \qquad [B.11]$$

$$\frac{\partial H_{C_t}}{\partial C_t} = U_{C_t} - k_t \stackrel{!}{=} 0 \Leftrightarrow U_{C_t} = k_t \qquad [B.12]$$

Eq. [B.10] states that the shadow price of the non-renewable resource, $n_t$ must be equal to the shadow price of human-made capital multiplied by the non-renewable's marginal product. The same logic applies to the shadow price of the renewable resource, $r_t$ in eq. [B.11]. The last static efficiency condition found in eq. [B.12] states that in each period the marginal utility of consumption, $U_{C_t}$ must be equal to the shadow price of human-made capital.

The consideration of natural capital in this optimal control problem framework also involves the derivation of dynamic efficiency conditions:

$$\dot{n}_t = \rho n_t - \frac{\partial H_{C_t}}{\partial N_t} = \rho n_t - k_t f_{N_t} \Leftrightarrow \frac{\dot{n}_t + k_t f_{N_t}}{n_t} = \rho \quad [B.13]$$

$$\dot{r}_t = \rho r_t - \frac{\partial H_{C_t}}{\partial R_t} = \rho r_t - r_t g_{R_t} - k_t f_{R_t} \Leftrightarrow \frac{\dot{r}_t + k_t f_{R_t}}{r_t} + g_{R_t} = \rho \quad [B.14]$$

$$\dot{k}_t = \rho k_t - \frac{\partial H_{C_t}}{\partial K_t} = \rho k_t - k_t(f_{K_t} - \delta) \Leftrightarrow \frac{\dot{k}_t}{k_t} = \rho - f_{k_t} + \delta \quad [B.15]$$

In sum, dynamic efficiency requires each asset earns an equal rate of return and that this rate of return is the same across all points in time. Eq. (B.13)-(B.14) are essentially modified versions of the Hotelling rule applied to the non-renewable and non-renewable resource respectively. Were we to abstract away from extraction costs and a renewable resource, the Hotelling rule would take the following form: $\frac{\dot{n}_t}{n_t} = \rho$. This simply states that the growth rate of the non-renewable resource's shadow price should equal the social utility discount rate. This is an intertemporal efficiency condition which must be satisfied by an *efficient* resource extraction process (Perman et al., 2003: pp. 485).

In its current modified variant, the Hotelling rule in eq. [B.13] states that the *net* growth rate of the non-renewable resource's shadow price must equal the social discount rate. The *net* growth rate takes into account the marginal product of the resource stock, $f_{N_t}$ multiplied by the shadow price of human-made capital, $k_t$. This multiplication represents the present value of the extraction costs that have been avoided by not extracting an additional unit of the stock (Gaudet, 2007: pp. 1036). Consequently, when it comes to the renewable resource, not only does the value of avoided extraction costs $(k_t f_{R_t})$ appear in the modified Hotelling rule, but so does the growth rate of the renewable resource, $g_{R_t}$.

Finally, we must also address the fact that the Hotelling rule prescribes no-arbitrage as a necessary condition for efficiency. This means that the holders of the natural resource stocks are considered to be indifferent between holding non-renewable, renewable or human-made capital assets (Hamilton, 1995). In order to arrive at this no-arbitrage condition for our specific example including extraction costs, depreciation, non-renewable and renewable resources we proceed in the following way (see Appendix 2 in: Neumayer, 2013)

Substitute eq. [B.10] into eq. [B.13]:

$$\rho = \frac{\dot{\overline{k_t f_{X_t}}} + k_t f_{N_t}}{k_t f_{X_t}} \Leftrightarrow \frac{\dot{k_t}}{k_t} + \frac{\dot{f_{X_t}}}{f_{X_t}} + \frac{f_{N_t}}{f_{X_t}} \tag{B.16}$$

Substitute eq. [B.11] into eq. [B.14]:

$$\rho = \frac{\dot{\overline{k_t f_{H_t}}} + k_t f_{R_t}}{k_t f_{H_t}} + g_{R_t} \Leftrightarrow \frac{\dot{k_t}}{k_t} + \frac{\dot{f_{H_t}}}{f_{H_t}} + \frac{f_{R_t}}{f_{H_t}} + g_{R_t} \tag{B.17}$$

Substitute eq. eqB.12 into eq. [B.15]:

$$\rho = \frac{\dot{k_t}}{k_t} + f_{K_t} - \delta \tag{B.18}$$

Hence, the explicit "dynamic-efficiency-Hotelling-rule" condition for our non-renewable resource as it appears in Hartwick (1978) is derived by setting eq. [B.18] equal to eq. [B.16]:

$$\begin{aligned} \frac{\dot{k_t}}{k_t} + f_{K_t} - \delta &= \frac{\dot{k_t}}{k_t} + \frac{\dot{f_{X_t}}}{f_{X_t}} + \frac{f_{N_t}}{f_{X_t}} \\ \frac{\dot{f_{X_t}} + f_{N_t}}{f_{X_t}} &= f_{K_t} - \delta \end{aligned} \tag{B.19}$$

Now, under the assumption of a general competitive equilibrium, $\dot{f_{X_t}}$ is the derivative of price of the *extracted* non-renewable resource with respect to time, while $f_{K_t}$ is the rate of interest on human-made capital. The L.H.S of the equation also takes into account the avoided cost as the result of not decreasing the non-renewable resource stock $(f_{N_t})$. Eq. [B.19] simply states that the rate at which the rent/shadow price of our non-renewable resource is rising must equal the interest rate over human-made capital minus depreciation.
For our renewable resource, we arrive at a similar result by setting eq. [B.18] equal to eq. [B.17]:

$$\begin{aligned} \frac{\dot{k_t}}{k_t} + f_{K_t} - \delta &= \frac{\dot{k_t}}{k_t} + \frac{\dot{f_{H_t}}}{f_{H_t}} + \frac{f_{R_t}}{f_{H_t}} + g_{R_t} \\ \frac{\dot{f_{H_t}} + f_{R_t}}{f_{H_t}} + g_{R_t} &= f_{K_t} - \delta \end{aligned} \tag{B.20}$$

Eq. [B.20] is almost identical to eq. [B.19] apart from the term $g_{R_t}$ which accounts for the effect of renewable resource harvesting on the stock of renewable resources and therefore its growth rate. If the growth rate is postive, $g_{R_t} > 0$ the renewable resource rent is increasing at a rate which is lower than that of the interest rate minus depreciation (on human-made capital). Since this means that $R_{t-1} < R_t$ it implies that continued harvesting of the renewable resource will have a negative effect on natural growth. Conversely, if the growth rate is negative, $g_{R_t} < 0$, the renewable resource rent is increasing at a rate which is higher than that of the interest rate minus depreciation. Since $R_{t-1} > R_t$, this implies that continued harvesting of the renewable resource will have a positive effect on natural growth[9].

It is under the explicit assumptions and derivations presented above that Hartwick derived his acclaimed rule. In a nutshell, the Hartwick rule implies what has already been suggested in eq. [B.1] of the previous section, namely that the depletion of natural capital must be compensated for by investments in human-made capital. Formally and in line with the short exposition above, the Hartwick rule takes the following shape:

$$\dot{K}_t = \underbrace{f_{X_t} X_t}_{i)} + \underbrace{f_{H_t} \cdot [H_t - g(R_t)]}_{ii)} \qquad \text{[B.21]}$$

Where $\dot{K}_t$ is the derivative of human-made capital with respect to time at time $t$ and this is set equal to i) the income derived from the extraction of the non-renewable resources at time $t$ plus ii) the income derived from the harvest of the renewable resource minus the income that would be derived if the increases in the renewable resource as the result of natural growth, would have been invested. Following this rule, respecting the intertemporal efficiency conditions presented in eqs. [B.19] - [B.20] all whilst the substitution possibilities between human-made capital $(K)$ and natural capital $(X, N, H, R)$ are high enough — allows the derivation of a constant consumption time path under conditions of constant population, no technical progress and sustained output as inputs asymptotically approach zero for $t \to \infty$ (Hartwick, 1978)[10].

According to Common and Perrings, 1992: pp. 13: "the Hartwick rule is driven by a condition on prices (the Hotelling rule), and not by a condition on the nature of the physical environment". This permits constant consumption across generations all whilst aggregate output is maintained and essential inputs asymptotically approach zero.

The paragraphs above aimed to present the implications of *weak* sustainability in an elementary rendition of the Solow-Hartwick model including both renewable and non-renewable resources. Evidently, the existence of a constant consumption path is complicated when one abandons the assumptions of zero population growth, technical progress, perfect competition, well-defined property rights and a closed economy. On the issue of technological change and population growth, an earlier contribution by Stiglitz (1974) shows that when only taking into account exhaustible resources, the necessary and sufficient condition for the existence of a constant consumption path is that the ratio between the rate of technical change and the rate of population growth is greater or equal to the share of natural resources in the economy.

Evidently, more recent work has built upon the incorporation of renewable resources and

[9] As previously mentioned, these effects on the natural growth rate are related to the fact that the renewable resource stock is assumed to follow a logistic growth path

[10] To prove that eq. [B.21] results in a constant consumption path, one re-arranges eq. [B.3] as $C_t = Y_t - \dot{K}_t - \delta K_t$ and takes its first time-derivative resulting in: $\dot{C}_t = \dot{Y}_t - \ddot{K}_t - \delta \dot{K}_t$. Taking the derivative of the production function and inserting the Hartwick rule ultimately results in $\dot{C}_t = 0$ (See Hartwick, 1978: pp. 87)

relaxing the aforementioned assumptions, but to discuss these contributions is beyond the scope of the current paper. The interested reader is suggested to study the contributions by among others Asheim et al. (2007a), Cheviakov and Hartwick (2009), Hoel (1981), Okuguchi (1981), Okumura and Cai (2007) and Solow (1986).

### B.3.2. Strong sustainability in steady-state models

As previously mentioned, the alternative to *weak* sustainability is *strong* sustainability. In a nutshell, the latter requires that mininum quantities of different types of capital should be maintained independently across future generations (Ayres et al., 1998). Of course, the crux of this argument is based on the recognition that natural resources are not only essential inputs but also that they cannot be subsituted for by human-made capital. In this section our aim is to expose how the former variant of *strong* sustainability paradigm contrasts itself to *weak* sustainability against the background of economic growth models. It is for this purpose that we will subsequently draw upon Herman Daly's interpretation of the *strong* sustainability paradigm in association with steady-state economies.

### B.3.3. Daly's argument for limited substitutability

Herman Daly's adherance to *strong* sustainability is derived from Georgescu-Roegen (1975)'s criticism of the "Solow-Stiglitz" production function as it appears in eqs. [B.6] and [B.7]. (Daly, 2008: pp. 130) argues that such a production function translates to the fiction that in order to bake a bigger cake, it is sufficient to increase the amount of bowls and ovens without increasing the amount of flour, sugar and eggs[11]. Hence, the starting point for the incorporation of *strong* sustainability in economic growth models is an adaptation of the assumption of substitutability in the production function.

If we apply Daly and Farley (2011)'s notion of complementarity between human-made capital and labour vis-a-vis natural capital to our example introduced in the previous section; the production function would take the following shape (Ibid, 2011: pp. 158):

$$Y_t = f(K_t, L_t, N_t, R_t; X_t, H_t) \tag{B.22}$$

Here, Daly explicitly implements Georgescu-Roegen (1971)'s distinction between funds, stocks and flows and assumes funds and flows to be complements. That is, human-made capital $(K_t)$ and labour $(L_t)$ are complementary to the flows of non-renewable resources $(X_t)$ and renewable resources $(H_t)$. At the same time though, substitutability *does* exist between human-made capital, labour and the stock/fund of both the non-renewable and renewable resources, since these a grouped to the right of the semi-colon $(;)$ in eq. [B.22]. Apart from specifying that the stocks of natural capital are already taken into account in terms of the flows they yield Daly

[11] The bowls and oven refer to human-made capital while flour, sugar and eggs refer to natural capital.

and Farley (2011) do not provide an explanation for why one should expect substitutability between the aforementioned funds[12] of human-made capital, labour and the stocks of natural resources.

A production function which exhibits complementarity between human-made capital and natural capital as seen in eq. [B.22] is also referred to as a limitational production function. And in order to make this exposition of *strong* sustainability as comparable to that of *weak* sustainability in the previous section, we introduce a slight adaptation of eq. [B.22] found in Hediger (2006):

$$Y_t = f(G(K_t, L_t), M(X_t, H_t), N_t, R_t, J_t) \tag{B.23}$$

An additional production factor, $J_t$, is considered and it is supposed to capture the state of technology (which can change over time) and its impact on the economy's output potential. Moreover; $f_v > 0$ and $f_{vv} < 0$ for $v = G(K_t, L_t), M(X_t, H_t), N_t, R_t, J_t$ as well as $G_{K_t}, G_{L_t}, M_{X_t}, M_{H_t} > 0$ and $G_{KK}, G_{LL}, M_{XX}, M_{HH} < 0$. This is the generalized constant elasticity of substitution (CES) production function, but it now considers different sets of elasticities of substitution: within and between pairs of inputs $(G(.), M(.), N_t, R_t, J_t)$. In order to meet Daly's critique of perfect substitutability between human-made capital and natural capital found in the Cobb-Douglas production function, the elasticities of substitution between $G(.)$ and $M(.)$ should be below 1[13]. This implies that the extent to which human-made capital can substitute for natural capital is lower than in the Solow-Hartwick model.

Having introduced the state of technology as an additional input in the production function, we must specify its dynamics. Hence, in addition to eqs. [B.3]-[B.5], we'll have:

$$\dot{J}_t = \alpha I_t - \beta J_t, \quad 0 < \alpha < 1, \quad 0 < \beta < 1 \tag{B.24}$$

This equation specifies a very simple form of endogenous technical progress found in Chiang (1999), where $\alpha$ is a research success coefficient (multiplying this with investment, $I_t$, provides a measure of "technologically succesful investment") and $\beta$ is a rate of technological decay.

Given that investment, $I_t$, now plays an explicit role in the dynamics of technological progress, the dynamics of human-made capital must be slightly adjusted to account for the fraction of

[12] Here, natural capital as a fund is specified to deliver indirect services that allow the transformation of input flows into a production output. For example, the water retention capacity of a forest and the service it provides with respect to agricultural production.

[13] This type of production function is inspired by the one used in Manne et al. (1977) and revisited in Perman et al., 2003: pp. 479. If output would solely depend on capital, labour, electric and non-electric energy $(K, L, E, N)$ the CES production function would look as follows:

$$Y = [a(K^{\alpha}L^{1-\alpha})^{\frac{\sigma-1}{\sigma}} + b(E^{\beta}N^{1-\beta})^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$$

Between i) $K$ and $L$ and ii) $E$ and $N$ there is unit elasticity, while there is constant elasticity between $(K, L)$ and $(E, N)$ with $\sigma < 1$.

accumulated capital allocated to innovation:

$$\dot{K}_t = Y_t - C_t - I_t - \delta K_t \tag{B.25}$$

Following a procedure similar to that in Section B.3.1 gives us the following formal representation of the optimization problem across time:

$$\begin{aligned} H_{C_t} &= U(C_t) + n_t(-X_t) + r_t(g(R_t) - H_t) + j_t(\alpha I_t - \beta J_t) \\ &\quad + k_t(f(G(K_t, L_t), M(X_t, H_t), N_t, R_t, J_t) - C_t - I_t - \delta K_t) \end{aligned} \tag{B.26}$$

The above current-value Hamiltonian is adjusted from the previous one in eq. [B.9] in order to capture the role of technical progress and investment. Hence, the inclusion of $j_t$ as technology's shadow price. One can then determine the intertemporal efficiency conditions through the prior derivation of both the static and dynamic efficiency conditions specific to eq. [B.26]. This ultimately results in the extended Hartwick rule in the presence of i) a limitational production function and ii) endogenous technological change:

$$\dot{K}_t + \frac{1}{\alpha}\dot{J}_t = f_M M_{X_t} X_t + f_M M_{H_t} \cdot [H_t - g(R_t)] \tag{B.27}$$

The interpretation of the extended Hartwick rule is quite straightforward. It requires that the rents accrued from both non-renwable and renewable resources must be invested in human-made capital $K_t$ and the state of technology $J_t$. Again, one is able to prove that following such an investment rule results in a constant consumption time path over time.
This result is simply a re-iteration of what has been argued in Hediger (2006) and more extensively so in Asheim et al. (2007b): the limitation of substitutability between human-made and natural capital in the production function does not imply the negation of a constant consumption path along which aggregate output is maintained while renewable and non-renewable inputs asymptotically approach zero. Evidently, this illustrates that the *strong* sustainability paradigm rests on more than the imposition of limited substitutability between human-made and natural capital. It also requires a secondary imposition regarding the dynamics of natural capital. This brings us to the discussion of Daly's argument for a steady state economy.

### B.3.4. Daly's argument for a steady-state economy

According to Czech and Daly (2004) a steady-state economy is one that isn't subject to either growth or recession. This requires the maintenance of a constant stock of labour and capital as well as a constant rate of the energy and materials used to manufacture goods and services. The reason we got rid of the assumption of constant technological change and opted to endogenize it, is in order to segue into Daly's considerations on technological progress and its impact on *throughput* efficiency. Daly (1986) distinguishes between two types of technological progress: i) one which leads to a lower amount of resources necessary for production (e.g. decreasing the extraction rate while keeping aggregate output constant) and ii) one which allows a higher extraction rate (Ibid, 1986: pp. 43-44).[14]

The aforementioned distinction is often used in more contemporary scholarly work on energy analyses to eludicate the difference between *development* and *growth* (see e.g. Giampietro and Mayumi, 2000; Giampietro et al., 2001). Accordingly, a steady-state economy is one which respects the biophysical limits of planet earth but simultaneously acknowledges that knowledge accumulation and technological progress (potentially) allow consumption/welfare to remain constant while the stocks of human-made and natural capital remain constant. But which natural capital stock?

Obviously, if the stock of non-renewable resources were to remain constant, there isn't a dynamic optimization problem. The solution would simply be to abort extraction and given that we've assumed the non-renewable resource to be *essential* and imperfectly substitutable with human-made capital; aggregate output would equal 0 and eradicate the possibility of an optimal and constant consumption path. It's interesting to note that such a conclusion holds in both the *weak* and *strong* sustainability paradigm since both consider renewable and non-renewable resources to be essential.

Within the economic growth modelling framework we have presented so far, Daly's steady-state economy alternative seems to suggust we keep the renewable resource and human-made capital constant while allowing for technological development (Hediger, 2006). This results in the following reformulation of the differential equations that define our dynamic system:

$$\dot{K}_t = \dot{R}_t = 0$$

The condition specifying that the stock of our renewable natural resource remain constant over time is by no means characteristic of Daly's adherance to the *strong* sustainability paradigm or the notion of a steady-state economy. From eq. [B.5] one can deduce that $\dot{R}_t = 0$ if $g(R_t) = H_t$. This is called "steady-state" harvesting of the renewable resource and has already been elaborated upon by Hartwick (1978, 1990). Depending on the value of our discount rate, one is able to deduce a maximum sustainable yield $g(R_t)^{max} = H(t)$ of the renewable resource. In turn, this is used to deduce its steady-state stock (see Perman et al., 2003: pp. 490).

What distinguishes Daly's notion of a steady-state for the economy as a whole is the fact that human-made capital is also kept constant (which abstracts away from depreciation) while technological change for the purpose of throughput minimization (development) is re-assured.

[14] For example, if $X_t$ was previously subject to $X_{max}$, technological change would result in $X^*_{max} > X_{max}$. These two types of technological change are by no means mutually exclusive.

This also translates to substitutability, but not between non-renewable resources and human-made capital but between the former and the accumulation of technical knowledge. Hence, the the modified Hartwick rule takes the following shape:

$$\dot{J}_t = \alpha f_M M_{X_t} X_t \qquad \text{[B.28]}$$

The above requires that the rents of non-renewable resource extraction be invested exclusively in technology that decreases throughput efficiency. One can also define this technological change as progress in Research & Development (R&D) which allows the cost of backstop technologies (e.g. solar energy instead of coal or hemp fibres as an alternative to plastics) to compete with the non-renewable resource.

As pointed out by D'Alessandro et al. (2010) some economists adhere to the hypothesis of an exogenous emergence of backstop technologies which requires the optimal allocation between production of goods and expenditure on R&D. Of course, in the formulation of Daly's steady-state, the optimal allocation would simply be to invest the rents from extraction into R&D since production is assumed to remain constant.

As exemplified above, the main difference between the *weak* and *strong* sustainability paradigms in economic growth models concerns the possibility of substitution between human-made capital and natural capital. As pointed out by Victor (1991), the *weak* sustainability paradigm is heavily compromised once one takes into account that the production of human-made capital, which is assumed to be a perfect substitute for natural capital, actually requires natural capital for its production[15]. Abandoning the assumption of perfect substitution results in the prescription that technological changes should improve throughput efficiency which would then decrease reliance on non-renewable resources.

The exposition in this section is far from the only one which considers limited or non-substitutability in production functions. Another example of such a consideration is given by England (2000) who treats human-made capital and natural capital (both renewable and non-renewable) as perfect complements through the deployment of a Leontief fixed coefficient production function. The aim of the exercise is to show which conditions imply Daly's notion of a steady-state economy. Contrary to the result arrived at in the previous paragraphs of this paper, the author argues that even when human-made and natural capital are treated as perfect complements, this does not necessarily imply an end to output growth. Again, the main reason for this is the presence of technological progress; where a distinction is made between labour-saving and natural capital-saving technologies. If natural capital-saving technologies which

[15] Victor (1991) provides a very simple result of taking into account that the production of human-made capital requires natural capital. If human-made capital is produced as follows: $K = K^d R^e L^f$ with $d, e, f > 0$ and $d + e + f = 1$, then solving for $K$ and substituting it in the original production function: $Y = K^a R^b L^c$ with $a, b, c > 0$ and $a + b + c = 1$ results in $Y = R^{(ae/(1-d)+b)} L^{(af/(1-d)+c)}$. A production function that exclusively relies on natural capital, $R$, and labour, $L$!

both preserve and increase the productivity of natural capital, dominate; sustained output growth can still be achieved. However, the author introduces the assumption of diminishing returns to technological knowledge accumulation which is what ultimately gears the economy to a steady-state à la Daly.

Finally, Comolli (2006) introduces an economic growth model in which different assumptions on substitutability are applied to the intermediate goods sector and the final goods sector. For the production of intermediate goods, the *stock* of renewable resources is considered substitutable for human-made capital (Cobb-Douglas functional form) while the production of final goods is based on the premise that the *flow* of renewable resources is a strict complement to human-made capital (fixed coefficient functional form). The exercise concludes that the lack of substitutability in the final goods sector creates either excess supply of demand for human-made capital if one attempts to keep the stock of renewable resources constant. Hence, policies which aim to sustain the stock of renewable resources are treated as ineffective or infeasible. Apart from that, the lack of substitutability in the final goods sector is said to result in a tendency of human-made capital to decline (de-industrialization) - unless the economy's savings rate or capital depreciation rate is sufficiently high or low respectively. Regarding technological progress, a long-run (steady-state) equilibrium is only said to exist if technological advancements are unbiased[16]. In other words, in this particular model, Daly's claim regarding the potential of technological advancements to achieve higher throughput efficiency, would not hold.

## B.4. Delineating the marginalist conjectures in *weak* and *strong* sustainability models

Those familiar with economic growth theory are probably aware of the fact that both the *weak* and *strong* sustainability models presented in Section B.3 are in fact neoclassical growth models. Both the Solow-Hartwick and Daly-Steady-State models retain much of the characteristics developed by Solow (1956) as an alternative to Keynesian growth models by Harrod (1939) and Domar (1946). This is somewhat ironic, given the fact that the main innovation of the Solow model is said to be accommodation of the marginalist principle of substitution between the factors of production in economic growth theory (Zamparelli, 2004).

Apart from the above, the sheer aggregation of heterogeneous capital in such aggregate production functions is widely known to have led to contention. Indeed, it can be argued that the Cambridge Capital Controversy's critique of the neoclassical treatment of capital as a single factor of variable form, is also valid with respect to the treatment of natural capital as a homogeneous input in aggregate production functions. But what interests us in this paper

[16] This is also called Hicks-neutral technological progress and implies that the innovations brought about by technological advancements increase both the average and marginal products of inputs in the same proportion. This results in the constancy of the marginal rate of substitution and capital-labour ratio (Sato and Beckmann, 1968).

is the heedless adoption of marginalist theory by two paradigms which are supposed to be radically opposed to each other.

According to Shaikh (2016), aggregate production functions like those introduced under the *weak* and *strong* sustainability paradigms rely on assumptions of i) constant returns to scale, ii) diminishing marginal productivities and iii) competitive equilibrium (Ibid, 2016: pp. 429-430). These marginalist assumptions have strong implications for the conception of distribution in the models introduced above. This is why the current section will firstly dissect the implications of marginalism in the *weak* sustainability paradigm, but from a static and microeconomic instead of the dynamic macroeconomic vantage point found in Section B.3.1.

Extensive critiques of marginalist factor substitution are far from novel when it comes to substitution between capital and labour. Many scholars argue that the foundation for these critiques was established by Piero Sraffa in Production of Commodities by Means of Commodities (see e.g. Garegnani, 1998; Molina, 2005; Mongiovi, 2002a; Petri, 2015). Instead, in this paper we will reconstruct an analysis of the factor substitution mechanism found in Petri (2021) but here we apply it to man-made and natural capital. We start with a treatment of *weak* sustainability since it assumes substitutability between human-made and natural capital, but the end of the section concludes that the *strong* sustainability paradigm is unable to rid itself of misapprehensions even if substitutability between man-made and natural capital is limited. The reason for this lies with the fact that *strong* sustainability in conjunction with the idea of a steady-state economy still deploys a marginalist approach to distribution.

### B.4.1. On the assumption of substitution between inputs

As mentioned before, at the heart of the *weak* sustainability paradigm lies the assumption of substitution between natural capital and human-made capital. In Section B.3.1 we found that a *weak* sustainability production function in an economic growth model takes the following functional form: $Y = f(K, L, X, H, N, R)$. The function is assumed to respect constant returns to scale and of the Cobb-Douglas type, hence concave and twice continuously differential. Let us grasp the underlying assumptions of the marginalist approach by considering the implications of accepting substitution between human-made and natural capital but in a static and microeconomic setting where the inputs are physical quantities instead of units of utils or monetary values.

Consider an economy which only produces one agricultural consumption good, e.g. wheat. The production of wheat occurs according to the following function: $Y = f(L, K, X, H)$, where $L$ is labour, $K$ is human-made capital and $X$ is the flow of our non-renewable natural capital and $H$ is the flow of renewable natural capital. The example presented in Section B.3.1 placed the stocks of natural capital in the production function in order to reflect a kind of "cost of using stocks". Here, we will only introduce this cost once we address fluctuations in the prices of $X$ and $H$. Since we have already commented on the functional form of this production function, let's clarify the production process a bit further.

Evidently, the production of wheat requires plots of land which, for simplicity we assume to be abundant[17]. Each firm operating in this agricultural industry meets its input requirements by drawing on a pool of labour $(L)$, machinery such as tractors for ploughing and harvesting $(K)$, exhaustible natural resources $(K)$ such as hydrocarbons that are required for the operation of $K$ and renewable natural resources such as water for the purpose of irrigation $(H)$. Each of the inputs is assumed to be homogeneous in quality and type. The theoretical implications of substitution between $K$ and $X, H$ can be shown with the figure below where $K$ is on the y-axis and $X, H$ are on the x-axis. Note that when we refer to $X, H$ the implication is either $X$ or $H$ and not a bundle.

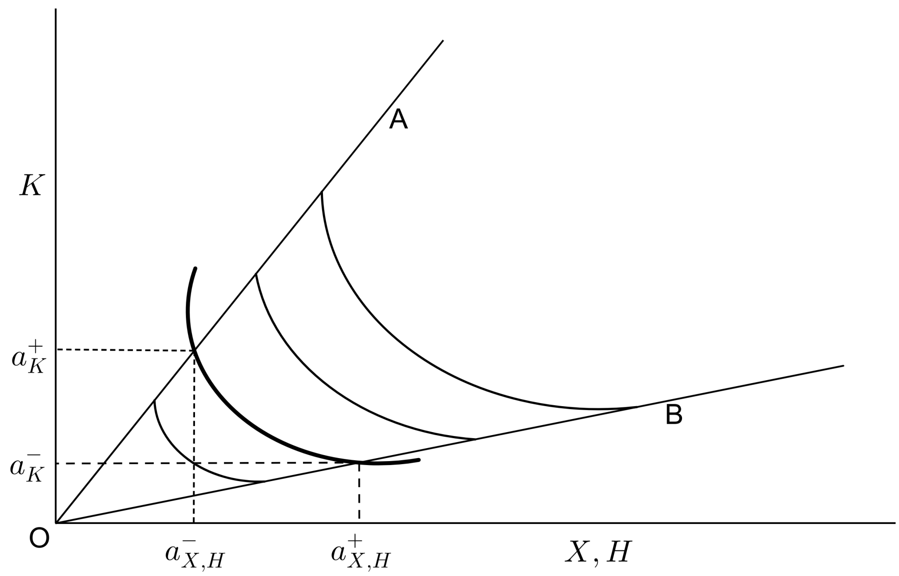


Figure B.1: Isoquants of wheat production with human-made and natural capital as inputs

The AOB-"cone" represents the partial[18] domain of our production function, which is specified as the region where the production isoquants are decreasing curves. Each isoquant indicates the combination of $K$ and $X, H$ that allow the production of a constant output quantity. In Figure B.1 the unit isoquant is bold; illustrating the quantities of the respective inputs that allow the production of exactly 1 unit of output. Specifically for the bold curve, one is able to read the input/output coefficients $(a_K, a_{X,H})$ on the respective axes.

Now due do the assumptions made on the functional form of our production function, each of the isoquants is a continuous but decreasing segment within the borders of the designated cone. This indicates the existence of a continuum of alternative production methods such that if $Y = f(\bar{a}_L, a_K, a_X, a_H) = 1$ then there exist extremely small values for $\epsilon$ and $\gamma$ such that,

[17] Even if this assumption is not realistic, the scarcity of land and inclusion of land-rents is not necessary to elucidate the implications of substitution between human-made and natural capital.

[18] Partial refers to the fact that we are only illustrating the relationship between human-made capital and either renewable or exhaustible natural capital in a two-dimensional space. Since our production function requires 4 inputs, the true domain would have to represented in a four-dimensional space.

e.g.: $Y = f(\bar{a}_L, a_K + \epsilon, a_X - \gamma, a_H) = 1$. This represents the crux of substitution and applied to our example it simply means that an increase of machinery $(K)$ in the agricultural industry necessarily implies a decrease in hydrocarbons $(X)$ or water $(H)$ all whilst keeping the output of wheat constant $(Y)$.

Put differently and in terms of the unit isoquant this means that $a_{X,H} = \phi(a_K)$ is a decreasing curve. Apart from that, the lower and upper edges of our AOB-"cone" for the unit isoquant curve represent the following pairs: $(a_K^+, a_{X,H}^-)$ and $(a_K^-, a_{X,H}^+)$. To understand the significance of these pairs requires us to discuss the marginalist interpretation of the partial derivatives of our production function, but before continuing let us reflect on the implied substitution mechanism.

It is absurdly clear that in our example of agricultural production, an additional unit of machinery is unable to keep output constant if the input of hydrocarbons and/or irrigation water decreases[19]. For agricultural production it is more plausible that a specific amount of harvested wheat always requires a fixed amount of hydrocarbons as well as irrigation. As argued by Daly in Section B.3.3, $K$ and $X, H$ are complementary inputs. But let us assume that this is not the case and continue with the exposure of the marginalist approach, perhaps the reader can think of an example in which substitution between $K$ and $X, H$ is more sensible.

Given that our production function, $Y = f(.)$, is concave and twice differentiable the derivatives for each of our inputs exist and are positive $(\frac{\partial Y}{\partial K}, \frac{\partial Y}{\partial X}, \frac{\partial Y}{\partial H} > 0)$ *within* the edges of our AOB-"cone". In marginalist theory, these derivatives are referred to as marginal products. The existence of *diminishing returns to increases of only one factor* is implied through the fact that the isoquants are decreasing curves within the edges of the AOB-"cone". Recalling the pair $(a_K^+, a_{X,H}^-)$ and $(a_K^-, a_{X,H}^+)$, $a_K^+$ on the upper edge of the AOB-"cone" in Figure (B.1) provides us with the maximum amount of human-made capital that can be applied in the production process while still ensuring that the marginal product $(\frac{\partial Y}{\partial K} = MP_K)$ is positive. According to marginalist theory, if the marginal product of an input is negative, it is better to restrict the use of the input to the amount which brings its marginal product back to zero and leave the excess unused. Assuming the other inputs remains fixed *and* at their optimal levels, marginal productivity is a decreasing function of the quantity applied in the production process.

Does this necessarily apply to the production of wheat? In the pen-ultimate paragraphs we already argued that an increase of $K$ while $X, H$ remains fixed will not increase production unless the additional unit of $K$ is somehow more efficient. Hence, the assumption of a decreasing marginal product with each additional unit of the input holds. But an increase in $X, H$ while $K$ remains constant need not necessarily imply the same. An additional unit of $X, H$ could on the one hand, allow the existing set of machines $K$ to operate for a longer period

[19] Unless one assumes that the additional unit of machinery somehow requires less hydrocarbons to produce an equal amount of output. But we are not assuming this, since our inputs are considered to be homogeneous and technological progress is absent.

of time and result in the harvest of more wheat[20]. Yes, a longer operation of machines might require more labour hours but this does not necessarily translate to an increase in the labour force $(L)$; an increase in the labour intensity per time unit will also suffice. Consequently, the marginal productivity of our non-renewable natural capital may remain constant for an additional $X$ units of input. Whether additional irrigation increases, decreases or keeps the marginal product of $H$ constant is debatable and also depends on the availability of seeds and soil quality which we are abstracting away from.

Nonetheless, these considerations melt as an ice-cube on Curaçao if we assume that the producer deploys the *most* efficient combinations of inputs from the get-go. This means that we assume that we are in a situation where the machines $K$ are operating at full-capacity utilization. In such a case, $MP_{X,H}$ can indeed be considered to decrease with each additional unit of $X, H$.

Regarding inputs $K$ and $X, H$, an isoquant basically represents $K$ as an implicit function of $X, H$ established through $f(K, L, X, H) - Y = 0$, where $Y$ is the given output to be produced. The slope of this function is given by $-\frac{\partial f/\partial X, H}{\partial f/\partial K} = -\frac{MP_{X,H}}{MP_K}$ and this is also referred to as the *technical rate of substitution* which indicates how many units of $X, H$ one more unit of $K$ can replace if output is to remain constant. Notice how at the lower edge of our AOB-"cone" in Figure B.1 the slope of the isoquant is 0, which implies that $MP_{X,H} = 0$, while the slope of the function at the upper edge approximates $\infty$, meaning that $MP_K$ approximates 0.

The previously discussed *diminishing returns to increases of only one factor* can also be established through the consideration of ratio's between $K$ and $X, H$, in Figure B.2 below we see a set of isoquants similar to those in Figure B.1, the only difference is that we have only highlighted two different isoquants. Along the ray from the origin both the two isoquants have the same technical rate of substitution.

[20] The implicit assumption here is that allowing a tractor to drive over a field 1 instead of 2 times results in a more precise harvest of the wheat crop

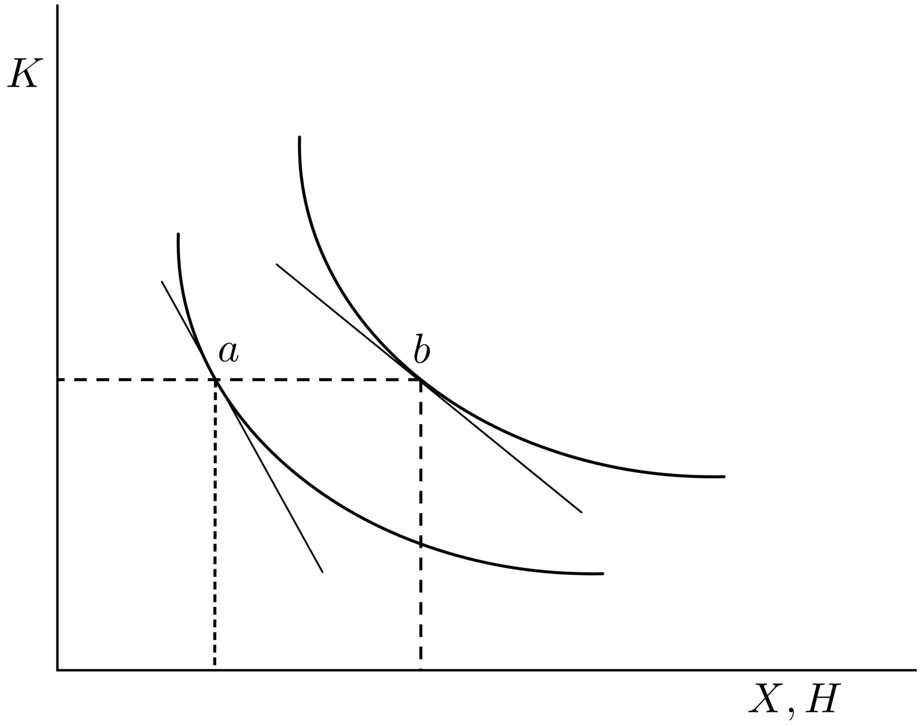


Figure B.2: Isoquants of wheat production with human-made and natural capital as inputs.

Starting from ratio $\frac{X,H}{K}$ designated by point $a$, we see that an increase in this ratio, through the additional deployment of $X, H$ while $K$ remains fixed, results in an isoquant-"shift" reaching point $b$. The slope of point $b$ is lower than that of point $a$, which must imply that $MP_{X,H}$ has decreased and/or $MP_K$ has increased.

### B.4.2. The role of substitution as an equilibrating mechanism

The assumption of a free and competitive market implies a situation in which an equilibrium between supply and demand exists on each of the markets the agricultural industry is involved with. In what follows we will focus on the determination of this equilibrium for non-renewable natural capital and how this determination depends on the substitution mechanism. While Section B.3.1 takes capital depreciation $\delta K$ into account, we will abstract away from this and furthermore assume that equilibrium exists on the wheat market itself. Hence, what remains for us to determine is the existence of equilibrium on our input markets (intermediate good markets).

Since the economy is highly competitive each of our agricultural firms is too small to influence prices and are therefore assumed to be price-takers for the price of wheat $(p_W)$. This means that for each given wage $(w)$, rent on machinery $(p_K)$, price per unit of hydrocarbons $(p_X)$ and price per unit of water $(p_H)$, the owner of the firm will attempt to maximize income after paying for the inputs. In other words, the owner of the firm will attempt to solve:

$$max_{L,K,X,H} \quad p_W Y - wL - p_K K - p_X X - p_H H \qquad \text{[B.29]}$$

This is an unconstrained maximization problem which means that the solutions are simply the following set of first order conditions:

$$p_W MP_L - w \stackrel{!}{=} 0 \Leftrightarrow p_P MP_L = w \quad \text{[B.30]}$$

$$p_W MP_K - p_K \stackrel{!}{=} 0 \Leftrightarrow p_P MP_K = p_K \quad \text{[B.31]}$$

$$p_W MP_X - p_X \stackrel{!}{=} 0 \Leftrightarrow p_P MP_X = p_X \quad \text{[B.32]}$$

$$p_W MP_H - p_H \stackrel{!}{=} 0 \Leftrightarrow p_P MP_H = p_H \quad \text{[B.33]}$$

The F.O.C's show that the optimal deployment of inputs $L^\circ, K^\circ, X^\circ, H^\circ$ requires the equality between the marginal product of each input multiplied by the price of the output (marginal revenue product) and the cost price of the respective input. If the marginal products are higher than the price $(MP_i > p_i)$, the additional deployment of a respective unit will increase production (output) more than it will increase costs. But, as previously argued, we are assuming *diminishing returns to increases of only one factor* which implies that the marginal product of the input decreases as the input itself increases. So it is convenient to increase the input up to the point where the marginal product is equal to the unit cost price.

Given that our focus is on the substitution between human-made capital and natural capital, let's assume that the labour market is in equilibrium; the supply of labour equals agricultural industry's demand for labour such that there is full employment. For a given full-employment wage, $w$, all firms in the wheat industry will want to achieve the same $MP_L$ and therefore adopt the same $K/L$, $(X, H)/L$ and $(X, H)/K$ ratios. But is this also guaranteed in terms of the F.O.C's in eqs. [B.29]-[B.32]?

The full employment of labour implies that $w/p_P = MP_L$ and that the equilibrium employment is known $(L^\circ)$. As seen for $X, H$ and $K$ in Figure B.1, a similar figure with $L$ on the y-axis and $K$ or $X, H$ on the x-axis, implies that for a given amount of output (isoquant) one is able to disseminate the amount of $K$ or $X, H$ and therefore also its marginal product, $MP_K$ or $MP_X$. However, there is no reason to expect that these marginal products respect eqs. [B.30]-[B.31] such that $MP_K = p_K/p_P$, $MP_X = p_X/p_P$ and $MP_H = p_H/p_P$ hold. This is because these ratios entirely depend on the price per unit of wheat set by individual firms (we are temporarily relaxing the assumption of price-taking behaviour).

If inequality exists between revenue and costs $(p_W Y \lesseqgtr wL + p_K K + p_X X + p_H H)$ for a given production quantity, an individual firm will find it attractive to either expand production indefinitely or shut down production. This results in fluctuations in the demand and supply of wheat, rendering the price, $p_W$, unstable. The inequality between marginal revenue and costs renders the simultaneous achievement of optimal input deployment impossible.

What the marginal approach requires in addition to smooth substitution between inputs is a mechanism which guarantees that all agricultural firms set the price per unit of wheat $(p_W)$

equal to the cost-price. If the cost price is defined as: $c(Y) = wL + p_K K + p_X X + p_H H$ then *perfect competition* renders undercutting and free entry/exit which will decrease $p_W$ if profits are positive and increase $p_W$ if profits are negative. Hence, the well-known production exhaustion theory where $p_W Y = wL^\circ + p_K K^\circ + p_X X^\circ + p_H H^\circ$ and profits are 0 translates to the tendency of competition to push wheat prices to the levels where profits are zero in the long-run. And this tendency is consistent with firms employing the optimal amounts of each input and paying each input its marginal product.

There is one final aspect and assumption of the marginalist approach that must be studied particularly with respect to natural capital. This is the assumption of decreasing demand curves for each of our inputs. Each of the aspects we discussed in previous paragraphs, particularly those related to marginal products, serve as ingredients that constitute the whole of such demand curves but we have not explicitly pointed it out yet.

Under the assumptions that i) in equilibrium each input is paid exactly their marginal product and ii) marginal products are decreasing functions of respective input quantities: a firm's demand for an input decreases as the price decreases. Such a curve is drawn for the natural capital input in Figure B.3 below.

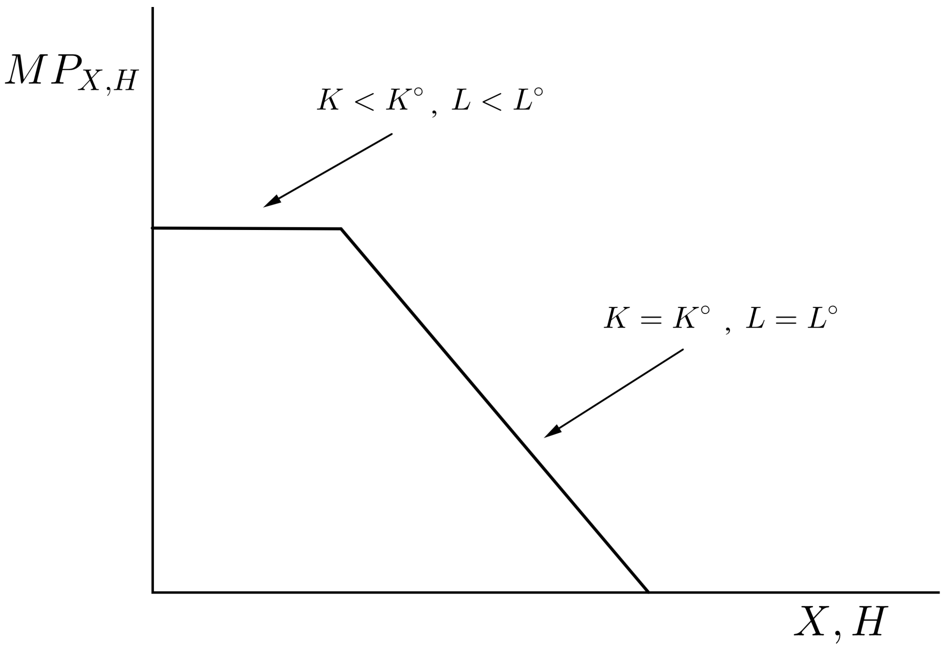


Figure B.3: The relationship between the marginal product of natural capital and the amount used in production

For a fixed amount of labour $(L^\circ)$ and human-made capital $(K^\circ)$, the initial segment is horizontal for low amounts of natural capital $(X, H)$. This is because the marginal product related to the ratio $K^\circ/(X, H)$ and $L^\circ/(X, H)$ indicates that we have stepped outside of the AOB-"cone" seen in Figure B.1. Hence, for sufficiently low amounts of $X, H$, a firm will prefer to use only the amounts of $K$ and $L$ which secure that $MP_K = MP_L = 0$ - the rest of $K$ and $L$ remains unused. The intersection of the curve with the y-axis is also called the *average* *productivity* of $X, H$, as long as $K < K^\circ$ and $L < L^\circ$ (indicating the partial employment of our other inputs) output is fully determined by $MP_{X,H}$. With each subsequent addition of $X, H$, both $L$ and $K$ are increased until they are fully utilized and once $L, K = L^\circ, K^\circ$, the curve starts to decrease with each addition of $X, H$.

Again, if we consider a situation of equilibrium where each input is optimally used, $Y = f(L^\circ, K^\circ, X^\circ, H^\circ)$, any addition of either inputs results in a decrease of their marginal products. This is the underlying thought behind decreasing demand curves for inputs in a situation where the agricultural firms are price-takers and minimize costs by deploying the amount of inputs which ensures that the marginal product is equal to the price of the input.

So far we have assumed that the marginal products of each of our inputs are either positive or zero. This translates to the assumption that the inclusion of an input either positively contributes to output or it doesn't, but it doesn't consider the realistic scenario that an input may negatively affect output. This is because, as previously argued, if the marginal product of an input is zero, this is assumed to be the result of a very large ratio between the input, of which the marginal product is zero, and other inputs. It means that the firm has found it convenient to partially employ an amount of inputs such that their marginal product equal to 0. This is where the story ends in the marginalist approach since negative marginal products are rarely taken into account even if realistic.

Applied to our example, it could be the case that an excess of hydrocarbons $X$, damages the machinery $K$ to the extent that output decreases by e.g. 50%. It may also be the case that excess irrigation with water $H$, results in soil erosion and nutrient leakage which reduces growth and total harvest. Of course, in the marginalist approach, which assumes a perfectly competitive market and complete information there is no reason why one should consider such mistakes. But what happens if we do?

To explore this possibility it is useful to consider the *total productivity curve* of an input. In our case, such a curve (Figure B.4) would show the total output of wheat as a function of natural capitals, $X, H$. It is important to iterate that this curve assumes that the input of labour and human-made capital is fixed.

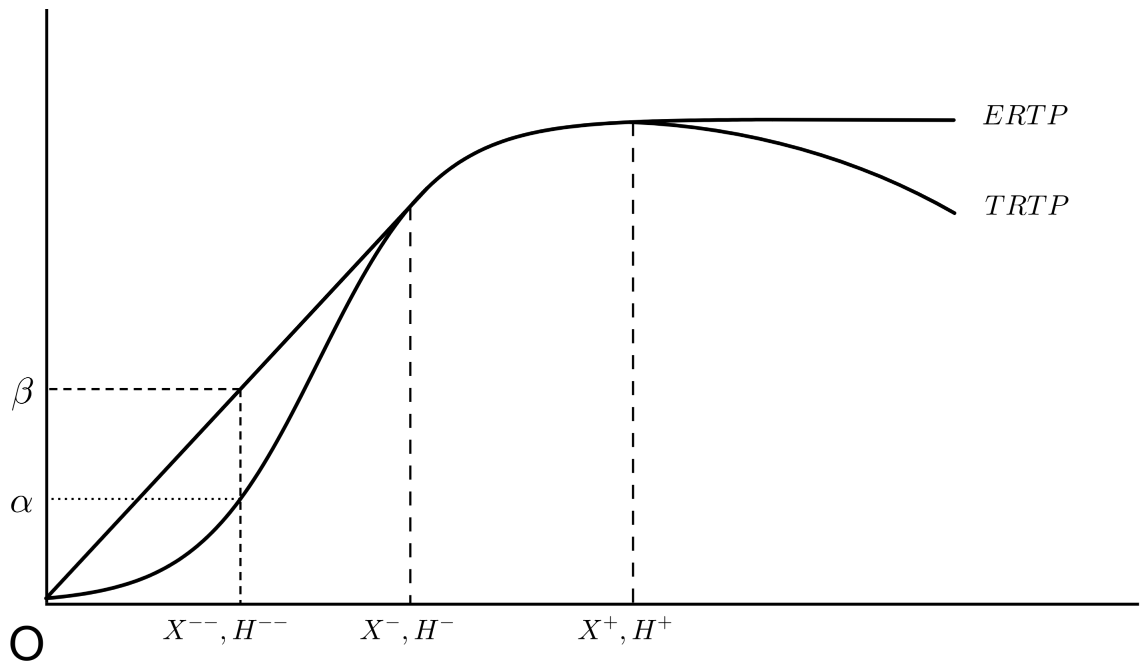


Figure B.4: Total factor productivity curves for natural capital

If one allows the marginal product to become negative the total productivity curve of $X, H$ decreases once $X = X^+, H = H^+$, in reference to Figure B.1 this means that for $X > X^+, H > H^+$, the implied quantity of $K$ is *outside* of our AOB-"cone" (lower edge). In fact, for the bold unit isoquant in Figure B.1, this possibility is illustrated given that the curve slightly bends backward outside of the AOB-"cone". This implies that the slope is becoming positive, hence $-\frac{MP_{X,H}}{MP_K} > 0$ which consequently implies that $MP_{X,H} < 0$. Instead, if the minimum value the marginal product of $X, H$ can take is 0, our curve continues as a horizontal line once $X^+, H^+$ is reached.

Now, let us reflect on the initial shape of the curve in Figure B.4 for $X \in (0, X^+), H \in (0, H^+)$. If starting from $X^+, H^+$ the deployment of $X, H$ decreases, this means that the $L/X, H$ and $K/X, H$ ratios increase. According to the previous assumptions, a sufficient decrease will result in $MP_L = MP_K = 0$ and *can* become negative if $X, H$ is reduced even further (upper edge of the AOB-"cone). In Figure B.4, the point where $MP_L = MP_K = 0$ is reached when $X = X^-, H = H^-$ and this is also the point where the marginal product of $X, H$ is maximized (see Figure B.3).

From this point onwards there are two possibilities; i) if all of $L$ and $K$ remain utilized, further decreases in $X, H$ will cause the average productivity of $X, H$ to decrease ii) if instead the firms chooses to reduce the $L$ and $K$ by the same proportion as $X, H$, the average productivity of $X, H$ will remain at its maximum due to constant returns to scale. As seen in Figure B.4 for $X = X^{--}, H = H^{--}$, option i) results in output $\alpha$ while option ii) results in output $\beta$, evidently output is higher under option ii).

Essentially, two different curvatures are presented in Figure B.4 and this distinction can be referred to as the *economically* vs. *technically* relevant total productivity curves ($ERTP$ vs. $TRTP$

in Figure B.4). The *economically* relevant curve is represented by straight line segment between 0 and $X^-, H^-$ and the horizontal line segment between $X^+, H^+$ and $X > X^+, H > H^+$. The *technically* relevant curve takes the S-like shape between 0 and $X^-, H^-$ and decreases between $X^+, H^+$ and $X > X^+, H > H^+$. The result of this distinction is that given an initial position of production under full employment of each factor, one can no longer be certain that changes in the use of $X, H$ will *keep* the other inputs $K, L$ fully employed and hence keep their respective markets in an equilibrium where supply meets demand.

So far we have not explicitly touched upon the fact that $X$ is a non-renewable resource, implying that the agricultural production of wheat reduces its stock $N$. Let's consider a situation where the price of $X$ increases because the stock $N$ is diminishing. One can imagine for example that the hydrocarbon extraction process is becoming more capital intensive due to the reduced concentration of the stock in one location. Within the marginalist approach, such a price increase can easily be formulated as the result of a shift in the supply curve to the left, allowing an intersection between supply and demand at a higher price level.

Now, as the result of substitution, if the firms want to produce and sell the same amount of wheat as before, hence remaining on the same output isoquant, they may decide to use less $X$ and more $K$ (assuming labour is fixed). This in order to reach a point where $MP_X/MP_K = p_X^+/p_K$, which assures that costs are minimized for an amount of output that is equal to the one before the price of $X$ increased. This may imply that the market for $K$, due to an increase in its demand, is out of equilibrium. On the other hand, the price increase could also incentivize firms to decrease output which implies a reduction of $X$ *without* an increase in $K$, a part of the already purchased human-made capital would then remain unused. The decreased output would correspond to less real incomes for consumers so one can assume that selling difficulties do not arise.

According to the marginalist approach, even if we are in a situation where $X$ is substituted by $K$ due to the price increase of $X$, this would imply a lower marginal product for $K$ due to a decrease in the $X/K$ ratio. As a result, the initial increase in the demand for $K$ is offset by a decrease due to its lower marginal product. Hence, an increase of $p_X$ will decrease the demand for $X$ without (only temporarily) increasing the demand for $K$. This ensures that the tendency toward full employment of each input is simultaneously operating on all input markets. This conclusion is based on the assumption that firms will always adjust their production to a point where the marginal product of an input is equal to its price and this fluid adjustment is entirely dependent on the fact that $X$ and $K$ are assumed to be substitutable for one another.

In sum, the marginalist foundation on which the *weak* sustainability paradigm establishes itself assumes the existence of a tendency towards the full employment as well as the existence of equilibria between supply and demand for each of the input markets. In such an equilibrium firms make neither profit nor loss, since each input is paid exactly their marginal product.

Inventive firms could only earn profits in disequilibrium through a faster adjustment to new opportunities before market mechanisms destroy these opportunities. Distributive justice under the *weak* sustainability paradigm only plays a role in terms of the future consumption opportunities. The underlying assumption for each generation at time $t$ is one in which every input is paid *exactly* their contribution to production.

## B.5. Discussion

So how does the *strong* sustainability paradigm as introduced in Section B.3.2 distinguish itself from *weak* sustainability with respect to the aforementioned marginalist assumptions? Evidently, the substitution mechanism between human-made and natural capital is either limited or completely restricted. This can be seen in the set-up of the production function in eq. [B.22], which we will rewrite as follows for simplicity:

$$Y = f(K, L; X, H)$$

Applied to our example of wheat production, the assumptions implied by such a production function are markedly problematic. The ; between two distinct input groups $(K, L)$ and $(X, H)$ still allows for substitution *within* the respective groups. In other words, continuous substitution between labour and machinery but also between hydrocarbons and irrigation water is entirely allowed. Apart from that it should be reiterated that *strong* sustainability in Daly's steady state model implies *limited* substitutability and not *perfect* complementarity between human-made capital and non-renewable capital. As pointed out by Comolli (2006), the introduction of a fixed coefficient production function in the final goods sector severely complicates the achievement of equilibrium between supply and demand. Let's understand why by iterating the static implication of perfect complementarity in the marginalist approach. The absence of substitutability between our inputs implies that only fixed-coefficient methods are known. Based on our example we could assert that the production of 1 unit of wheat requires 2 units of hydrocarbons $X$, 3 units of irrigation water $H$, 4 units of machinery $K$ and 8 units of labour $L$. Our production function would then take the following form:

$$Y = min\{4K, 8L, 2X, 3H\}$$

Any increase in $K, L, X$ or $H$ while other inputs remain fixed would keep output constant (in this case at 1 unit of wheat) since the inputs are now treated as compliments. Such a production function is referred to as the *Leontief* production function and since partial derivatives are mathematically indeterminate, the possibility to draw the marginal product of an input as a function of its demand is restricted to a vertical line. Applied to $X$, this means that demand neither increases or decreases as a function of its price, $p_X$, it is simply dictated by the amount the firm wants to produce $X = Y/2$.

In this case, the optimal ratio between $X$ and $K$ is $X/K = 0.5$, if $X/K > 0.5$ this implies that a portion of $X$ remains unused and if $X/K < 0.5$ this implies that a portion of $K$ remains unused. From a marginalist perspective, the firms decision to employ $X$ such that $MP_X = p_X$ is unattainable with the use of the Leontief production function. Furthermore, departing from a situation in which the optimal ratio $(X/K = 0.5)$ holds and introducing a price-shock as the result of sufficient decreases in the natural capital stock, $N$, necessarily implies a reduction in the use of $K$ *if* the firm's response to such a price increase is to reduce the use of $X$. Similar conclusions apply to changes in $L, H$ with respect to $K$ or with respect to each other. As a result, full employment and the equilibrium for all inputs is not guaranteed.[21]

The steady-state model introduced in Section B.3.4 assumes a production function with *limited* instead of zero substitutability. The direct implication of which is the ability to guarantee equilibrium on each of the input markets as well as the specification of the steady-state in which the stocks of both human-made and non-renewable natural capital remain constant.

With respect to distribution, the introduction of limited substitutability under the *strong* sustainability paradigm offers no concrete challenge to the marginalist idea of inputs being subject to decreasing demand curves. Even if the limited substitutability implies less fluid adjustments in the composition of inputs in the face of price-shocks, the notion of zero profits in equilibrium due to inputs receiving compensation which is equal to the marginal product still holds. In fact, the investment rule in eq. [B.28] is composed of the marginal products of human-made capital and non-renewable natural capital.

Nevertheless, one can argue that limited substitutability in conjunction with the proposition of a steady-state economy respects planetary boundaries to a greater extent than the *weak* sustainability paradigm. But how much of a productive departure is this from the *weak* sustainability paradigm if it still relies on marginalist assumptions concerning the functioning of the economy?

One the one hand, the idea that a physically non-growing economy is the only way to achieve ecological sustainability sounds convincing in light of the fact that technological advancements have thus far not allowed for *green growth* (see Hickel, 2019; Lorek and Spangenberg, 2014). The implementation of a steady-state economy for the purpose of remaining within planetary boundaries concentrates on the achievement of two additional goals: i) just distribution and ii) efficient allocation. Distribution refers to the division of resource flows embodied in final goods and services within and across generations. A *just* distribution is one which manages to keep the degree of inequality within an acceptable range (Daly, 1992).

[21] It should be noted that the substitution mechanism highlighted in this section is but one of the mechanisms that ensure sufficiently elastic and decreasing demand curves. Another mechanism, called the *indirect* substitution mechanism regards the influence of changes in relative prices on consumer choice. This mechanism is important for the existence of unique and stable equilibria. The reason we have not discussed it in this paper is because the aggregate welfare function optimized in our brief exposition of the *weak* and *strong* sustainability paradigms is a direct function of production ($C_t = Y_t - \delta K_t - \dot{K}_t$). Consumer preferences don't play a role since we are dealing with aggregated values.

Intergenerationally speaking, both the *weak* and *strong* sustainability paradigms aims to diminish the inequality to zero by framing the dynamic optimization problem around the existence of a constant consumption path. Intragenerationally, however, both sustainability paradigms fall short given the marginalist conjectures they depart from. If each input, including labour, is fully employed and paid exactly its contribution to production than why even discuss intragenerational distribution?

Daly's main argument is one of order or sequence; at the time the central ideas on the steady-state economy were formulated mainstream economics was accused of not taking sufficient account of "scale" or planetary boundaries. Hence, the determination of just distribution and "desirable" levels of inequality is prescribed to take into account the changes that a re-organized, "planetary boundaries-respecting" production system will bring about. Thereafter, the efficient allocation is freely allowed to operate by means of the market mechanism and individual preferences expressed through their willingness to pay.

Indeed, as pointed out by Pirgmaier (2017), the notion of steady-state economies, even under adherance to the *strong* sustainability paradigm, falls victim to shortcomings which are inherent in scholarly fields that advocatesì for infinite economic growth and substitutability between human-made and natural capital. This is because the so-called radical departure from *weak* sustainability is perfectly possible to articulate within the confinements of marginalist theory.

In our opinion this is a regrettable development in terms of economic theory; as the world-wide collapse of ecological systems becomes more and more apparent, most (not all) of the theoretical efforts aimed at integrating ecological systems are still anchored in a theory which results in modelling efforts that depict the economy in a half-baked fashion. Each input always receives a reward which is exactly equal to its marginal product and those who own the means of production are justified in receiving rents because they chose to invest instead of consume. Under such premises, where even labour exploitation and alienation are disparaged, the derivation of a price dismantles the idea that nature is exploited or appropriated. Its treatment as natural capital and hence, an input in a production function indicates that it is subject to a marginal product where the beneficiaries of this marginal product are not nature itself, but the actors who happen to own the geographical territories where "productive nature" is situated. The, perhaps subliminal, dominance of marginalism with respect to the theoretical treatment of nature in the field of economics may help us explain why in practice various types of natural capital, previously too complex to characterize, are currently undergoing joint processes of monetization and "efficient" assignments of property rights. It may also help explain why the demise of ecological systems has rarely been associated with labour exploitation or alienation in theoretical economic frameworks.

A few decades ago, the development of Ecological Economics as a radical departure from Environmental and Resource Economics seemed promising since it challenged the ignorance of planetary boundaries, treated the economic system as a highly dependent *subsystem* of the broader bio/geo/ecological system and encouraged methodological pluralism by advocating for the integration of various disciplines (Venkatachalam, 2007). One of the prominent ways this departure manifested itself in the field of formal economics is through the distinction between *weak* and *strong* sustainability. We argue that this departure is a façade precisely because of its strong adherence to marginalist theory, a true departure would challenge marginalism and its fairy-tale description of the economy. It would attempt to frame economy-ecology configurations with the use of economic theory which more accurately describes the dynamics and functioning of capitalism. We contend that the surplus approach based on Piero Sraffa's critique of marginalism offers an attractive opportunity to explore alternative economic landscapes.

## Chapter 4

# A computational approach to the metabolic rift in a 3-sector Sraffian model*


### Abstract

This paper aims to assess the transition from appropriated to capitalized nature in a simple open economy with 2 capitalist sectors and 1 subsistence sector. The analytical distinction between appropriated and capitalized nature is based on the world-ecology notion of an ecological surplus and its role in determining the ease of accumulation by means of labour productivity gains. Where capitalized nature *enters* a formally defined production function, we allow appropriated nature to influence the technical coefficients that characterize the respective production function. In our case, appropriated nature represents an agro-ecological system which is subject to a measure of fertility. The transition of the agro-ecological system to a capitalized state entails the use of external inputs in order to artificially increase fertility levels to their maximum. We demonstrate this transition by means of a simulation model. Our aim is to assess the interdependency between the intensity of an exogenous expansion shock, distribution, exploitation and agro-ecological degradation. We find that this interdependency is related to the specific strategies each of the sectors deploy in the face of labour shortages. When the agro-ecological system is still in a state of appropriation, worker well-being and agro-ecological well-being are intimately tied. Worker well-being is captured through the measure of exploitation and agro-ecological well-being is captured through the measure of ferility. Following Marx's labour process theory, there are two channels which mediate worker and agro-ecological well-being: material metabolism and purpose realisation. We find that within the confines of our model, purpose realisation dominates the mediation and therefore the initial stage of the metabolic rift between the society and ecological processes. Upon the capitalization of the agro-ecological system these channels are entirely eradicated resulting in the last stage of the metabolic rift. In this way we hope to provide the field of Ecological Economics with a preliminary attempt at an alternative formalization of economy-ecology configurations.



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## Introduction

Over the past couple of years, joint considerations on Marxist Political Economy and Ecological Economics (EE) have gained more and more attention. Part of this trend is related to the emergence of Ecological Marxism, or eco-Marxism. This is a consolidated field which places capitalism as a socio-economic system at the foreground of analysis when it comes to ecological disruptions, environmental justice and climate change.

To the best of our knowledge, academic efforts directed at the clarification of eco-Marxism's usefulness for EE have predominantly highlighted how a failure to incorporate Marx's analysis of capitalism holds EE captive to orthodox or mainstream economic methodologies. For example, Douai (2017) argues that a balanced assessment of Marx's legacy allows EE to critically reflect on the i) neoliberal conservation of nature, ii) the logic of growth and accumulation inherent to capitalism and iii) ecologically unequal exchange between countries at the core and periphery of the current globalized capitalist economy. On the other hand, Pirgmaier (2017) provides a critique of the steady-state economy devised by one of EE's founding fathers Herman Daly. In dissecting why steady-state economics internalizes neoclassical economic theory and reasoning, Pirgmaier pointedly draws on both Marx and (eco-)Marxist scholars to ultimately conclude that the field of EE requires a stronger embrace of heterodox economics. In a later publication this call is put forward more explicitly through the establishment of new research agenda for EE. The agenda is based on three realisations: a) taking the planetary scale and its limits seriously, b) placing social relations and social conflicts at the heart of analysis and c) bidding farewell to neoclassical economic theory and explicitly inviting heterox alternatives (Pirgmaier and Steinberger, 2019). Supplementing each of these recent publications with that of Spash (2020), allows us to conclude that eco-Marxism has slowly started to permeate EE's economic theoretical foundations.

One result of the aforementioned turn of events is a strengthened critique of the status-quo and the garnishment of conviction that change is indeed necessary. Another result could be the concrete institution of alternative frameworks, abstraction processes, mathematical formalizations and modelling efforts. In our view, the latter is much less explored. Exceptions are Pirgmaier (2021), who argues that the better alternative for neoclassical value theory is Marx's labour theory of value and Rammelt (2020) who provides a conceptual representation of economy-ecology configurations based on a system's dynamic representation of stocks, flows and funds alongside David Harvey's diagram of *value in motion*.

In light of the above, the intention of this paper is to provide an eco-Marxist inspired alternative to the status-quo of mathematical abstraction in the field of EE. In a nutshell, the prevailing formal representation of economy-ecology configurations in the field of EE still hinges on the notion of natural capital, an aggregate measure of exhaustible and renewable natural resources. Natural capital is usually formalized as an input which *enters* the production function. We draw on eco-Marxism to formulate a more extensive representation of economy-ecology configurations in terms of renewable natural resources. The representation we come up with rests on an analytical distinction between appropriated and capitalized ecological processes and is derived from world-ecology, a strand of eco-Marxism known for its concept of the ecological surplus: the ratio between appropriated (unpaid) and capitalized (paid) inputs pertaining to a production process (Moore, 2014: pp. 295). Apart from that, our interest lies with the formal assessment of the interdependence between distribution, exploitation (alienation) and ecological degradation throughout the transition of an ecological process from an appropriated to a capitalized state.

Such an assessment is provided by means of a mathematical description of a 3-sector economy which develops through 2 or 3 distinct phases: preliminary, expansion, capitalization. The economy consists of an industrial, agricultural and subsistence sector where commodity production in the agricultural sector relies on an appropriated agro-ecological system. The development throughout these phases is subsequently explored by way of a computational analysis or simulation. It is important to note that our modelling effort is based on the Sraffian/neo-Ricardian approach which is considered to be diametrically opposed to marginalist/neoclassical approaches.

The paper is divided into two parts and in Section 4.1.1 of Part I, we provide a literature review which aims to substantiate our equations and the assumptions concerning the inclusion/exclusion of various variables and the formally defined relationships between them. Section 4.1.2 of Part I then describes the operation of the economy in terms of economic reproduction, wages, labour exploitation, long-period positions and the exogenously imposed expansion shock. Apart from this, the section clarifies how we abstract the transition of the agro-ecological system from an appropriated to a capitalized state. In Section 4.1.3 of Part I, we describe the process of simulating this model and highlight the main causal loops in the diagram presented in Figure 4.1. This concludes Part I of which the aim was to introduce the reader to the building blocks of the simulation.

In Part II, Section 4.2.1 provides an extensive discussion of the results of our simulation exercise. This discussion is based on a selection of 13 scenarios, each distinguished by a different measure of expansion intensity. Initial values and parameters for the simulation exercise are provided in Appendix C. The variables we discuss in this section are output, uniform and actual profit rates, unemployment, wage-rates, agro-ecological degradation, exploitation and w(r)-curves. For each discussed variable, only relevant scenarios are highlighted and an overview of the development of the variables for *each* scenario can be found in Appendix D.

Section 4.2.2 in Part II attempts to summarize the results in terms of a general finding on the interrelationship between distribution, exploitation and ecological degradation. In essence, we highlight the different channels through which higher expansion intensities are positively related to agro-ecological degradation in the post-expansion long-period position. In addition, we briefly reflect on the ecological surplus and its quantification and variability within the confines of our model. The last subsection of Section 4.2.2 provides a deliberation on the relevance of our isolated and non-calibrated insights for the broader issue of climate change. Thereafter, Section 4.2.2 concludes Part II as well as the whole paper.

# PART I

### 4.1.1. Literature review

The aim of the current section is to review some of the literature which we expect to corroborate the various assumptions made in the economic model. Key elements are the idea of a dual economy, soil fertility and its relationship to the metabolic rift, worker bargaining power, structural change & growth and the labour theory of value. Given that the model is set in a Sraffian framework, the final subsection additionally addresses existing ecological considerations in Sraffian/neo-Ricardian literature and then highlights the distinctiveness of the approach taken in this paper.

**The dual economy**

One of the crucial assumptions of the model introduced in this paper is the idea of a *dual economy*. This concept was first introduced by Arthur W. Lewis in the paper called *Economic development with unlimited supplies of labour*. In this seminal work, Lewis argued that it makes sense to assume the existence of a surplus (or subsistence) labour force in countries which are in an early stage of capitalist development (Lewis, 1954: pp. 403-404).

According to Gollin (2014) and Fields (2004) the decades-old idea of a dual economy captured and still captures a key reality for economies which are characterized by a large informal sector. This explains why contemporary research on growth and development adopts the idea of a surplus labour force and either expands on Lewis' original theoretical model (de Oliveira and Lima, 2020; Vollrath, 2009; Wang and Piesse, 2013) or empirically verifies its assumptions (Bourguignon and Morrisson, 1998; Cai, 2010; Kwan et al., 2018; Temple and Wößmann, 2006). As a recent example of the latter; Radley (2020) shows how the existence of an artisanal (informal) mining sector alongside an industrial mining sector in the Democratic Republic of Congo results in stagnant wages in the latter sector — regardless of a 25-fold increase in labour productivity.

For the intent and purpose of computationally assessing ecological degradation in a three-sector open economy, we have incorporated the following assumptions of a dual economy in our modelling approach:

- The existence of a subsistence sector with negligible capital intensity
- The ability of capitalist sectors to freely draw on subsistence labour
- The existence of a subsistence wage determining the minimum wage in capitalist sectors

Apart from the above, the subsistence sector plays a particular role with respect to ecological processes. This role is addressed in the following subsection on soil fertility and the eco-Marxist concept of the metabolic rift.

**Eco-Marxism, the metabolic rift and soil fertility**

Contemporary Marxist treatments of ecological degradation are commonly referred to as the *metabolic rift theory* which is an eco-Marxist generalization of Marx's insights on capitalist industrialization and its impact on soil fertility in the agricultural sector (Foster, 1999). Our model remains faithful to this comprehension and strictly focuses on the interaction between capitalistically organized agriculture and soil fertility; a renewable resource or ecological process. One can argue that Marx's analysis is outdated since it was based on the situation in late nineteenth century Great Britain. Yet, the impact of agricultural intensification on soil health is still a contemporary ecological issue. The 2015 Status of World's Soil Resources Report emphasizes five current threats to global soils and their functions: i) erosion by wind and water, ii) organic matter decline, iii) compaction, iv) salinization and v) landslides of soil and rock material (FAO, 2015: pp. 8). In our modelling approach we centralize soil organic matter (SOM) decline as it plays a crucial role for the sustenance of soil fertility (Fageria, 2012; Feller et al., 2012; Tiessen et al., 1994).

Soil fertility is defined as the capacity of soil to provide plants with the essential nutrients required for its life-cycle (McGrath et al., 2014). The depletion of SOM as the result of intensive agricultural practices not only decreases nutrient pools (Lavelle et al., 2005) but also reduces the soil's water retention capacity (Rawls et al., 2003). Furthermore, SOM positively contributes to the biodiversity of soil microbiome around the roots of plants. For example, Lehmann et al. (2020) points out that higher biodiversity increases crop resilience to pathogens. All in all, decreases in SOM reduce crop productivity which consequently tends to increase fertilizer, pesticide, herbicide and irrigation dependency. This gradually transforms soils into net $CO_2$ emitters and pillagers of biodiversity (Gomiero, 2016).

Evidently, the extent of each of the above impacts depends on much more than the quantity of SOM. It also depends on the soil and crop type, climate (temperature and rainfall variability), altitude etc. In our modelling approach however, we introduce an abstraction which focuses on the relationship between agricultural productivity, soil fertility and a metabolic parameter.

This metabolic parameter is a function of both a physiological and cognitive component. The physiological component is strictly based on the quantity of SOM reintroduced in the production process. Instead, the cognitive component aims to capture the potentiality to both reproduce and apply knowledge which leads to the actualization of reintroducing SOM to the soil (Schneider and McMichael, 2010). In our view the dependence of ecological processes on a physiological and cognitive component falls in line with Marx's description of the labour process through the concepts of 'material metabolism' and 'purpose realisation' (see Section 3.3.2 in Chapter 3).

Coming back to the dual economy, scholars often point out that it is precisely the subsistence sector which sustains both components of the metabolic parameter. For example, Rosset and

Martínez-Torres (2012) indicate that agro-ecology plays an important role for peasant families that struggle for autonomy in the face of big agribusiness. The experience of peasant territories in the Brazilian Zona da Mata show how non-capitalistically organized agriculture contain "socio-ecological, cultural-political and politico-institutitonal base that harbours and nourishes a pool of horizontal relations between nature and people, natural resources, ... , skills, ... and ideas" (van den Berg et al., 2019: pp. 18).

The idea of a metabolic parameter which is "optimal" in the subsistence sector resonates with Salleh (2010)'s introduction of *meta-industrial labour* as harbourers of *metabolic value*: the intrinsic capacity of an ecosystem to organically reproduce itself. By taking the subsistence sector as a baseline to compare against, we decided to model the previously mentioned cognitive component as a function of the relative working conditions in the capitalist agricultural sector with respect to the subsistence sector. We assume that such relative working conditions represent the extent to which worker's purpose realisation is still in line with the accommodation of metabolic value given the alienating circumstances of capitalist production. The relationship between alienation and ecological systems flows from authors who build on Marx's theory of alienation in order to argue that alienation results in scarce knowledge and therefore diminished concern for nature. One important driver of such an alienation process is the technical division of labour which results in the the denial of worker's access to the abstract knowledge necessary for production (Dickens, 1996: pp. 48). This restriction of knowledge detaches labourers from the ecological conditions the production process they take part of depends on. Other authors argue that the society-wide alienation of labour culminates a real separation between nature and society or human labour and ecological processes — laying the ground for ecological degradation (Mikati, 2020).

In our modelling approach we abstract away from the technical division of labour and focus on a trivial representation of alienation *from nature* by taking into account the intensity and the length of the working day relative to those in the subsistence sector. In the end, the metabolic metabolic parameter determines fertility by means of a logistic growth function. This type of function is often used to model crop yield, biomass or canopy cover over time and in response to variations in water availability, temperature, farming techniques etc. (Dong et al., 2018; Koya and Goshu, 2013; Raes et al., 2009; Wang et al., 2017).

**Aggregate demand & capacity utilization**

In modelling the development of output in the capitalistically organized sectors, we assume that target output is periodically adjusted to consumption in the previous period. This is to say that changes in output are demand-driven and that the intersection between aggregate demand and supply need not coincide with the full employment of labour *by definition* (Arestis and Sawyer, 2009; Dutt, 2006; Fazzari et al., 2020). However, the vast literature on demand-led growth in the post-Keynesian tradition also stresses the role of capacity utilisation in the adjustment of output to demand. While our modelling approach disregards the full employment of labour, we do not consider fixed capital and the depreciation thereof. As such, considerations on capacity utilisation are obsolete and in order for supply to meet an increase in demand, the assumptions in our model require investment in additional circulating capital (import goods) if the stock of inventories is not sufficient.

**Bargaining power**

The previous section on the dual economy, mentioned that the subsistence wage is a determinant of wages in the capitalistically organized sectors. In addition, we introduce a measure of employment (or worker's bargaining power) as a determinant of the final wages in the aforementioned sectors. Allowing wages to fluctuate according to employment is an assumption typically found in the essay *A growth cycle* by Richard Goodwin (Duménil and Lévy, 2003). Nowadays, the post-Keynesian tradition adopts the measure of unemployment as a proxy for class struggle which is said to determine firm's mark-up on the price of inputs (Lavoie, 2015: pp. 174). We follow the Goodwin tradition and allow the wage-premium over the subsistence wage, to fluctuate with employment. Bellofiore et al. (2000) justify this assumption on the basis that workers perceive the threat of being laid off more seriously when unemployment is high. The less replaceable a worker becomes, the higher their bargaining power and hence, in our case, the wage-premium.

**Structural change & growth**

The exogenous shocks in our modelling approach are i) an increase in the consumption basket of the working class, ii) the production of an industrial export good and iii) downward adjustments to technical and labour coefficients. When it comes to an increase in the consumption basket, we postulate that the industrial sector, previously strictly producing an intermediate or investment good, adopts a labour-saving technology and additionally engages in the production of a consumption and export good. Capitalization of the agro-ecological system also reflects a change in the productive structure of the agricultural sector. The use of fertilizers represents a new production process which relies on an additional input. This new production process is labour-saving and capital-saving (as long as soil degradation doesn't manifest itself).

In reference to economic literature both of these shocks can be referred to as very trivial iterations of structural change: "a complex, intertwined phenomenon ... because economic growth brings about complementary changes in various aspects of the economy ... but also because these changes ... in turn affect the growth processes" (Matsuyama, 2018: pp. 13202). According to Syrquin (2008), the impact of structural change on economic growth is ambiguous; it can either contribute to or hamper growth depending on its direction and pace (among other variables). In the field of development economics, theories on structural change are widely deployed precisely in order to understand how heterogeneity in the productive, social and institutional structures of developing economies results in heterogeneous development or growth paths (Dutt, 2019). With reference to Lewis' concept of the dual economy, some scholars treat the existence (or persistence) of a significant subsistence labour force as a determining structure when it comes to the assessment of economic growth. As an example, Temple (2005) uses a dual economy model in order to discuss changes in factor misallocation, urban unemployment, international productivity differences and economic growth as the result of structural change.

A clear-cut application of ideas, theories and findings regarding development and structural change is rather limited in our modelling approach. This is because our modelling aim is oriented towards the assessment of these structural changes on the development of the agro-ecological system. Evidently, changes in the agro-ecological system feed back into economic production processes and hence growth. But we abstain from drawing conclusions on the direct link between structural change and economic growth. Scholarly works on the relationship between structural change and environmental degradation are not absent however, the hypothesis that structural changes, which embody a shift to low energy and resource intensity sectors, decrease environmental degradation[1] is widely discussed (see e.g. De Bruyn, 1997; Panayotou et al., 2000; Pasche, 2002).

### The labour theory of value and labour exploitation

Our modelling approach is peculiar in that it relies on Sraffian theory to derive relative prices in a framework which is based on physical quantities. At the same time, we address labour exploitation, more or less following the classical Marxist convention. In this section we will expand on the literature which addresses these two approaches and argue that their combination may be superfluous but not contradictory.

It goes without saying that a discussion of Sraffian relative prices in relation to Marx's method of analysis by means of labour values falls under the broader controversy surrounding the labour theory of value (LTV). In discussing the LTV and its application in our modelling approach we draw heavily on Mohun and Veneziani (2018). The authors provide an axiomatic treatment of the LTV and its various interpretations. Their treatment is based on a classification which draws the distinction between the LTV's i) purpose, ii) view and iii) level of analysis. The LTV's purpose can be predictive, descriptive or normative. Its view can be oriented towards the derivation of equilibrium or long-period prices or exploitation as a condition for profits. When it comes to the level of analysis, the LTV can be applied to aggregate or disaggregate magnitudes resulting in a macro and micro level distinction. Evidently, this classification is not mutually exclusive, approaches regarding the LTV can share overlapping purposes, views and levels of analysis. For Sraffians, the LTV is considered to be redundant and irrelevant and we

[1] This is also known as the environmental Kuznets curve hypothesis, which is actually an adaptation of Kuznet's initial hypothesis on the inverse-U relationship between income on the x-axis and income inequality on the y-axis (Kuznets, 1955).

will now discuss why based on the two different *views* on the LTV.
When it comes to the equilibrium price view, the standard Sraffian interpretation treats Marx's theory as a dual system: a *value* and a *price* system. The value system operates in terms of simple prices expressed in labour time units, while the price system operates in terms of production prices expressed in monetary units. If simple prices are proportional to production prices, the value and monetary rates of profit are equal and the simple prices of inputs can be transformed into production prices. However, *relative* simple prices more than often fail to coincide with *relative* production prices. Thus, Marx's *inconsistency*, commonly referred to as the transformation problem, is said to be the result of deriving the rate of profit in value terms and using this rate of profit to derive input prices in monetary terms (Steedman, 1977: pp. 29-36; Hunt and Glick, 1990: pp. 357-358). Some Sraffian scholars argue that Sraffa's *Standard System* offers an "auxiliary" solution to the transformation problem (Perri, 2014: pp. 106; Eatwell, 1975). More generally however, it can be said that the Sraffian framework avoids the transformation problem by assessing economic production in terms of *physical values*. The Sraffian method of analysis is referred to as *physicalist* which means that the theoretical models are based on "the physical structure of inputs and outputs measured in given quantities of use-values" (Carter, 2011: pp. 1122). This allows the calculation of the rate of profit and the social surplus without expressing inputs in terms of labour values or monetary prices.
In turn, for the profits and exploitation view, Sraffians argue that Marx's adoption of labour values, as a means to demonstrate that production under capitalism generate profits through exploitation, is unnecessary. The fact that an appropriation of surplus takes place after all inputs are paid for, is said to be a sufficient condition for both positive profits and the general sociological phenomenon of exploitation and alienation (Mongiovi, 2002b: pp. 398). This is related to the argument expressing that the choice of labour power, as the unique input which capitalists exploit, is arbitrary since any other input can be used to tell the same story. In the Sraffian system of equations, which determines relative prices and the uniform wage or profit rate, capitalists obtain a positive profit through a markup on *every* input. In other words, from a Sraffian perspective, the source of capitalist profits is not *just* the exploitation of labour but of *all* inputs. In sum, positive profits are said to manifest themselves when i) the economy is able to produce a physical surplus and ii) this surplus is denied to workers (Hahnel, 2017b: pp. 32; Garegnani, 2018: pp. 641). In the table below, we summarize the difference between the traditional[2] Marxist and Sraffian evaluation of prices, profits and exploitation:

[2] A variety of Marxist scholars have addressed Marx's transformation problem and claim to have solved it in different ways. Addressing each these approaches fall beyond the scope of this paper, for an elegant overview of these solutions see Mohun and Veneziani (2018).

| | **Marxists** | **Sraffians** |
|---|---|---|
| **Equilibrium prices** | Simple prices proportional to prices of production | Relative prices based on a numéraire* |
| **Condition for profits** | Positive surplus value (labour time) | Positive physical surplus* |
| **Profit rate** | Surplus value rate = monetary rate of profit | Physical surplus rate evaluated at relative prices* |
| **Exploitation** | Exploitation rate = surplus value rate | Redundant |

Table 4.1: Characteristics of the Marxist and Sraffian methods of analysis

The characteristics marked by an asterisk (*) aim to capture our approach throughout the rest of this paper. Basically, we adopt the standard Sraffian framework when it comes to the derivation of equilibrium prices, conditions for a positive profit and the derivation of the uniform profit rate. When it comes to exploitation however, the calculations we engage in do not equate it to the surplus value rate but is not treated as redundant either. This is because our theoretical framework additionally relies on a measure of *labour intensity* in deriving i) the uniform rate of profit, ii) the rate of exploitation and iii) the state of the agro-ecological system.

In Chapter 17 of *Capital: Volume I*, Marx describes variations in relative surplus extraction and defines an increased intensity as the: "increased expenditure of labour in a given time" (Marx, 1887a: pp. 370). As such, a measure of labour intensity is often used by scholars in the Marxist tradition to iterate the difference between absolute and relative surplus value[3] extraction. In describing the advance of machinery and modern industry in Chapter 15, Marx argues that increasing the intensity is a logical consequence of a shorter working-day due to the either an institutionally enforced maximum working day or the introduction of machinery which decreases the working-day (Ibid, 1887a: pp. 284/295). While contemporary Marxist scholars continue highlighting the inverse relationship between the length of the working day and labour intensity (Mavroudeas and Ioannides, 2011; Reuten, 2004: pp. 125), our modelling approach does not follow such a logical sequence and assumes that increasing the labour intensity is a strategy which capitalists are freely able to choose in the face of labour shortages. Such increases in the intensity of the labour are not considered to be the result of nor the trigger for changes in the length of the working day. Let us clarify the purpose of an exploitation rate in our framework by regarding the standard derivation of the exploitation rate for an economy which only produces one commodity:

[3] Both relative and absolute surplus value are identified in measures of labour time. Where absolute surplus value is increased by increasing the length of the working day, relative surplus value is increased by raising labour intensity of productivity (Fine and Saad-Filho, 2004: pp. 40-44).

$$\lambda = \lambda a + l \qquad [4.1]$$

$$\lambda = \frac{l}{(1-a)} \qquad [4.2]$$

$$e = \frac{\lambda Y - \lambda bL}{\lambda bL} \qquad [4.3]$$

Where $\lambda$ represents the labour embodied in one unit of output, $a$ is the technical coefficient of the production process expressed in necessary input per unit of output and $l$ is the labour coefficient expressed in necessary labour hours per unit of output. Eq. [4.2] then represents the calculation of $\lambda$ based on the indirect $(a)$ and direct $(l)$ amount of labour in the production process. The rate of exploitation or surplus value rate, $e$, is calculated by multiplying total output, $Y$, with $\lambda$ and subtracting the labour embodied in the wage-bill. The wage-bill is calculated through a multiplication of the hourly physical wage-basket, $b$, with the total amount of labour deployed in production, $L$. Multiplying the wage-bill by $\lambda$ then gives us the labour embodied in the wage-bill. The numerator of [4.3] then represents surplus labour.

Screpanti (2003) argues that the above-mentioned measure of exploitation fails to account for the social relation between workers and capitalists. He mentions that: "unlike production prices, labour values do not change when class relations change, for instance, when income distribution changes" (Ibid, 2003: pp. 158). In a later publication Screpanti returns to this argument related to the divergence of relative prices from relative labour values. According to Screpanti, the exploitation rate determined in a normalized[4] price system will always be larger than that determined by a labour value system. This could mean that surplus labour is generated somewhere outside the sphere of production (Ibid, 2019: pp. 49-53).

If the measure introduced in [4.3] neither captures the subordination of workers at the hand of capitalists during the production process nor reflects the actual behaviour of a market economy subject to production prices, then what is its usefulness to us? The reason why we nevertheless adhere to a slightly adapted measure of labour exploitation is in order to introduce a previously overlooked configuration between labour and ecological processes. Our adapted measure of labour exploitation relies on a measure of labour intensity, which in our opinion succeeds in capturing more of capitalist social relations than the measure introduced under [4.3] does. The fact that capitalists are able to increase labour intensities to meet their necessary labour inputs captures that they are able to produce more while their costs are held constant. This represents a unique one-way social relation between capitalists and workers. Furthermore, the aim of our measure is not to illustrate the distribution between workers and capitalists; this is already succeeded through the Sraffian approach and its analysis of the physical surplus and relative prices.

[4] Normalized to ensure that $\lambda bL = pbL$ where $p$ indicates the price of the commodity.

In sum, the way we deploy our measure of exploitation supports the aim of bringing together i) the subordination and alienation of workers and ii) the degradation of ecological processes under capitalist production processes. In a trivial way, the measure of exploitation allows us to explore the interrelationship between worker and agro-ecological well-being. The curious reader can skip ahead to Section 4.1.2 to understand what this reasoning formally looks like.

**Ecological considerations in Sraffian frameworks**

Ecological considerations within Sraffian or Neo-Ricardian frameworks are not unique. This is not a surprise since Adam Smith, David Ricardo and Karl Marx each discussed the phenomenon of land rent in their seminal works. Smith is said to have treated rent as a monopoly price on the productive potential that a privately owned plot of land bore relative to the demand for produce (Aspromourgos, 2009). Ricardo, in turn, elaborately built upon the ideas of predecessors in order to distinguish between *intensive* and *extensive* rent; a distinction which is commonly adopted by contemporary neo-Ricardians (see e.g. Kurz, 1978; Kurz and Salvadori, 2015). Marx on the other hand, introduced his own categories of rent in order to elaborate on the conjecture between i) the natural basis of rents as the result of varying fertility and ii) the social basis of rents as the result of the social distinction between landlords, capitalists and workers. This led to the development of the concept of *surplus profits* which are transformed to capitalist *ground-rent* by means of privately owned landed property (Das and Basu, 2020).

Our modelling approach abstracts away from considerations on rent, even if land and the agro-ecological system it is subject to plays an important role. In any case, the relatively limited stream of Sraffian literature which addresses ecological degradation can be categorized as follows: i) considerations on exhaustible resources, ii) considerations on renewable resources and iii) considerations on the generation and disposal of waste flows.

When it comes to exhaustible resources, Bidard and Erreygers (2020) argue that the book chapter *Exhaustible Natural Resources and the Classical Method of Long-Period Equilibrium* by Sergio Parrinello was the first to fully integrate exhaustible resources into classical theory. The aim of Parrinello's analysis was to examine the compatibility between Sraffa's formalisation and the Hotelling's Rule. The latter describes the development of economic rents as a natural resource is exhausted over time. Given the intertemporal character of Hotelling's rule, subsequent Sraffian approaches to exhaustible resources have adapted the traditional Sraffian framework in order to account for complex dynamics (see e.g. Huang, 2018; Kurz and Salvadori, 2003; Ravagnani, 2008).

The literature which addresses renewable resources in a Sraffian framework is far more limited, but an example is given by Erreygers (2015) and Hahnel (2017a). Erreygers introduces a corn-tuna model and incorporates the dynamics of fish stocks in a Sraffian 4-sector model for corn, tuna, boat and pond commodities. This is done in order to discuss how the cost advantage of wild fishing vs. fish farming impacts the population size of wild tuna. Hahnel on the other hand, introduces a homogeneous measure of nature which is able to regenerate itself. He argues that in order to prevent the throughput of nature to exceed its regeneration level, leisure inducing labour productivity increases and throughput efficiency increasing technologies are necessary. Finally, when it comes to the generation and disposal of waste flows, Hosoda (2001) builds on the corn-guano model introduced by Bidard and Erreygers (2001) in order to understand the dynamic substitution between the landfilling and recycling of waste-flows. Hosoda concludes that if landfilling space is widely available, recycling fails to be competitive with with landfilling but once landfilling space becomes scarce, recycling becomes cheaper and is activated as a waste-treatment process.

In light of this stream of literature, the modelling approach presented in this paper is rather outlandish. We abstract away from land-rents, disregard Hotelling's rule and intertemporal dynamics, postulate the existence of a subsistence sector, incorporate a measure of exploitation based on labour intensities and simulate the dynamics of an economy across three long-period positions. While each of the aforementioned approaches operate in a framework which assumes complementarity and thus avoid the Neoclassical derivation of prices on the basis of an equality between supply and demand, exhaustible or renewable natural resource are subject to a rent or price, which indicates that they are *capitalized*. Land which is subject to higher fertility levels is simply assumed to be subject to higher rents without regard for the fact that fertility levels are not a static given. The gap this paper aims to fill is related to the absence of considerations on economic reproduction, *appropriated* ecological processes, exploitation as a measure of alienation and distribution.

### 4.1.2. A 3-sector model operating on the basis of ecological appropriation

The equations we introduce in the following section aim to describe the operation a simple open economy with 2 capitalist sectors and 1 subsistence sector. The 2 capitalist sectors under consideration are i) an agricultural sector and ii) an industrial sector. The subsistence sector produces a commodity which is equivalent to that of the agricultural sector but with a zero capital intensity (negligible mechanization). As a result, the average productivity (output per unit of labour) in the subsistence sector is lower than in the capitalist sector. Average productivity in the subsistence sectors determines the subsistence wage and therefore the minimum wage in our open economy. Another characteristic of the subsistence sector is its employment of superfluous labour which results in the existence of a surplus labour pool from which both capitalist sectors are able to cheaply draw from.

In the sections that follow we will treat the production process in each of the sectors and sketch out a simplistic representation of the agro-ecological system (nature) that both the subsistence and capitalist agricultural sector interact with. We then discuss the (potential) transition from appropriated to capitalized nature as the result of exogenously imposed industrialization or *socio-economic progress by means of industrial expansion*. Depending on the trajectory the economy follows to achieve the industrialization process, the interaction between economic and agro-ecological reproduction will or will not incentivize the capitalization of nature. If the reader is not interested in a clarification of each and every equation that underpins the simulation, they may skip ahead to Section 4.1.3 which provides an explanation of the simulation through a causal loop diagram relating key variables.

**Economic reproduction**

**The subsistence sector.** As mentioned in the introduction, subsistence agricultural production takes place with a minimum amount of circulating capital. For simplicity we assume the exact amount to be zero. This means that aggregate subsistence agricultural production takes place according to two inputs: seed $(S^S)$ and labour $(L^S)$. The piecewise fixed coefficient production function then takes the following shape:

$$Y^S = \begin{cases} a_S^S \cdot S^S & \text{for } L^S \geq \overline{L^S} \quad \text{and for } S^S \leq \overline{S^S} \\ min\{a_S^S \cdot S^S; l^S \cdot L^S\} & \text{for } L^S < \overline{L^S} \quad \text{and for } S^S \leq \overline{S^S} \end{cases} \qquad [4.4]$$

Assuming that the cultivated plots of land are fixed (constant amount of hectares), we'll have that $a_S^S$ is the output per unit of $S^S$ and $l^S$ is the output per unit of $L^S$ (in labour hours). $Y^S$ is the total output on the cultivated plot of land which we assume to remain fixed across the rest of our analysis. The reason why we introduce a piecewise function is in order to capture that production in the subsistence sector deploys more labour than what is strictly required by the technical coefficient, $l^S$. For a given amount of output, $Y^S$, the labour requirement dictated by $l^S$ is equal to $\overline{L^S} = \frac{Y^S}{l^S}$. Then if the subsistence sector deploys $L^S > \overline{L^S}$, the piecewise function allows us to keep output constant by only taking into account the amount of seed and its related technical coefficient. It also allows us to derive a variable labour coefficient when $Y^S = a_S^S \cdot S^S$ holds. That is:

$$l_v^S = \frac{Y^S}{L^S} \qquad \text{for: } L^S \geq \overline{L^S}, \qquad \text{where: } l_v^S < l^S \qquad [4.5]$$

All of this is to capture that beyond $\overline{L^S}$ the marginal product of an additional hour of labour is zero which means that a decrease in labour hours will not decrease output if the labour hours remain above $\overline{L^S}$.

The amount of labour hours expended in production is a function of the length of the working day $(h^S)$, the number of workers in the subsistence sector $(N^S)$ and the length of the production period $(z)$ which is uniform across all sectors:

$$L^S = N^S \cdot h^S \cdot z \qquad [4.6]$$

We assume that the subsistence sector produces explicitly for the workers themselves and their families. The net output is then given by:

$$Y_M^S = Y^S - S^S \qquad [4.7]$$

A part of the output is set aside and reintroduced as seed, $(S^S)$, for the subsequent production period. Since all of the surplus is consumed by subsistence workers, we'll have that:

$$R^S = p^S \cdot Y_M^S \qquad [4.8]$$

$$P^S = R^S - w^S \cdot L^S \qquad [4.9]$$

Where $R^S$ is revenue, $p^S$ is the price of the subsistence commodity, $P^S$ indicates profits and $w^S$ is the wage of subsistence workers. Under the assumption of zero profits we'll have that the wage is:

$$w^S = \frac{R^S}{L^S} = p^S \cdot \frac{Y^S - S^S}{L^S} = p^S \cdot b^S \qquad [4.10]$$

This essentially represents the average net product per hour of labour expended and coincides with the physical quantity embodied in the subsistence wage-basket $(b^S)$. Total consumption of the subsistence good then becomes:

$$\begin{aligned} C^S &= w^S \cdot L^S \\ &= Y_M^S \end{aligned} \qquad [4.11]$$

**Agro-ecological Reproduction.** Before addressing production in the capitalistically organized agricultural sector, it is important to address the agro-ecological system the agricultural production process depends on. We do so by taking into account a measure of fertility $(F)$ both the subsistence and agricultural sector soils are subject to. Following eco-Marxist theory, we aim to illustrate the impact of capitalistically organized production on the relationship between labour and ecological processes. This is why in discussing the measure of fertility, $F$, we treat the subsistence sector as a baseline to compare against. On the whole, the level of fertility is a function of a metabolic parameter, $M$:

$$F(M) \quad \text{with } \frac{dF}{dM} > 0 \quad \text{and } \frac{d^2F}{dM^2} < 0 \text{ for } M \in (0,1]$$

The above shows that fertility is assumed to be a positive function of the metabolic parameter; an increase of the metabolic parameter increases fertility with a decreasing slope. This behaviour of $F$ for $M \in (0,1]$ can be approximated with a logistic growth function:

$$F(M) = \frac{F^{max} + Z}{1 + e^{-kM}} - Z \quad [4.12]$$

$$F^{max} = F(M^*) + 1$$
$$= F^* + 1 \quad [4.13]$$

$$Z = F^{max} - 2F^b \quad [4.14]$$

$$M = \frac{n}{n^*} \cdot \left(\frac{I^S \cdot h^S}{I \cdot h}\right)^{\alpha} \quad [4.15]$$

$$M^* = 1$$
$$n^* = b(Y - \frac{Y}{a_S^{A^*}})$$

$$\frac{dF}{dn} = \frac{k \cdot e^{-kM}(F^{max} + Z)}{(1 + e^{-kM})^2} > 0 \quad [4.16]$$

Where $F^{max}$ indicates the curve's maximum value in the limit, for $M \rightarrow \infty$, which is why we take the optimal level of fertility, $F^*$ as a unit measure below the maximum (eq. [4.13]). $Z$ determines/is a function of the land specific baseline fertility $F^b$ where $k$ is an exogenous measure characterizing the steepness of the curve. On the one hand, the metabolic parameter, $M$, is a function of the optimum amount of nutrients returned, $n^*$ and the actual nutrients returned, $n$. On the other hand it is a function of relative working conditions with respect to the subsistence sector: the length of the working day, $h$ and the intensity of the working day $I$. The parameter $\alpha \geq 1$, captures the weight of working conditions in the determination of the metabolic parameter.

Following eco-Marxist theory, the nutrients returned to the soil $(n)$ are a positive function of the agricultural labour force's consumption of the agricultural commodity. This is because of the geographical vicinity of agricultural consumption to agricultural production site (land). Hence, it is assumed that the nutrients required to maintain the fertility of the soil are contained in the food-waste/leftovers and that the agricultural labour force is knowledgeable of the fact that returning this waste as compost to the land is beneficial for the soil. Exogenous parameter $b$ is contained in $(0, 1]$ and expresses that the optimal nutrients returned are fraction of the net product. The activity of returning nutrients to the soil and the labour spent in doing so is assumed to be fully left unaccounted for by capitalists and is therefore absent in capitalist decision-making processes and considerations. This physiological determinant of the relationship between labour and ecological processes demonstrates how the attempt of our model to incorporate material metabolism aspect of the labour process. The reason why $F$ is not only a function of the ratio between actual and optimal nutrients returned to the soil (proving parameter $b$ to be redundant), is because we follow eco-Marxist theory in assuming that the effectiveness of returning nutrients to the soil is a additionally determined by purpose realisation. We trivially parametrize this by means of the length of the working day, $h$ and the intensity of the working day, $I$.

Since we assume that the subsistence and agricultural sector produce an equal commodity on homogeneous land and soil, both sectors are subject to the same functional form of fertility, $F(n)$ for $M \in (0,1]$, and optimal fertility, $F^{S^*} = F^{A^*}$. This optimum can be reached under different production circumstances (e.g. size of output) and we'll have that $n^{S^*} \neq n^{A^*}$ for $Y^S \neq Y^A$. Fertility in the subsistence sector is given by:

$$F^S = \frac{F^{max} + Z}{1 + e^{-k \cdot M^S}} - Z \quad [4.17] \qquad F^{S^*} = \frac{F^{max} + Z}{1 + e^{-k}} - Z \quad [4.18]$$

Where $F^{S^*}$ represents the optimum level of fertility, achieved by the optimum metabolic parameter, $M^* = 1$ which is given by:

$$M^S = \frac{n^S}{n^{S^*}} \cdot \left(\frac{I^S \cdot h^S}{I^S \cdot h^S}\right)^{\alpha} \quad [4.19]$$

$$n^{S^*} = b \cdot (Y^S - \frac{Y^S}{a^S_S}) \quad [4.20]$$

$$n^S = b \cdot C^S = n^{S^*} \quad [4.21]$$

This finally brings us to the following relationship (power function) between fertility and the technical coefficient for seed:

$$a^S_S = (F^S_{-1}(M^S_{-1}))^m \quad [4.22] \qquad a^{S^*}_S = F^{S*m}_{-1} = a^S_S \quad [4.23]$$

Where $m$ is an exogenous parameter and the above equation indicates that when it comes to the production function as found under eq. [4.4], the technical coefficient for seed input is actually a function of agro-ecological reproduction proxied by the measure of fertility in the previous period (indicated with the subscript $_{-1}$).

In the capitalistically organized agricultural sector, we assume that the very first production period is subject to a seed coefficient determined by the optimal fertility found in the subsistence sector. Subsequent production periods will face a situation where a less than optimal amount of nutrients is returned to the land given that not all of the product's consumption takes place at/near the production site resulting in: $n^A < n^{A^*}$. Furthermore, we impose that the working conditions in capitalistically organized sections are different than in the subsistence sector, that is: $h^A > h^S; I^A \geq I^S$. This decreases the measure of fertility and the technical coefficient of seed for the subsequent production periods. As a result we'll have that output is temporarily lower than what it was in the first production period (assuming that an equal amount of seed $S^A$ is replanted). We assume that capitalists are able to adjust to the new seed coefficient and regain the foregone output by planting more seeds — according to $a^A_S(F^A) < a^A_S(F^{A^*})$. The production periods in which adjustment towards the new seed coefficient takes place is called the *stabilizing* production phase and if other production conditions remain constant; the seed coefficient will stabilize once the aforementioned adjustment process takes place.

The main point here is that even if the initiation of a new agricultural production process faces a tumultuous start as the result of $a^A_S(F^A)$, capitalists take the inferior production circumstance as given and *do not* consider/are not aware of how $F^A$ is a function of on-site consumption and working conditions (material metabolism and purpose realisation). In sum, the following equations hold for the capitalist agricultural sector:

$$F^A = \frac{F^{max} + Z}{1 + e^{-k \cdot M^A}} - Z \qquad [4.24]$$

$$F^{A^*} = \frac{F^{max} + Z}{1 + e^{-k}} - Z \qquad [4.25]$$
$$= F^{S^*}$$

$$F^A_0 = F^{S^*} \qquad [4.26]$$

$$M^A = \frac{n^A}{n^{A^*}} \cdot \left(\frac{I^S \cdot h^S}{I^A \cdot h^A}\right)^{\alpha} \qquad [4.27]$$

$$n^{A^*} = b(Y^A - \frac{Y^A}{a^{A^*}_S}) \qquad [4.28]$$

$$n^A = b \cdot C^A_{W_a} \qquad [4.29]$$

$$a^A_S = F^A_{-1}(M^A_{-1})^m \qquad [4.30]$$

$$a^{A^*}_S = F^{A^m}_0 \qquad [4.31]$$
$$= a^S_S$$

Where $C^A_{Wa}$ represents the consumption of the agricultural product by agricultural workers. Having introduced a very simplistic representation of the state of the agro-ecological system, how it relates to the location of consumption and workplace conditions we can now turn to production in the agricultural sector.

**Agricultural production.** Capitalist agricultural production per unit of land takes place according to three inputs, seed $(S^A)$, an industrial circulating capital good $(Y^I_A)$[5] and labour $(L^A)$. The fixed coefficient production function then takes the following shape:

$$Y^A = min\{a^A_S(F^A_{-1}) \cdot S^A; a^A_I \cdot Y^I_A; l^A \cdot I^A \cdot L^A\} \qquad [4.32]$$

Where $a^A_S(F^A_{-1})$ is the output per unit of $S^A$, $a^A_I$ is the output per unit of $Y^I_A$ and $l^A$ is the output per unit of $L^A$ (in labour hours). The additional coefficient, $I^A \geq 1$ represents the intensity of the working day, by means of which capitalists are able to demand workers to perform a higher

[5] The most obvious example of industrial goods used up in agricultural production are a variety of tools such as plows, axes, shovels, sickles etc. But one can also think of hydrocarbons used for the purpose of e.g. mechanized ploughing and harvesting techniques. While it is more realistic to treat the tools as fixed capital instead of circulating capital which get used up during production, we will nevertheless treat them as circulating capital for the sake of simplicity. E.g. we assume that the circulating capital input is completely worn out after one production period has taken place. Any further mention of capital in this exposition will refer to circulating capital.

amount of labour per hour of production. For example, if $I^A = 2$, one hour of production does not reflect the output as a result of one hour of labour but two hours of labour.[6] As with the subsistence sector, the output is based on a given and fixed amount of hectares of land of uniform quality. The amount of labour hours expended in production is a function of the length of the work day $(h^A)$ and the number of workers $(N^A)$:

$$L^A = N^A \cdot h^A \cdot z \quad [4.33]$$

$$h^A \leq h_A^{max} \quad [4.34]$$

Where $h_A^{max}$ is an exogenously determined maximum length of the working day in the agricultural sector. Production takes place according to expected demand, which is assumed to be a function of worker consumption of the agricultural commodity, $C^A$, an exogenous demand for exports, $E^A$ and the respective seed-coefficient taken into account by capitalists. The target output for each production period then becomes:

$$Y^{A^T} = C^A_{-1} + E^A_{-1} + (Y^{A^T} / a^A_{S_{-R^a}})$$

$$Y^{A^T} = \frac{C^A_{-1} + E^A_{-1}}{1 - (1/a^A_{S_{-R^a}})} \quad [4.35]$$

The above indicates that worker and foreign demand are 1-period lagged variables while the seed coefficient is lagged by an exogenous period amount $R^a$. Changes in the seed coefficient occur due to changes in the level of soil fertility and we impose that it may take one or more periods before capitalists take such changes into account: $R^a \geq 1$. Based on the target output, $Y^{A^T}$, we'll have the following *necessary* inputs required for production in the prevailing period:

$$L^A_N = \frac{Y^{A^T}}{l^{AI}} \quad [4.36]$$

$$Y^A_{I_N} = \frac{Y^{A^T}}{a^A_I} \quad [4.37]$$

$$S^A_N = \frac{Y^{A^T}}{a^A_{S_{-R^a}}} \quad [4.38]$$

When it comes to the labour input, the sector assesses whether $L^A_N$ exceeds or falls behind the labour input at its disposal. Note that this is done according to the coefficient $l^{AI} = l^A \cdot I^A$, which represents an intensity-adjusted labour coefficient. If $L^A_N < \omega \cdot L^A_{-1}$ we assume the sector lays off workers. Exogenous parameter $\omega > 1$ captures the extent to which capitalists are able to engage in lay-offs due to institutionally determined worker protection. For example if

6 One can think of a re-organization of the production process as a mechanism which allows more labour to be performed during one hour of production.

$\omega = 1.1$, capitalists are only able to lay-off workers if hired labour exceeds necessary labour by 10%. If $L^A_N > L^A_{-1}$ we assume the sector adjusts working conditions or hires labour from the subsistence sector; a choice which depends on the constraints and costs of each option.
When it comes to the seed input, the sector equally assesses whether $S^A_N$ exceeds or falls behind the seed stock, $S^A_S$:

$$S^A_S = S^A_{S_{-1}} - (S^A_{-1} - S^A_{I_{-1}}) + (Y^A_{-1}/a^A_{S_{-(R^a+1)}}) \quad [4.39]$$

$$S^A = \begin{cases} S^A_N & \text{if} \quad S^A_S \geq S^A_N \\ S^A_S + S^A_I & \text{if} \quad S^A_S < S^A_N \end{cases} \quad [4.40] \qquad S^A_I = \begin{cases} 0 & \text{if} \quad S^A_S \geq S^A_N \\ S^A_N - S^A_S & \text{if} \quad S^A_S < S^A_N \end{cases} \quad [4.41]$$

Where $S^A_I$ represents seed imports when the seed stock fails to meet the necessary seed input for the prevailing production period. After the agricultural sector sets aside a part of its product as seed (required for production in the subsequent period), it is left with a marketable output. Here it is important to note that we assume that the decision concerning how much to seed to set aside is based on the reproduction of current output. In other words, we abstract away from expectations concerning a growth in demand and assume that the set-aside seed input is a function of the prevailing output, $Y^A$, and the seed coefficient, $a^A_{S_{-R^a}}$:

$$Y^A_M = Y^A - Y^A \cdot a^A_{S_{-R^a}} = Y^A \cdot (1 - (1/a^A_{S_{-R^a}})) \quad [4.42]$$

Total revenue for the agricultural sector then becomes:

$$R^A = p^A \cdot Y^A_M \quad [4.43]$$

Where $p^A$ is the price of the agricultural commodity. Profits are then expressed as revenue minus the costs of production while the profit rate is determined as profits over total costs:

$$P^A = R^A - p^I \cdot Y^I_A - w^A \cdot L^A \quad [4.44]$$

$$r^A = \frac{P^A}{p^A \cdot S^A + p^I \cdot Y^I_A + w^A \cdot L^A} \quad [4.45]$$

$p^I$ is the price of the industrial capital good and $w^A$ is the hourly wage-rate. Each period can be further characterized by a physical surplus which is determined as follows:

$$P^S_A = Y^A \cdot (1 - (1/a^A_{S_{-R^a}})) - C^A - E^A \quad [4.46]$$

In the case of a negative surplus, we assume that the agricultural sector imports an equivalent commodity in order meet both domestic and foreign demand. Hence, apart from seed imports the sector can also be subject to agr. commodity imports:

$$Y^A_{I_M} = \begin{cases} 0 & \text{if} \quad P^S_A \geq 0 \\ -1 \cdot P^S_A & \text{if} \quad P^S_A < 0 \end{cases} \tag{4.47}$$

Both seed imports and agr. commodity imports are funded out of savings given that we are abstracting away from a banking sector. We assume that there is no consumption out of profits meaning that all profits are saved:

$$S_A = S_{A_{-1}} + P^A + P^S_A - I_A \tag{4.48}$$

$$I_A = p^{A_I} \cdot (S^A_I + Y^A_{I_M}) \tag{4.49}$$

$$p^{A_I} = m^R \cdot p^A \tag{4.50}$$

The value of imports, $I_A$, is calculated by summing up both seed and agr. commodity imports. For the sake of simplicitity we assume that the price for imports is inflated by an exogenously determined rate, $m^R$ resulting in $p^{A_I} > p^A$. If savings fall below zero, the sector incurs a debt, $D^A$, which for the sake of simplicity is subject to a zero interest rate. When a debt is incurred, savings automatically become 0. As soon as accumulated savings meet or exceed accumulated debt, the debt is cancelled:

$$D^A = \begin{cases} 0 & \text{if} \quad S_A \geq 0 \\ 0 & \text{if} \quad S_A \geq D^A_{-1} \quad \Rightarrow S_A = S_A - D^A \\ -1 \cdot (S_A) + D^A_{-1} & \text{if} \quad S_A < 0 \quad\quad \Rightarrow S_A = 0 \end{cases} \tag{4.51}$$

**The industrial sector.** Unlike the capitalist agricultural sector, the industrial sector produces its output $(Y^I)$ using only two inputs, a part of its own output $(Y^I_I)$ and labour $(L^I)$. Here, we assume that any raw material/natural resource necessary for the industrial process is freely available and abundant. From an ecological perspective, this is a very harsh simplification, but we maintain it for the purpose of strictly highlighting the metabolic interaction between labour and ecological processes in the agricultural sector. In any case, the fixed coefficient production function then takes the following shape:

$$Y^I = min\{a^I_I \cdot Y^I_I ; l^I \cdot I^I \cdot L^I\} \tag{4.52}$$

As with the agricultural sector, the amount of labour hours expended in the industrial production process is a function of the length of the working day $(h^I)$ and the number of workers ($N^I$):

$$L^I = N^I \cdot h^I \cdot z \quad [4.53]$$

$$h^I \leq h_I^{max} \quad [4.54]$$

As the agricultural sector, the industrial sector is subject to an exogenous maximum length of the working day. Production takes place according to expected demand; a function of worker's consumption ($C^I$), exports ($E^I$) and the agricultural sector's demand for the industrial good ($Y_I^A$) in the previous period. Hence, the target output for each production period takes the following shape:

$$Y^{I^T} = Y^A_{I_{-1}} + (Y^{I^T}/a_I^I)$$

$$Y^{I^T} = \frac{Y^A_{I_{-1}} + C^I_{-1} + E^I_{-1}}{1 - (1/a_I^I)} \quad [4.55]$$

The industrial sector will then be subject to the following *necessary* inputs required for production in the prevailing period:

$$L_N^I = \frac{Y^{I^T}}{l^{II}} \quad [4.56] \qquad Y^I_{I_N} = \frac{Y^{I^T}}{a_I^I} \quad [4.57]$$

Just like the agricultural sector, an assessment is made on whether $L_N^I$ exceeds or falls behind the available labour input. If $L_N^I < \omega \cdot L^I_{-1}$, industrial workers will be laid off to the subsistence sector and if $L_N^I > L^I_{-1}$ the sector adjusts its working conditions or hires labour from the subsistence or agricultural sector (depending on the constraints and costs to each option).
When it comes to the industrial good input, the sector assesses whether $Y^I_{I_N}$ can be drawn from the industrial good stock/inventory, $Y_S^I$:

$$Y_S^I = Y^I_{S_{-1}} - (Y^I_{I_{-1}} - Y^I_{I_{I_{-1}}}) + (Y^I_{-1}/a_I^I) \quad [4.58]$$

$$Y_I^I = \begin{cases} Y^I_{I_N} & \text{if} \quad Y_S^I \geq Y^I_{I_N} \\ Y_S^I + Y^I_{I_I} & \text{if} \quad Y_S^I < Y^I_{I_N} \end{cases} \quad [4.59] \qquad Y^I_{I_I} = \begin{cases} 0 & \text{if} \quad Y_S^I \geq Y^I_{I_N} \\ Y^I_{I_N} - Y_S^I & \text{if} \quad Y_S^I < Y^I_{I_N} \end{cases} \quad [4.60]$$

Where $Y^I_{I_I}$ represents industrial good imports when the stock feels to meet the necessary industrial good input. After the industrial sector sets aside a part of the output, it is left with a marketable output and the decision on how much to set aside is based on the reproduction of current output. Hence, we'll have that:

$$Y_M^I = Y^I - Y^I \cdot a_I^I = Y^I \cdot (1 - (1/a_I^I)) \tag{4.61}$$

Total revenue for the industrial sector then becomes:

$$R^I = p^I \cdot Y_M^I \tag{4.62}$$

Where $p^I$ is the price of the industrial commodity. Profits are then expressed as revenue minus the costs of production while the profit rate is determined as profits over total costs:

$$P^I = R^I - w^I \cdot L^I \tag{4.63}$$

$$r^I = \frac{P^I}{p^I \cdot Y_I^I + w^I \cdot L^I} \tag{4.64}$$

Where $w^I$ is the hourly wage-rate in the industrial sector and the physical surplus in each period is determined as follows:

$$P_I^S = Y^I \cdot (1 - (1/a_I^I)) - Y_I^A - C^I - E^I \tag{4.65}$$

In the case of a negative surplus, the industrial sector can import an equivalent industrial commodity in order to meet both domestic and foreign demand:

$$Y_{I_M}^I = \begin{cases} 0 & \text{if} \quad P_I^S \geq 0 \\ -1 \cdot P_I^S & \text{if} \quad P_I^S < 0 \end{cases} \tag{4.66}$$

Each respective import, $Y_{I_I}^I$ and $Y_{I_M}^I$ are funded out of savings which we assume are equal to accumulated to profits given that we abstract away from consumption out of profits. Hence, we'll have that savings and total imports are expressed as follows:

$$S_I = S_{I_{-1}} + P^I + P_I^S - I_I \tag{4.67}$$

$$I_I = p^{I_I} \cdot (Y_{I_I}^I + Y_{I_M}^I) \tag{4.68}$$

$$p_I^I = m^R \cdot p^I \tag{4.69}$$

As in the agricultural sector we assume that the price for imports is inflated by an exogenously determined rate, $m^R$ resulting in $p^{I_I} > p^I$. Incurred debt, $D^I$ for the industrial sector is defined as:

$$D^I = \begin{cases} 0 & \text{if} \quad S_I \geq 0 \\ 0 & \text{if} \quad S_I \geq D^I_{-1} \quad \Rightarrow S_I = S_I - D^I \\ -1 \cdot (S_I) + D^I_{-1} & \text{if} \quad S_I < 0 \quad \Rightarrow S_I = 0 \end{cases} \tag{4.70}$$

**Wages**

Recalling what was mentioned in the introduction on the wage-rate in the subsistence sector $(w^S)$ we'll have that:

$$\begin{aligned} w^A &= p^A \cdot (b^S + \epsilon) + p^I \cdot b_I^A \\ &= p^A \cdot \underbrace{(\frac{Y^S - S^S}{L^S} + \epsilon)}_{=b_A^A} + p^I \cdot b_I^A \end{aligned} \tag{4.71}$$

$$\begin{aligned} w^I &= p^A \cdot (b^S + \epsilon) + p^I \cdot b_I^I \\ &= p^A \cdot \underbrace{(\frac{Y^S - S^S}{L^S} + \epsilon)}_{=b_A^I} + p^I \cdot b_I^I \end{aligned} \tag{4.72}$$

As mentioned before, the minimum agricultural wage-basket is equal to the average net product per labour hour in the subsistence sector (see eq. [4.10]). Assuming that the two agricultural commodities are homogeneous, the capitalist sectors must guarantee that their workers are able to purchase a physical amount of the agricultural commodity which is higher than $b^S$. The difference, which is captured by $\epsilon$ is assumed to be determined by class struggle and the bargaining dynamic between the respective labour forces and capitalists. One trivial way to account for class struggle or "worker's power", $WP$, and its subsequent impact on $\epsilon$ is given below:

$$WP = \frac{N^{WC}}{N^T} \tag{4.73}$$

$$\epsilon = f(WP_{-1}) \quad \text{with:} \quad \frac{d\epsilon}{dWP_{-1}} > 0 \tag{4.74}$$

Where $N^{WC}$ represents the size of the working class and $N^T$ represents the total working population, including the subsistence sector, $N^S$. Without introducing a specific functional form, we postulate that the wage-premium, $\epsilon$ is an increasing function of worker's power which essentially represents an employment measure.[7] In contrast, the industrial good component of the wage-basket, $b^I$ is taken as exogenously given. Throughout the rest of the paper we assume that the entire wage of both agricultural and industrial workers is spent on the consumption of commodities; workers are not subject to any savings. Physical consumption levels *per worker* at the end of each production period then become:

[7] For an increase of employment, the wage-basket in capitalist sectors will increase as the result of a higher average product in the subsistence sector as well as a higher wage-premium. We admit that the dual impact of employment on the wage-rates in capitalist sectors is redundant, one measure or the other would have been sufficient.

$$C^A_A = \frac{w^A}{p^A} \cdot h^A \cdot z$$
$$= (b^S + \epsilon) \cdot h^A \cdot z \qquad [4.75]$$
$$C^I_A = b^A_I \cdot h^A \cdot z \qquad [4.76]$$

$$C^A_I = \frac{w^I}{p^A} \cdot h^I \cdot z$$
$$= (b^S + \epsilon) \cdot h^I \cdot z \qquad [4.77]$$
$$C^I_I = b^I_I \cdot h^I \cdot z \qquad [4.78]$$

### Labour exploitation

Given that the subsistence sector is not capitalistically organized, we only treat the rates of exploitation in the capitalist agricultural and industrial sector. After taking into account the following procedure for deriving the rate of exploitation, it can easily be verified that the rate of exploitation in the subsistence sector is zero ($e^S = 0$) if the intensity of the working day to be equal to 1 ($I^S = 1$). Treating the rate of exploitation essentially means that we draw a comparison between the labour embodied in one unit of output and the labour embodied in the hourly wage-basket. The rate of exploitation in the agricultural sector ($e^A$) then takes the following shape:

$$e^A = \frac{\frac{Y^A}{L^A} \cdot \frac{L^{AI}}{Y^A} - V^A \cdot b^A_A - V^I \cdot b^A_I}{V^A \cdot b^A_A + V^I \cdot b^A_I} \qquad [4.79]$$

Evidently, $\frac{Y^A}{L^A}$ is equal to $l^A$, that is the output per unit of labour according to the length of the working day, the production period and number of workers (see eq. [4.33]). $e^A$ also depends on the variable $L^{AI}$, which expresses the total amount of labour hours used up in the production of output $Y^A$ *but* adjusted for the intensity of the working day:

$$L^{AI} = N^A \cdot h^A \cdot z \cdot I^A \qquad [4.80]$$
$$I^A \leq I^{max}_A \qquad [4.81]$$

Where $I^A$ is a parameter that adjusts the labour expended during production according to the intensity of the working day. We introduce an endogenous upper bound to $I^A$ by means of $I^{max}_A$. In the Marxist tradition the distinction between $L^A$ and $L^{AI}$ is also referred to as the difference between *labour power*, that which is sold to the capitalists, and *labour*, that which actually occurs during the production process. The variable $V^A$ in eq. [4.79] captures the *labour* *power* embodied in one unit of the agricultural commodity which comprises the wage-basket:[8]

$$V^A = \frac{1}{l^A} + \frac{V^A}{a_S^A} + \frac{V^I}{a_I^A} \qquad [4.82]$$

$$V^I = \frac{1}{l^I} + \frac{V^I}{a_I^I} \qquad [4.83]$$

Eqs. [4.82] and [4.83] essentially represent a system of two equations in two unknowns; $V^A, V^I$ since the technical coefficients $(l^A, l^I)$ are taken as given. This means that we are able to solve for both $V^A$ and $V^I$ such as to determine the rates of exploitation. Following eq. [4.79] it can easily be seen that the rate of exploitation is positive if:

$$\frac{Y^A}{L^A} \cdot \frac{L^{AI}}{Y^A} > V^A \cdot b_A^A + V^I \cdot b_I^A$$

Which means that the labour (adjusted for intensity) expended per hour per production must be strictly larger than the sum of *labour power* embodied in the hourly wage/consumption. Equivalently, in the industrial sector the rate of exploitation takes the following shape:

$$e^I = \frac{\frac{Y^I}{L^I} \cdot \frac{L^{II}}{Y^I} - V^A \cdot b_A^I - V^I \cdot b_I^I}{V^A \cdot b_A^I + V^I \cdot b_I^I} \qquad [4.84]$$

$\frac{Y^I}{L^I}$ is equal to $l^I$, the output of the industrial commodity per unit of labour according to the length of the working day. As with the rate of exploitation in the agricultural sector; $L^{II}$ represents the total amount of labour hours used up in the production of $Y^I$ but adjusted for the intensity of the working day:

$$L^{II} = N^I \cdot h^I \cdot z \cdot I^I \qquad [4.85]$$

$$I^I \leq I_I^{max} \qquad [4.86]$$

Where $I^I$ is a parameter that adjusts the labour embodied in output according to the intensity of the working day. As in the agricultural sector, $I^I$ is constrained by an endogenously determined upper bound, $I_I^{max}$. As mentioned in our literature review, the rate of exploitation in this model serves as a trivial measure of alienation or worker well-being. Higher levels of consumption decrease exploitation and thus increase worker well-being while higher labour intensities increase exploitation and decrease worker well-being.

[8] One can treat $V^A$ as a variable which captures the *labour* embodied in one unit of $Y^A$, but the point we aim to convey is based on the *social relation* between capitalists and workers. This social relation implies a difference when it comes to the purchase of labour. If a worker were to sell one unit of $Y^A$ in return for labour hours, we assume that the maximum amount of labour hours is dictated by $V^A$ which is based on *labour power* and not *labour*. This is the result of the fact that workers do not own the means of production with which they could organize labour should that one hour of production contains more than one hour of labour.

### Adjustment and coordination

In this section our aim is to introduce the reader to i) an adjustment mechanism in the face of labour shortages in either sector and ii) a coordination mechanism which determines how much each sector should produce in the very first production period.

**Adjustment to labour shortages.** As previously mentioned, we assume that each sector compares their *necessary* labour input to the prevailing labour fund. We impose that labour excesses are dealt with by means of lay-offs while labour shortages lead to either adapted working conditions or an increase of the labour force. Here, we clarify what happens in the face of labour shortages. When it comes to the agricultural sector, one can summarize the different strategies or options with respect to a labour shortage in Table 4.2 below:

| Strategy | Changes | Constraint | Substrategies |
|---|---|---|---|
| Increase in the intensity of the working day | $I^A \uparrow$ | $I^{max}$ | - |
| Increase of the length of the working day | $h^A \uparrow$ | $h^{max}$ | - |
| Draw on surplus labour | $N^S \downarrow, N^A \uparrow$ | $N^S_{min}$, $m^S_A$ | $h^A \uparrow$<br>$h^A \downarrow$, $h^A \geq h^S$ |

Table 4.2: Strategies as consequence of labour shortage in agr. sector

Both the intensity and length of the working day are limited by $h^{max}$ and $I^{max}$ respectively. These are institutionally determined limits, which we take as exogenous variables that more or less capture the general state of working conditions in the economy. Drawing on surplus labour in the subsistence sector is periodically constrained by $N^S_{min}$:

$$N^S_{min} = \frac{Y^S}{z \cdot h^S \cdot l^S} \quad [4.87]$$

This captures that the subsistence labour force will not fall below what is necessary to produce the exogenously determined subsistence output, $Y^S$. Furthermore, the exogenous parameter $m^S_A$ is introduced to determine the amount of workers that can be mobilized from the subsistence sector into the agricultural sector *per production period*:

$$N^M_{S \to A} = N^S \cdot m^S_A \quad [4.88]$$

Drawing on the surplus labour may subsequently lead to changes in $h^A$. Such changes depend on $N^M_{S \to A}$ and whether the increase of the labour force exceeds or falls short of the *necessary* labour input. An increase in $h^A$ and/or $N^A$ will increase demand for the commodities in the wage-basket leading to further adjustments in the consecutive target outputs of both sectors. The different strategies or options available for the industrial sector are summarized in Table 4.3 below:

| **Strategy** | **Changes** | **Constraint** | **Substrategies** |
|---|---|---|---|
| Increase in the intensity of the working day | $I^I \uparrow$ | $I^{max}$ | - |
| Increase of the length of the working day | $h^I \uparrow$ | $h^{max}$ | - |
| Draw on surplus labour | $N^S \downarrow, N^I \uparrow$ | $N^S_{min}, m^S_I$ | $h^I \uparrow$<br>$h^I \downarrow, h^I \geq h^S$ |
| Draw on agricultural labour | $N^A \downarrow, N^I \uparrow$ | $N^A_{min}, m^A$ | $h^I \uparrow$<br>$h^I \downarrow, h^I \geq h^S$ |

Table 4.3: Strategies as consequence of labour shortage in ind. sector

As under the agricultural sector, the option/strategy to increase the intensity of the working day is limited by the maximum intensity in the industrial sector and the same holds for the option to increase the length of the working day. Drawing on the surplus labour is constrained by $N^S_{min}$ introduced in eq. [4.87] and the amount of workers that can be mobilized from the subsistence sector into the industrial sector *per production period*:

$$N^M_{S \to I} = N^S \cdot m^S_I \quad \text{with:} \quad m^S_I < m^S_A \tag{4.89}$$

Here it is important to note that we impose that it is harder for the industrial sector to draw on the subsistence sector than it is for the agricultural sector ($m^S_I < m^S_A$). We justify this assumption by means of the fact that the labour performed in the agricultural sector is more similar to that of the subsistence sector as well as the geographical vicinity of the agricultural workplace to that of the subsistence sector. But the industrial sector is also able to draw on the agricultural labour force (while reverse mobilization is not considered) — constrained by exogenous variables $m^A$ and $N^A_{min}$. The amount of agricultural workers that can be mobilized from the agricultural sector into the industrial sector *per production period* is given by:

$$N^M_{A \to I} = N^A \cdot m^A \quad \text{with:} \quad m^A > m^S_I \tag{4.90}$$

The fact that $m^A > m^S_I$ assumes that for equal population sizes, $N^A = N^S$, the *per production period* amount of labour which can be mobilized from the agricultural sector into the industrial sector is higher than the amount of labour which can be mobilized from the subsistence sector into the industrial sector. In this case this assumption is justified on the basis that there exists a higher incentive for agricultural labourers to switch to the industrial sector due to the existence of a wage-differential. Hence, for the industrial sector there exists a trade-off between offering a higher wage and being more able to meet its labour shortage. The wage-differential is defined as follows:

$$w^I = w^A + \epsilon^I \qquad \text{if:} \quad N^I \uparrow \text{ and } N^A \downarrow \qquad [4.91]$$

$$\epsilon^I = b^{\epsilon}_A \cdot p^A \qquad \text{if:} \quad b^I_I < 0 \quad \text{with:} \quad b^{\epsilon}_A < b^I_A \qquad [4.92]$$

$$\epsilon^I = b^{\epsilon}_I \cdot p^I \qquad \text{if:} \quad b^I_I > 0 \quad \text{with:} \quad b^{\epsilon}_I < b^I_I \qquad [4.93]$$

Where $\epsilon^I$ represents the industrial wage-premium, which is evaluated in terms of an exogenously determined wage-premium basket based on either the agricultural or industrial commodity. Drawing on the subsistence or agricultural sector may lead to changes in $h^I$, depending on whether the increase of the labour force meets the necessary labour input. Just like in the agricultural sector, increasing the length of the working day, $h^I$, or drawing from the subsistence labour force will increase the demand for the goods contained in the wage-basket. Evidently, drawing on the agricultural labour force will drive the agricultural sector into a labour shortage problem, to which the agricultural labour force is able to adjust itself by means of the strategies mentioned in Table 4.2. Both sectors choose among strategies based firstly, on the ability to *directly* meet their labour requirement and secondly, on the costs of each feasible option (cost-minimization).

**Output coordination**

In the very first production period we take the techniques in each sector (and hence technical coefficients) and the demand for exports as given. With an exogenously defined output in the subsistence sector and size of the respective labour forces, one is able to derive the agricultural wage-basket. If the wage-basket consists of the industrial good in the first production period, its quantity is taken as given. This leads to the following system of equations in two unknowns.

$$Y_0^{A^T} = \frac{Y_0^{A^T}}{a_S^{A^*}} + \frac{Y_0^{A^T}}{l^A} \cdot b_A^A + \frac{Y_0^{I^T}}{l^I} \cdot b_A^I + E^A \qquad [4.94]$$

$$Y_0^{I^T} = \frac{Y_0^{I^T}}{a_I^I} + \frac{Y_0^{A^T}}{l^A} \cdot b_I^A + \frac{Y_0^{I^T}}{l^I} \cdot b_I^I + E^I \qquad [4.95]$$

Where the unknowns are; $Y_0^{I^T}, Y_0^{A^T}$. It is important to note that the coordination of target outputs in the very first production period is based on the optimal seed-coefficient, $a_S^{A^*}$. As previously mentioned, the impact of the production process and the related working conditions on the soil fertility are an aspect that capitalists fail to take into consideration.

### Accounting identities

Wrapping all of the above up, we'll have the following socio-economic accounting identities:

| | | |
|---|---|---|
| Total Population: | $N^T = N^S + N^A + N^I$ | [4.96] |
| Working Class: | $N_{WC} = N^A + N^I$ | [4.97] |
| Working Class Labour Hours: | $L^T = L^A + L^I$ | [4.98] |
| Total Output: | $Y = p^A \cdot Y^A + p^I \cdot Y^I$ | [4.99] |
| Growth Rate: | $g = \frac{Y - Y_{-1}}{Y_{-1}}$ | [4.100] |
| Total Consumption Agr. Comm.: | $C^{A^T} = C^A_A + C^I_A + E^A$ | [4.101] |
| Total Consumption Ind. Comm.: | $C^{I^T} = Y^A_I + C^I_A + C^I_I + E^I$ | [4.102] |
| Total Revenue: | $R^T = R^A + R^I$ | [4.103] |
| Total Profits: | $P^T = P^A + P^I$ | [4.104] |
| Total Savings: | $S_T = S_A + S_I$ | [4.105] |
| Avg. Rate of Exploitation: | $\bar{e} = \frac{e^A + e^I}{2}$ | [4.106] |

### Long-period positions

As the result of fluctuations in the agricultural seed coefficients and the related adjustments with respect to labour, the growth rate of the economy will ostensibly fluctuate. However, since we are not taking into account any internal or external mechanism which sets the economy on a permanent growth path, the agro-ecological system and exogenous expansion shocks are the *only* factors contributing to a deviation from a non-zero growth-rate. In periods where the growth rate is zero, we are then able to assess Sraffian long-period positions — characterized by a uniform rate of profit across sectors as the result of competition *within* and *between* sectors. The capitalistically organized sectors can be described with the following input/output table:

| | material inputs | | | | outputs | |
|---|---|---|---|---|---|---|
| | agr. com. | ind. com. | labour | | agr. com. | ind. com. |
| agr. prod. | $\boldsymbol{a^A_S}$ | $\boldsymbol{a^A_I}$ | $\boldsymbol{l^{A^I}}$ | $\rightarrow$ | 1 | - |
| ind. prod. | - | $\boldsymbol{a^I_I}$ | $\boldsymbol{l^{I^I}}$ | $\rightarrow$ | - | 1 |

Table 4.4: Inputs per unit of output in each sector

Where each technical coefficient in bold represents the inverse of the technical coefficients we have introduced in eqs. [4.32] and [4.52]. For example, we'll have that: $\boldsymbol{a_S^A} = a_S^A(F_{-1}^A)^{-1}$, which indicates we are now working with technical coefficients that represent the necessary input per unit of output instead of the output per unit of input. When it comes to labour coefficients however, we'll have that long-period positions are calculated with coefficients which are adjusted for intensity. For example, when $I^A = 1$ we'll have that $\boldsymbol{l^{A^I}} = \boldsymbol{l^A} = l^{A^{-1}}$ but when $I^A > 1$, we'll have that $l^{A^I} = l^A \cdot I^A$ and hence: $\boldsymbol{l^{A^I}} < \boldsymbol{l^A}$. In other words, increasing the intensity is treated as a type of labour productivity increase.

Following Sraffian terminology the representation in Table 4.4 indicates that the industrial commodity is a *basic* commodity in that it functions as an input *both* production processes. The agricultural commodity on the other hand, only functions as an input in its own production process which at first glance means that it is a particular type of non-basic commodity (Kurz and Salvadori, 1997: pp. 58-84). Usually this will lead to an analysis which is different from a framework strictly considering *basic* commodities. However, since the agricultural commodity is included in the physical wage-basket (which we assume to be *advanced*), our analysis falls in line with the usual basic commodity framework. In sum, the capitalist sectors are subject to the following input matrix, **A** and price vector, **p**:

$$\mathbf{A} = \begin{pmatrix} \boldsymbol{a_S^A} & \boldsymbol{a_I^A} \\ \boldsymbol{a_A^I} & \boldsymbol{a_I^I} \end{pmatrix} \quad [4.107] \qquad \mathbf{p} = \begin{pmatrix} p^A \\ p^I \end{pmatrix} \quad [4.108]$$

As previously specified, since the agricultural commodity does not enter the production process of the industrial commodity we'll have that $\boldsymbol{a_A^I} = 0$. The wage-basket matrix, **b**, labour input vector, **l** and uniform wage, $w$ are then specified as follows:

$$\mathbf{l} = \begin{pmatrix} \boldsymbol{l^{A^I}} \\ \boldsymbol{l^{I^I}} \end{pmatrix} \quad [4.109] \qquad w = \mathbf{bp} \quad [4.111]$$

$$\mathbf{b} = \begin{pmatrix} b_A^A & b_I^A \\ b_A^I & b_I^I \end{pmatrix} \quad [4.110]$$

If we are dealing with heterogeneous wages across the sectors due different qualities of labour, we'll have the following adaptation of the labour input vector (Kurz and Salvadori, 1997: pp. 322-325):

$$\mathbf{L} = \begin{pmatrix} l_A^A & l_I^A \\ l_A^I & l_I^I \end{pmatrix} \quad [4.112]$$

$$l_A^A = l^{A^I}$$
$$l_I^I = l^{I^I}$$

$$\mathbf{w} = \mathbf{bp} = \begin{pmatrix} w^A \\ w^I \end{pmatrix} \quad [4.113]$$

$$w = w^A \quad [4.114]$$

$$\hat{\mathbf{w}} = w^{-1}\mathbf{w} = \begin{pmatrix} w^A/w \\ w^I/w \end{pmatrix} \quad [4.115]$$

$$\mathbf{l} = \mathbf{L}\hat{\mathbf{w}} = \begin{pmatrix} \hat{l^A} \\ \hat{l^I} \end{pmatrix} \quad [4.116]$$

By means of the above transformations we are essentially reducing the differences in labour quality to equivalent differences in terms of quantity. Eq. [4.114] shows that we have chosen the wage in the agricultural sector as the baseline wage (we could have also chosen the wage in the industrial sector). Vector $\hat{\mathbf{w}}$ represents a relative wage vector which is multiplied with vector $\mathbf{L}$ in order to arrive at a labour coefficient vector $\mathbf{l}$ which is adjusted for the differences in labour quality reflected through the wage differentials. This results in the following two sets of system of equations, depending on whether wages are uniform or not:

**Uniform wages**

$$(1+r)(p^A \cdot a_S^A + p^I \cdot a_I^A + w \cdot l^{A^I}) = p^A$$
$$(1+r)(p^I \cdot a_I^I + w \cdot l^{I^I}) = p^I$$

**Heterogeneous wages**

$$(1+r)(p^A \cdot a_S^A + p^I \cdot a_I^A + w \cdot \hat{l^A}) = p^A$$
$$(1+r)(p^I \cdot a_I^I + w \cdot \hat{l^I}) = p^I$$

**General matrix notation**

$$(1+r)(\mathbf{Ap} + w\mathbf{l}) = \mathbf{p} \quad [4.117]$$

Since the agricultural commodity enters the physical and *advanced* wage-basket of industrial workers, $b_A^I > 0$, one can nevertheless argue that the agricultural commodity is a basic commodity and derive a solution to either set of simultaneous equations. With a given wage-basket, determined by the subsistence sector, and taking the price of the agricultural commodity as a numéraire, $p^A = 1$, the above systems of equations can be solved for the uniform rate of profit, $r$, and the relative price of the industrial commodity, $p^I$.

Ideally, we'll have that the *actual* rates of profit as calculated from eqs. [4.45] and [4.64] are equal to each other and hence $r$. However, even in long-period positions $r^A$ and $r^I$ can show either a positive or negative divergence from $r$ as the result of labour market conditions which constrain the equality between necessary labour inputs and actual labour inputs. This is important when it comes to *capitalization* and will discussed in subsequent subsections.

### Socio-economic progress by means of industrial expansion

As mentioned in the introduction, in the exposition at hand, socio-economic progress refers to an expansion of the industrial sector geared at the production of (additional) consumption and export goods. This shift bears a couple of implications and new set of assumptions:

- The expansion of the industrial sector is facilitated by accumulated savings which, in absence of a banking sector, directly translates to accumulated profits minus imported circulating capital and finished goods (see eq. [4.68]). The investment is assumed to acquire the fixed capital necessary for the deployment of a labour-saving technique. After the introduction of the new technique, we assume that the production process for the industrial consumption and export goods are exactly equal to that of the intermediate good/circulating capital consumed by the agricultural sector (no joint production).
- We assume an exogenous increase in the wages for workers in both the agricultural and industrial sector, otherwise the new consumption good cannot be purchased, hence $w^A \uparrow$ and $w^I \uparrow$. For the sake of simplicity we assume this increase to occur at the beginning of the production period in which the new consumption good is produced.
- Even under the introduction of a labour-saving technique where, $l^{I^*} < l^I$, the industrial sector will nevertheless require additional labour hours in order to meet a new target level of output, $Y^{I^T}$. This results in an adjustment to a labour shortage with all the repercussions thereof for the agricultural sector.

Successful expansion and subsequent stability of production in both sectors is assumed to pave the way for a second long-period position based on altered variables such as $l^I_I$, $a^A_S(F^A_{-1})$, $b^S$, $w^A$ and $w^I$.

**Output coordination.** Just like in the very first production period, under socio-economic progress, the *new* technique in the industrial sector, the industrial wage-basket and the demand for exports are taken as given. This leads to a similar system of equations in two unknowns; $Y^{I^T}_{t_{ex}}, Y^{A^T}_{t_{ex}}$, which can be solved to determine the new target outputs in both sectors.

$$Y^{A^T}_{t_{ex}} = \frac{Y^{A^T}_{t_{ex}}}{a^A_S} + \frac{Y^{A^T}_{t_{ex}}}{l^A} \cdot b^A_A + \frac{Y^{I^T}_{t_{ex}}}{l^I} \cdot b^I_A + E^A \quad [4.118]$$

$$Y^{I^T}_{t_{ex}} = \frac{Y^{I^T}_{t_{ex}}}{a^I_I} + \frac{Y^{A^T}_{t_{ex}}}{l^A} \cdot b^A_{I^*} + \frac{Y^{I^T}_{t_{ex}}}{l^{I^*}} \cdot b^I_{I^*} + E^{I^*} \quad [4.119]$$

### From appropriation to capitalization

As mentioned in the introduction, one of the aims of this paper is to assess the transition of a natural entity, in this case the agro-ecological system, from a state of appropriation to a state of capitalization. Before discussing the capitalization of the agro-ecological system, it is important to summarize the different time periods we are considering.

| **Pathway** | **Time period** | **Description** |
|---|---|---|
| 1/2 | $[t_0 : t_1)$ | First stabilizing period with occurrence of first metabolic rift |
| 1/2 | $[t_1 : t_{ex})$ | First long-period position |
| 1/2 | $[t_{ex} : t_2)$ | Socio-economic progress (potential exacerbation of metabolic rift) |
| 1 | $[t_2 : T]$ | Second long-period position |
| 2 | $[t_2 : t_{cap})$ | Second long-period position |
| 2 | $[t_{cap} : t_3)$ | Capitalization of fertility |
| 2 | $[t_3 : T)$ | Third long-period position |

Table 4.5: Summary of pathways in terms of time periods

In the table above one can read that there are two different pathways towards a post-expansion long-period position. One keeps fertility in an appropriated state (pathway 1) while the other results in the capitalization of fertility (pathway 2). Whether or not the economy embarks on the first or second pathway depends on whether the agricultural sector's *actual* rate of profit in the second long-period position, $r_2^A$ is higher or lower than the agricultural sector's *actual* rate of profit in the first long-period position, $r_1^A$. As mentioned before, even if the uniform rate of profit, $r_2$ turns out to be higher, labour market conditions can result in either positive or negative divergences in either sector. In any case, the existence of such a profit-differential and whether it is negative or not depends on the set of initial values and parameters as well as the combination of strategies deployed by the industrial and agricultural sector at the moment of expansion.

Essentially the capitalization of fertility implies the deployment of fertilizers and upon their introduction the production function in the agricultural sector is modified in the following way:

$$Y^A = min\{a_S^{A^*} \cdot S^A; a_I^A \cdot Y_I^A; a_F^A \cdot Y_F^A; l^{A^*} \cdot I^A \cdot L^A\} \quad [4.120]$$

Where $Y_F^A$ indicates the fertilizer input and $a_F^A$ represents the related technical coefficient. The introduction for fertilizers bears three implications. First, the seed coefficient, $a_S^{A^*}$ is restored to its optimum which is equal to the seed coefficient found in the subsistence sector (see eq. [4.31]). Second, the introduction of fertilizer increases labour productivity resulting in $l^{A^*} > l^A$. Third and most importantly, the introduction of fertilizers *dismantles* the metabolic relationship between labour and nature or more specifically between i) worker well-being and the ii) agro-ecological well-being. Fertility is now subject to the following functional form:

$$F^A_{cap} = \begin{cases} F^{A^*} = F^S & \text{if:} \quad Y^A_{FC} \leq max(\mathbf{n^{A^*}}) \\ F^A(D) = \dfrac{F^{max} + Z}{1 + e^{-kD^\gamma}} - Z & \text{if:} \quad Y^A_{FC} > max(\mathbf{n^{A^*}}) \quad \text{with:} \quad \gamma \geq 1 \end{cases} \qquad [4.121]$$

$$Y^A_{FC} = \sigma \cdot \sum_{t=t_{cap}}^{t} Y^A_F \quad \text{with:} \quad \sigma \in (0,1) \qquad [4.122] \qquad D = \frac{max(\mathbf{n^{A^*}})}{Y^A_{FC}} \qquad [4.123]$$

$$n^A_{cap} = 0 \qquad [4.124]$$

Eq. [4.121] captures that fertility remains at its optimum level as long as the accumulated fertilizer residual, $Y^A_{FC}$, is lower than the maximum amount of hypothetical optimal nutrients returned over time, $max(\mathbf{n^{A^*}})$. Where $\mathbf{n^{A^*}}$ represents a vector collecting the optimal amounts over time. When this is no longer the case, fertility relapses to its previous functional form, however, in terms of a measure of soil degradation, $D$, instead of the metabolic parameter, $M$. Exogenous parameter $\gamma$ is a compound parameter which captures both the characteristics of the soil and the fertilizer. The higher $\gamma$ is the more responsive the fertility is to soil degradation as the result of accumulated fertilizer and/or the higher the impact of accumulated fertilizer on fertility (e.g. due to the chemical properties of the fertilizer).

Another characteristic of the fertilizer in use is captured through the parameter $\sigma$ in eq. [4.122] which indicates the fraction of deployed fertilizer which is accumulated. Eq. [4.123] represents a trivial soil degradation parameter; the ratio between the maximum amount of hypothetical optimal nutrients returned and accumulated fertilizer. Finally, eq. [4.124] captures that the actual nutrients returned by the agricultural labour force after capitalization has taken place are zero. This is based on an assumed re-organization of production which disincentives the independent act of returning nutrients to the soil.

The capitalization of the agro-ecological system also results in an adaptation of the system of equations regarding the labour embodied in each the commodities — we'll have that:

$$V^A = \frac{1}{l^{A*}} + \frac{V^A}{a^A_S} + \frac{V^I}{a^A_I} + \frac{V^F}{a^A_F} \qquad [4.125]$$

$$V^I = \frac{1}{l^{I*}} + \frac{V^I}{a^I_I} \qquad [4.126]$$

The above goes to show that the labour embodied in the agricultural commodity increases as the result of fertilizer used and the labour embodied therein (exogenously given $V^F$ and $a^A_F$). Evidently, this feeds back into the rate of exploitation in both the industrial and agricultural sectors. Furthermore, the use of fertilizer as an input requires us to rewrite the system of equations related to the third long-period position. We do so by introducing an the vector $\mathbf{F} = \begin{pmatrix} \boldsymbol{a}_F^A \\ \boldsymbol{a}_F^I \end{pmatrix} = \begin{pmatrix} \boldsymbol{a}_F^A \\ 0 \end{pmatrix}$, which represents the technical coefficients regarding fertilizer as input. With the relative price of fertilizer, $p^F$, taken as a given, we'll have that:

**Uniform wages**

$$(1+r)(p^A \cdot \boldsymbol{a}_S^A + p^I \cdot \boldsymbol{a}_I^A + p^F \cdot \boldsymbol{a}_F^A + w \cdot \boldsymbol{l}^A) = p^A$$
$$(1+r)(p^I \cdot \boldsymbol{a}_I^I + w \cdot \boldsymbol{l}^I) = p^I$$

**Heterogeneous wages**

$$(1+r)(p^A \cdot \boldsymbol{a}_S^A + p^I \cdot \boldsymbol{a}_I^A + p^F \cdot \boldsymbol{a}_F^A + w \cdot \hat{\boldsymbol{l}}^A) = p^A$$
$$(1+r)(p^I \cdot \boldsymbol{a}_I^I + w \cdot \hat{\boldsymbol{l}}^I) = p^I$$

**General matrix notation**

$$(1+r)(\mathbf{Ap} + p^F\mathbf{F} + w\mathbf{l}) = \mathbf{p} \qquad [4.127]$$

### 4.1.3. A simulation approach to the metabolic rift

The previous section concludes our introduction to the equations and variables which are necessary for the simulation of an open economy and its interaction with the ecological processes its production depends on. In the current section, we summarize this interaction by means of a causal loop diagram in Figure 4.1. It is important to note that the arrows and their sign + or − *always* describe the relationship between variables based on the assumption of an *increase* in the variable from which the arrow departs.

The diagram only represents a *part* of the dynamics both the agricultural and industrial sectors are subject to in the face of instability in the agro-ecological system and hence *outside* of long-period positions. This is to say that not all of the variables in the actual simulation model are represented in Figure 4.1. Particularly of interest for us to highlight for the reader is the impact of positive changes in the agricultural target output, $Y^{A^T}$. Recalling eq. [4.35], we know that target output at time $t$ is a function of consumption and exports in the previous time period, time $t-1$. Assuming constant returns to scale and hence stable technical coefficients, we'll have that an increase in $Y^{A^T}$ requires an increase in labour input, $L^A$. Each of the strategies in Table 4.2 is represented in Figure 4.1 by means of the dotted circles below $Y^{A^T}$.

For example, if at time $t$ the agricultural sector increases $h^A$ as a means to meet its labour requirement, $L_N^A$, then one is able to read that a positive change in $h^A$ causes a positive feed back into $Y^{A^T}$. This feedback however, only occurs in the *subsequent* production period, at time $t+1$. In fact, any arrow characterized by a "//" indicates that the feedback occurs at either $t+1$ or $t+R_a$. From the diagram one can also read that a positive change in $h^A$ negatively affects soil fertility, $F^A$. Recalling eq. [4.30], a positive change in the measure of fertility will increase the seed coefficient measured as output per unit of input or $a_S^A$ at time $t+1$. Variable $R_a$ captures the time it takes for capitalists to "notice" changes in the seed-coefficient, where a positive change in the coefficient will negatively affect the target output $Y^{A^T}$ at time $t+R_a$.[9] The diagram also shows that an increase in the intensity of working day, $I^A$, bears no repercussions for target output in the subsequent period while it negatively affects fertility and positively effects the rate of exploitation, $e^A$. Finally, an increase of the agricultural labour results in a decrease of the subsistence sector population, $N^S$, which in turn holds a negative relationship towards agricultural output at $t+1$. In general, positive changes in the subsistence sector population are related to negative changes in the aggregate measure of worker power, $WP$, which following eqs. [4.73] and [4.74] holds a positive relationship towards the wage-premium earned above the subsistence wage-basket. Such an increase in the agricultural wage-basket will evidently result in a decrease of the exploitation rate in both the agricultural and industrial sectors.

Apart from the above, a positive change in the agricultural sector's target output, $Y^{A^T}$ will also feed back into the target output of the industrial sector, $Y^{I^T}$ at time $t+1$ since part of the industrial output is produced for the agricultural sector. Hence, when it comes to the industrial sector, we'll have that the strategy of increasing the length, $h^I$, and intensity, $I^I$ of the working day have repercussions which are similar to that of the agricultural sector. The only difference is that there aren't any feedbacks towards soil fertility in the agricultural sector. When it comes to an increase in the industrial labour force; drawing on the subsistence sector population bears the same implications as when the agricultural labour sector does so. The only strategy through which the industrial sector interacts with soil fertility is by drawing on the agricultural labour force, $N^A$. When the industrial sector increases its own labour forces through an increase of the agricultural labour force, the amount of the agricultural commodity consumed at the "production site" decreases. This impacts the fraction of nutrients returned with respect to the optimum (see eqs. [4.28] and [4.29]). Evidently, this change feeds back into the measure of soil fertility which in turn influences the $a_S^A$ and $Y^{A^T}$ at time $t+R_a$.

The red arrows in Figure 4.1 capture the additional causal links that are established once the industrial wage good is added to the worker's wage-basket as the result of socio-economic progress. Changes in $h^I, h^A$ and $N^S$ will then affect both the agricultural and industrial sector's target output. Finally, the green arrows and crosses, $\times$, capture the additional and redundant causal linkages if the capitalization of soil fertility takes place by means of fertilizer use. The length $(h^A)$, intensity $(I^A)$ and fraction of nutrients returned to the soil (by means of $N^A$) no longer influence $F^A$ since fertilizers artificially spike the fertility level to its optimum, $F^{A^*}$. Of

[9] All else constant, *negative* changes in the seed-coefficient, $a_S^A$, result in a decrease of *actual* output, $Y^A$. Whereas positive changes in $a_S^A$ bear no impact due to the fact that we are deploying a fixed-coefficient production function. As a result of this ambiguity, Figure 4.1 does not display any arrows between $Y^A$ and $a_S^A$.

course, this lasts as long soil degradation, $D$, as the result accumulated fertilizer residue is absent (see eqs. [4.121] and [4.122]).

The above discussion of the simulation diagram concludes Part I of our paper. Part II will provide an extensive discussion of the simulation results and highlights its main insights with respect to economy-ecology configurations.

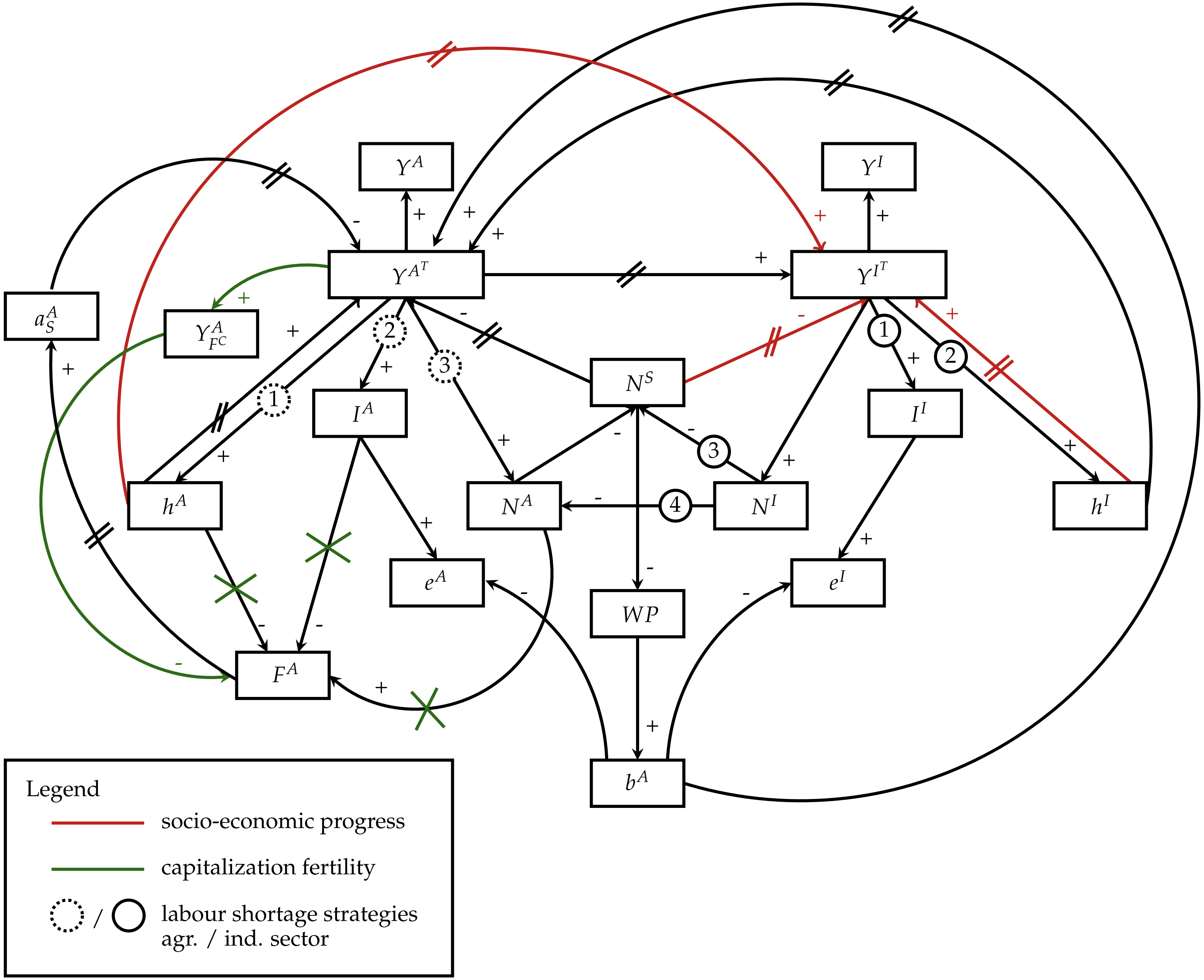



Figure 4.1: A simulation approach to the metabolic rift

# PART II

### 4.2.1. Simulation results

In discussing the results of our simulation runs, a distinction is made between a low worker protection (LWP) scheme and a high worker protection (HWP) scheme. In this context, worker protection captures the ease at which capitalists are able to lay off workers upon the adoption of a labour-saving technique or the introduction of a labour-saving production organization method. While the former is characterized by technological advances which decrease baseline labour coefficients $\boldsymbol{l^A}$ and $\boldsymbol{l^I}$, the latter is characterized by adjustments to labour intensities, $I^A$ and $I^I$. If actual labour coefficients for the agricultural sector are derived as $\boldsymbol{l^{AI}} = \frac{\boldsymbol{l^A}}{I^A}$, a labour-saving technique implies a reduction of the nominator while a labour-saving production organization method implies an increase in the denominator.

When capitalists engage in either of the adjustments, they may face labour excesses and thus have an incentive to lay-off workers which results in increased unemployment. The LWP scheme allows capitalists to lay-off workers when their rate of over-employment exceeds 10% of their *necessary* labour input. The HWP scheme allows capitalists to lay-off workers when their rate of over-employment exceeds 40% of their *necessary* labour input. We assume that the measure of worker protection is institutionally determined and therefore exogenous.

We have chosen to denote the inability to lay-off workers as worker protection, however, another way to look at the phenomenon is in terms of a preference for spare or excess labour capacity. In our modelling approach we don't assume continuous expansive investment out of retained profits. As the result of socio-economic progress retained profits, or savings, are used to fund the necessary machinery, but this is a one-shot investment. Retained profits are also used to fund imports in the face of supply shortages. All in all, we do not simulate any expansive investments which aim to increase the number of factories or hectares of land for the purpose of cultivation at a specific growth rate. This is, among other things, a result of the fact that we don't model population growth. Were we to simulate such expansive investments, however, it would make sense to additionally assume that capitalists "plan" accordingly and purposefully allow over-employment, or excess/spare labour capacity, in order to expand in some future. This was just a small side-step to highlight that there are different ways to look at the inability to lay-off workers. In absence of considerations on expansive investments, we stick to the worker protection view.

Our simulation is based on an equal set of scenarios for the LWP and HWP schemes. We discuss our results on the basis of a comparative statics exercise based on the variability of the newly introduced industrial commodity wage-basket, $b^{I^*}$, and industrial exports, $E^{I^*}$. We denote the joint impact of $b^{I^*}$ and $E^{I^*}$ on output levels as the expansion intensity.[10] For an overview of the

[10] The joint magnitude is measured as the difference between total output, $Y$, *at the moment of expansion* and one

parameters and initial values we've chosen, the reader is directed to Appendix C. An overview of the scenarios selected for a discussion of the results is provided below:

| **Scenario** | $b_{I^*}$ | $E^{I^*}$ | $N^M_{S\to I}$ | $N^M_{A\to I}$ | $h^I_{se_l}$ | $I^I_{se_l}$ | $N^M_{S\to A}$ | $h^A_{se_l}$ | $I^A_{se_l}$ |
|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.12 | 5000 | ✗ | ✗ | 6.4667* | 1.1667 | ✗ | 7.2667* | 1.0667* |
| **2** | 0.12 | 10000 | ✗ | ✗ | 6.4667* | 1.2 | ✗ | 7.2667* | 1.0667* |
| **3** | 0.14 | 0 | ✗ | ✗ | 6.4667* | 1.2667 | ✗ | 7.2667* | 1.1 |
| **4** | 0.14 | 5000 | ✗ | ✗ | 6.4667* | 1.2667 | ✗ | 7.2667* | 1.1333 |
| **5** | 0.18 | 5000 | ✗ | ✗ | 6.4667* | 1.5 | ✗ | 7.2667* | 1.2333 |
| **6** | 0.18 | 15000 | ✓ | ✗ | 7.9333 | 1.0667* | ✗ | 7.2667* | 1.2667 |
| **7** | 0.18 | 20000 | ✗ | ✗ | 9.3667 | 1.0667* | ✗ | 7.2667* | 1.2667 |
| **8** | 0.18 | 25000 | ✓ | ✗ | 8.1333 | 1.0667* | ✗ | 7.2667* | 1.2667 |
| **9** | 0.18 | 30000 | ✗ | ✗ | 9.6 | 1.0667* | ✗ | 7.2667* | 1.3 |
| **10** | 0.20 | 110000 | ✓ | ✗ | 10.7 | 1.2 | ✓ | 9.0333 | 1.2667 |
| **11** | 0.22 | 110000 | ✓ | ✗ | 11.7333 | 1.1667 | ✗ | 10.9667 | 1.2 |
| **12** | 0.23 | 100000 | ✗ | ✓ | 10.6667 | 1.2333 | ✓ | 11.4333 | 1.2333 |
| **13** | 0.25 | 100000 | ✗ | ✓ | 11.8333 | 1.2333 | ✓ | 12 | 1.2667 |

Table 4.6: Overview of scenarios

The aim of Table 4.6 is to summarize the different strategies taken by the industrial and agricultural sector in each of the scenarios. The scenarios are ordered according to the expansion intensity in an ascending fashion. When values of variables are marked by an asterisk (*), this means that they have not changed with respect to the preliminary phase/first long-period position. The strategies and related adjustments are equal across the LWP and HWP schemes.

Table 4.6 also indicates the absence of a concrete "turning point" between the strategy which increases the working day, $h^I \uparrow$, and the strategy which draws on subsistence labour, $N^I \uparrow$ , $N^S \downarrow$. For example, from scenario 6 to 9, there is an alternation between the former and latter strategy. The absence of this "turning point" is the result of the fact that the industrial sector is only able to mobilize a *fixed* amount of labourers from the subsistence sector. Hence, there exists a trade-off between i) increasing $h^I$ for the existing industrial labour force and ii) increasing both the labour force and $h^I$ to a lower extent. Expected costs are evaluated on the basis of $N^I \cdot h^{I^*} \cdot z \cdot w^I$ for the first strategy and $(N^I + N^M_{S\to I}) \cdot h^{I^{**}} \cdot z \cdot w^I$ for the second strategy. Where $h^{I^{**}} < h^{I^*}$ holds. One is able to verify that for a pair of succeeding scenarios (in terms of expansion intensity) where $(h^{I^*} - h^{I^{**}})^i = (h^{I^*} - h^{I^{**}})^{i+1}$ holds, the cost-minimizing strategy for scenario $i+1$ is to increase the length of the working day. Which is to say that for the higher expansion intensity the cost of hiring additional labour off-sets the benefit of a lower working day. Evidently, once the increase in the working day is such that $h^{I^*} > h^{max}$, the only possible strategy becomes to draw on the surplus labour force.

period before expansion takes place: $\Delta Y = Y_{se} - Y_{se-1}$

In any case, the following scenario-specific discussion will clarify that the variability of output levels, profit rates, unemployment, wage-rates, agro-ecological fertility and rates of exploitation do not *always* stand in a linear relationship to expansion intensity. This is because their variability is determined by the specific strategies the industrial and agricultural deploy in the face of labour shortages (see Tables 4.3 and 4.2). Additionally, the variability depends on whether we are considering a LWP (prone to unemployment) or HWP (less prone to unemployment) scheme.

In each of the following subsections, the development of variables for the scenarios which provide the most interesting results are displayed in figures. For a graphical overview of every scenario in terms of the variables we discuss, the reader is able to address Appendix D.

### The development of output

As mentioned in the previous section, the development of output from the moment of expansion up to the post-expansion long-period (and eventual post-capitalization long-period) depends on i) the expansion intensity, ii) the strategies deployed in the face of labour shortages and the iii) measure of worker protection. Figure 4.2 shows the development of sectoral outputs in scenarios 1 and 10 under the low worker protection scheme:

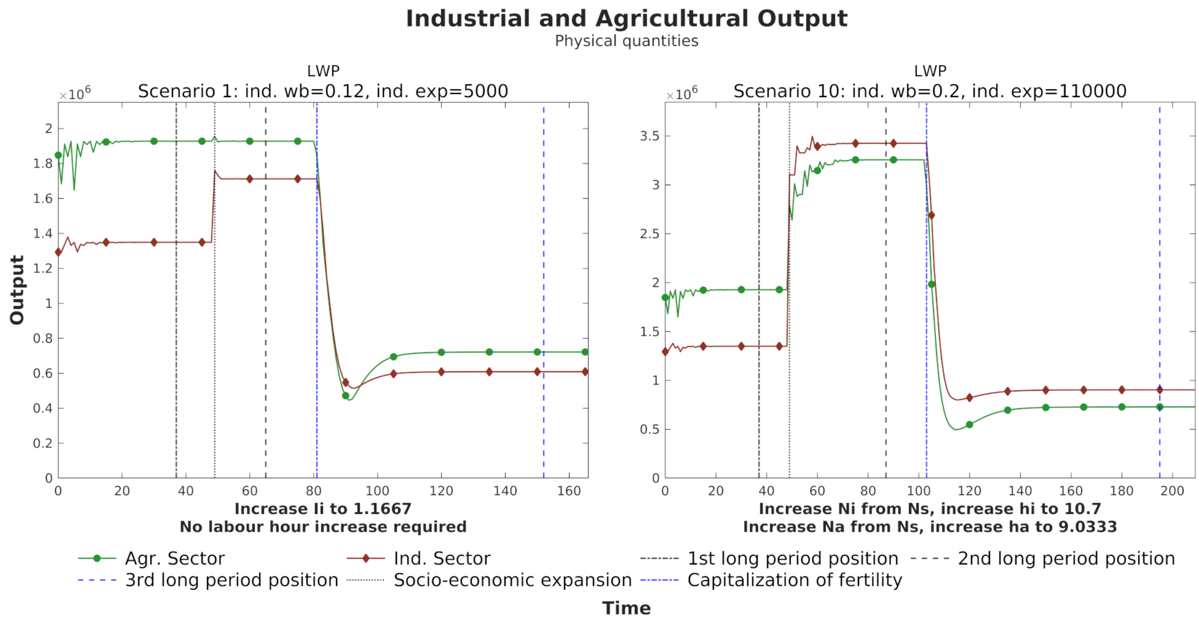



Figure 4.2: Development of output for scenarios 1 and 10 under LWP

The figure shows the *per period* output levels for the agricultural and industrial sectors. We chose to contrast scenario 1 with scenario 10 in order to highlight the evident effect of the expansion intensity on output levels in the post-expansion period. In discussing scenario 1, we see that at the moment of socio-economic expansion, the industrial sector experiences a significant increase in its output levels, while the increase for the agricultural sector is minimal. The figure also indicates a temporary peak in output levels for both sectors. The impermanence of this peak is related to the fact that the coordination mechanism among sectors at the moment of expansion is based on the absolute increase of labour hours — which has repercussions for the demand in each sector. In other words, the coordination mechanism does not foresee adjustments to labour intensities by either sector.

In the consecutive period, when target outputs are adjusted to demand in the previous period, output levels falter. For the agricultural sector, the expansion intensity is such that its output falls back to its pre-expansion level. For the industrial sector, the drop is less severe, and output remains at a level which is significantly higher. Scenario 10 on the other hand, is characterized by a stronger increase in output levels for *both* sectors. On the one hand this is related to the expansion intensity, on the other hand it is related to the fact that the coordination mechanism is unable to foresee additional increases in demand as the result of higher employment rates. Indeed, scenario 10 is characterized by labour mobilization from the subsistence sector into the industrial and agricultural sector. This feeds back into the agricultural wage-basket through i) an increase in the average product of the subsistence sector, $b^S \uparrow$ and ii) an increase in the wage-premium, $\epsilon \uparrow$, as the result of worker-power or employment.

The fluctuations in sectoral output levels until the post-expansion long-period position are the result of the agro-ecological system and the measure of fertility which feeds back into the production process. Increases in the working-day negatively impact fertility which subsequently increases the seed-coefficient, $\boldsymbol{a}_S^A$, and therefore the demand for the agricultural output. A higher level of agricultural output will require a higher level of industrial output given that it supplies the agricultural sector with an intermediate circulating capital good. If the strategy deployed by agricultural sector is to increase $I^A$ or $h^A$, this further decreases fertility and requires higher output levels. Eventually, this dynamic between the agro-ecological system output stabilizes.[11]

Finally, both scenarios are subject to capitalization, which result in a significant fall of output; below the levels in the preliminary phase. This is a result of the fact that capitalization, or the use of fertilizers, is modelled as the application of a new technique which results in ($\boldsymbol{l}^{\boldsymbol{A}} \downarrow$ , $\boldsymbol{a}_S^A \downarrow$). As such, the demand for agricultural output drastically decreases to the extent that over-employment exceeds 10% — allowing the agricultural sector to engage in lay-offs.

The increase in unemployment reduces the agricultural wage-basket and decreases demand even more all whilst these lower agricultural production levels feed back into the industrial sector. The reason why output levels experience a slight increase after the initial drop is related to soil degradation, as the result of fertilizer use, and its impact on the seed-coefficient. In most of the scenarios we are currently discussing, the resulting labour shortages as the result of soil

[11] The reason behind stabilization is related to the incorporation of the realistic assumption that both labour intensities and the length of the working day are not continuously variable. For example, if the necessary labour input and the labour coefficient dictate an increase in the working day of 0.0025 hours, it is impossible for capitalists in our simulation to introduce a working day of say 8.0025 hours. Instead, we impose that capitalists are able to adjust variables measured in hours up to $1/30^{th}$ of an hour, or 2 minutes. Which is still unrealistic, but less so than to allow an adjustment in the range of seconds.

degradation are addressed by means of adjustments in the labour intensity.
Under a HWP scheme, however, capitalization is not guaranteed to result in lay-offs and the absence of lay-offs prevents the drastic output decreases depicted in Figure 4.2. To illustrate this difference, Figure 4.3 displays scenario 1 for both a LWP and HWP scheme:

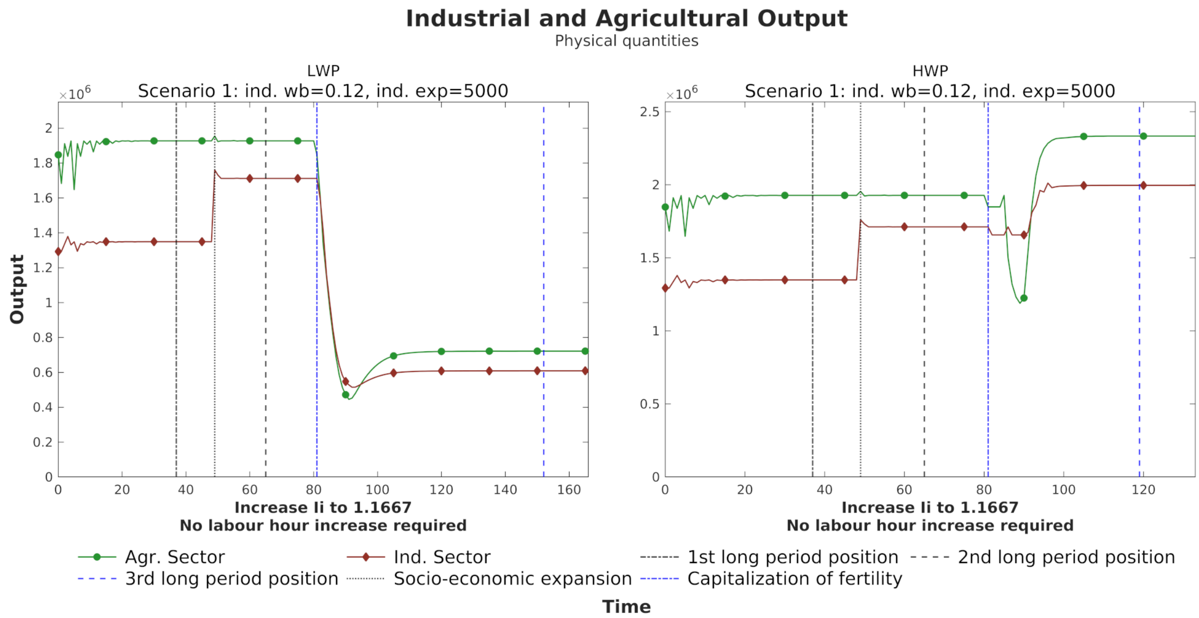



Figure 4.3: Development of output for scenario 1 under LWP and HWP

Under the HWP, capitalization results in a slight decrease of output as the result of the lower seed-coefficient, $a_S^A$. As soon as fertilizer residue build-up induces soil degradation, sectoral output levels temporarily increase as capitalists attempt to "catch up" to the upward adjustment in the seed-coefficient by assuming that fertility is at its pre-capitalization level. At that point in time, the *actual* seed-coefficient is lower than what is assumed by capitalists and this explains the short-lived peak a few periods after capitalization. As the intensity of soil degradation increases, agricultural output falls as the result of the inability of capitalists to predict how the agro-ecological system behaves and influences the seed-coefficient. After some periods, fertility stabilizes at its baseline level, $F^b$, and capitalists are finally able to catch-up to the upward adjustments in the seed-coefficient.
Due to the HWP and the inability to lay off workers, the agricultural wage-basket remains constant and sectoral outputs settle at levels which are higher than in the post-expansion long-period. Furthermore, adjustments in working conditions or the labour force are near absent, given that HWP additionally translates to a higher excess labour capacity. This means that both sectors are able to meet increased target outputs in the face of soil degradation. Not all scenarios result in the adoption of the capitalization technique. This is because its adoption is conditional on a negative differential between the post-expansion and preliminary agricultural rates of profit. Figure 4.4 illustrates the development of output for scenario 5 under a LWP and HWP scheme:

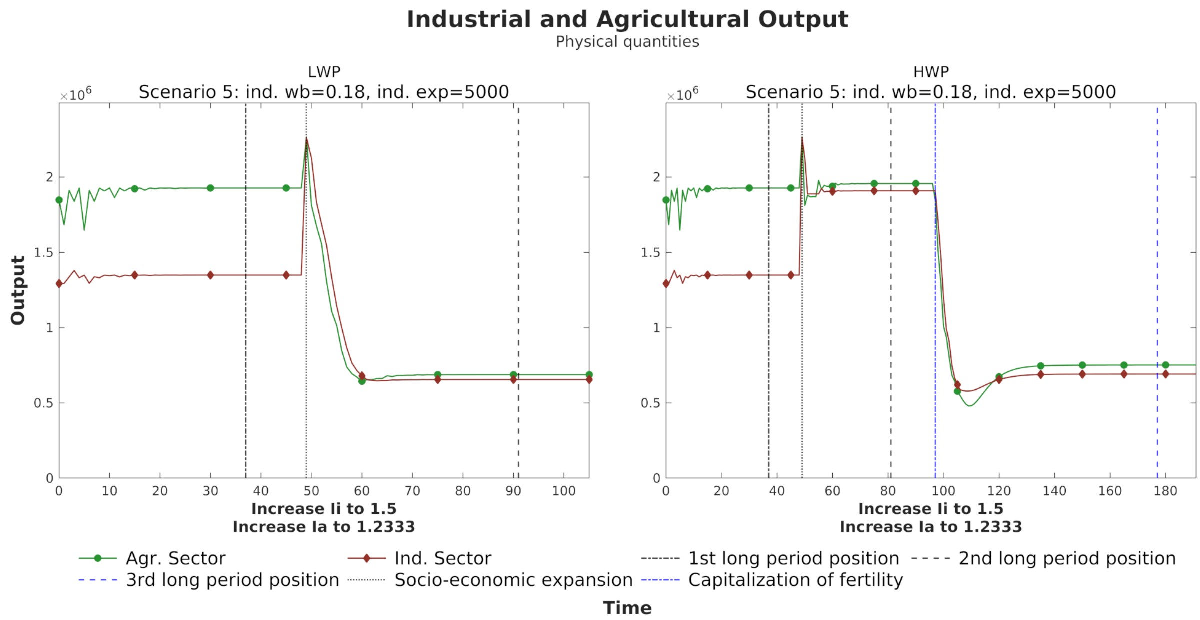



Figure 4.4: Development of output for scenario 5 under LWP and HWP

Under the LWP scheme, capitalization is absent as the result of strong adjustments to $I^I$ and $I^A$ and which result in over-employment rates that surpass 10%. Consequent lay-offs reduce the agricultural wage-basket through the mechanisms mentioned above result. This increases the agricultural profit-rates in the post-expansion long-period, *even if* the increase in $I^A$ results in significant upward adjustments to the seed-coefficient. This is not the case for scenario 5 under a HWP scheme; in the post-expansion period, over-employment is not sufficient to engage in lay-offs, $< 40\%$. In absence of a lower agricultural wage-basket, the labour intensity adjustments are not able to off-set the down-ward pressure on profit rates as the result of the addition of the industrial commodity to the wage-basket. When capitalization takes place, however, over-employment is such that the agricultural sector is able to engage in lay-offs — resulting in the previously discussed drop of sectoral output levels.

So far, the discussion on output levels has indicated that higher expansion intensities do not necessarily lead to capitalization. Some hints were given as to why this is the case, in the following section we will summarize uniform and actual profit rates to provide some additional clarifications on the adoption of capitalization.

### On the uniform and actual profit rates

| $b^{I*}$ | | $r$ | $\Delta r$ | $r^A$ | $\Delta r^A$ | $r^I$ | $\Delta r^I$ | $O^A$ | $O^I$ |
|---|---|---|---|---|---|---|---|---|---|
| | **PP** | 0.1322 | - | 0.1207 | - | 0.1213 | - | 2.3626% | 2.2476% |
| 0.12 | **S1*** | 0.1317 | - 5.17E-04 | 0.1192 | - 1.52E-03 | 0.1179 | - 3.32E-03 | 2.3626% | 2.8236% |
| | **S2** | 0.1370 | +4.81E-03 | 0.1245 | +3.79E-03 | 0.1123 | - 8.98E-03 | 2.3626% | 5.1473% |
| 0.14 | **S3** | 0.1489 | +1.67E-02 | 0.1215 | +7.15E-04 | 0.1097 | - 1.16E-02 | 5.2386% | 8.2886% |
| | **S4*** | 0.1567 | +2.45E-02 | 0.1155 | - 5.28E-03 | 0.1215 | +2.63E-04 | 8.0951% | 7.4265% |
| 0.18 | **S5** | 0.4548 | +3.23E-01 | 0.4394 | +3.19E-01 | 0.4401 | +3.19E-01 | 3.8102%[1] | 3.7475% |
| | **S6** | 0.3555 | +0.2233 | 0.3383 | +0.2175 | 0.3372 | +0.2159 | 4.5669%[2] | 4.2370% |
| | **S7*** | 0.1291 | - 0.0031 | 0.0976 | - 0.0231 | 0.0952 | - 0.0260 | 6.8804% | 7.0969% |
| | **S8*** | 0.1086 | - 0.0236 | 0.0977 | - 0.0230 | 0.0865 | - 0.0348 | 2.3176% | 4.5784% |
| | **S9** | 0.3681 | +0.2360 | 0.3523 | +0.2316 | 0.3509 | +0.2296 | 4.3820%[3] | 4.0580% |
| 0.20 | **S10*** | 0.0845 | - 0.0477 | 0.0754 | - 0.0453 | 0.0743 | - 0.0470 | 1.8784% | 2.0592% |
| 0.22 | **S11*** | 0.0821 | - 0.0501 | 0.0756 | - 0.0452 | 0.0692 | - 0.0521 | 1.3560% | 2.6373% |
| 0.23 | **S12*** | 0.0697 | - 0.0625 | 0.0670 | - 0.0538 | 0.0654 | - 0.0559 | 0.5567% | 0.8742% |
| 0.25 | **S13*** | 0.0672 | - 0.0650 | 0.0626 | - 0.0581 | 0.0581 | - 0.0632 | 0.9773% | 1.8561% |

[1] The over-employment rates in the period prior to lay-offs are $O^A = 18.357\%$ and $O^I = 23.567\%$
[2] The over-employment rates in the period prior to lay-offs are $O^A = 10.098\%$ and $O^I = 10.452\%$
[3] The over-employment rates in the period prior to lay-offs are $O^A = 11.695\%$ and $O^I = 11.814\%$

Table 4.7: Profit rates and over-employment in the post-expansion lpp under LWP

Table 4.7 summarizes the uniform and actual profit rates for each of the scenarios in the post-expansion long-period position under a LWP scheme. The first row, marked as **PP**, indicates the profit and over-employment rates in the preliminary phase or first long-period position. The first column groups the scenarios according to the industrial wage-basket which is a key determinant for the post-expansion uniform rate of profit. Profit-rate differentials, indicated by $\Delta$, are based on the difference between post-expansion and first long-period position profit rates. Additionally, we show the sectoral measures of over-employment in each of the scenarios. Scenarios which are marked by an asterisk (*) serve to indicate that capitalization takes place.

The first thing to notice is that the magnitude of the profit differentials, particularly in low expansion scenarios, is particularly small. Still, our simulation model takes the slightest difference between actual agricultural profit rates in the first and post-expansion long-period positions as an incentive for capitalization. This behaviour can be adjusted by taking into account a minimum threshold of divergence and would be an improvement for next simulation runs.

Another observation is related to a discrepancy between the *uniform* and *actual* profit rate differentials. Under scenarios 2 and 3 for example, the uniform and agricultural profit rate in the post-expansion long-period are higher than they were in the first long-period. The industrial profit rates however, are lower. This is related to the fact that the industrial sector adjusts $l^I$ but is unable to lay off workers. In general, over-employment results in a divergence from the *uniform* rate of profit. In scenarios 2 and 3 the divergence is such that the *actual* industrial profit rate decreases under the post-expansion long-period. Scenario 4 tells a similar story but with respect to the agricultural sector. While scenario 3 is also subject to a an adjustment of $l^A$, it is not such that over-employment decreases the actual profit rate in the agricultural sector. In scenario 4 however, it is.[12]

In assessing the *uniform* rate of profit against against expansion intensities, the movement of the variables in relationship to each other depend on the labour shortage strategies deployed by each sector and the ability to lay off workers. For scenarios 1 to 4, there seems to be an increasing trend in the uniform rate of profit as expansion increases. This is the result of adjustments to $l^I$ and potentially $l^A$ which, in conjunction with $\boldsymbol{l}^{\boldsymbol{I}^*}$, offset the downward pressure on $r$ as the result of an increased wage-rate. Scenario 5 is characterized by a drastic increase in $r$, because the adjustments to $l^A$ and $l^I$ are such that the sectors are able to engage in lay-offs. This decreases $b^A$ and drives $r$ upwards. Scenarios 6 to 9 are subject to the same wage-rate increase, but are additionally characterized by the ability to lay-off workers, resulting in significantly higher profit-rates. The profit rate under scenario 9 is higher, due to a higher adjustment to labour intensity, $l^A$, as the result of a higher $E^I$.

For scenarios 7 and 8 however, the difference between the profit rates is related to the fact that scenario 8 is subject to labour mobilization from the subsistence sector into the industrial sector. This increases employment and hence $b^A$, ultimately resulting in a lower profit rate compared to scenario 7 where employment remains constant. Finally, for scenarios 10 through 13, it seems that there is a decreasing trend in the *uniform* rates of profit as the result of the increasing trend in $b^{I^*}$. However, as under the previous scenarios, this is not the only determinant. In comparing scenario 10 and 11 for example, the difference in profit rates is minimal and again, this is related the fact that labour mobilization is higher under scenario 10 than under 11. Hence the absence of an increased $b^A$ under scenario 11, is able to offset some of the impact of a higher $b^{I^*}$ on $r$.

The above discussion on expansion intensities, profit rate differentials, over-employment and divergences from the uniform profit rate aim to show that the relationship between capitalization and expansion intensities is not so straight-forward in our simulation model. Expansion intensity dictates the overall increase in $Y^A$ and $Y^I$ which in turn determine the strategies deployed by each of the sectors. In the end, it is the repercussion of these strategies which dictate *actual* profit rates and hence the implementation of capitalization. Table 4.8 summarizes over-employment and profit-rates under a HWP:

[12] In general, the higher the measure of over-employment the higher the divergence from the uniform rate of profit. The sector with a higher measure of over-employment is usually subject to a lower profit rate. For scenarios 6 and 9 actual profit rates are not higher for the sector with the lowest amount of over-employment. We assume that this the result of rounding errors in the simulation.

| $b^{I*}$ | | $r$ | $\Delta r$ | $r^A$ | $\Delta r^A$ | $r^I$ | $\Delta r^I$ | $O^A$ | $O^I$ |
|---|---|---|---|---|---|---|---|---|---|
| | **PP** | 0.1322 | - | 0.1207 | - | 0.1213 | - | 2.3626% | 2.2476% |
| 0.12 | **S1*** | 0.1317 | - 5.17E-04 | 0.1192 | - 1.52E-03 | 0.1179 | - 3.32E-03 | 2.3626% | 2.8236% |
| | **S2** | 0.1370 | +4.81E-03 | 0.1245 | +3.79E-03 | 0.1123 | - 8.98E-03 | 2.3626% | 5.1473% |
| 0.14 | **S3** | 0.1489 | +1.67E-02 | 0.1215 | +7.15E-04 | 0.1097 | - 1.16E-02 | 5.2386% | 8.2886% |
| | **S4*** | 0.1567 | +2.45E-02 | 0.1155 | - 5.28E-03 | 0.1215 | +2.64E-04 | 8.0951% | 7.4265% |
| 0.18 | **S5*** | 0.1986 | +6.64E-02 | 0.1167 | - 4.08E-03 | 0.1156 | - 5.63E-03 | 16.5799% | 18.5616% |
| | **S6*** | 0.1089 | - 0.0233 | 0.0939 | - 0.0268 | 0.0903 | - 0.0309 | 3.1910% | 3.8203% |
| | **S7*** | 0.1291 | - 0.0031 | 0.0976 | - 0.0231 | 0.0952 | - 0.0260 | 6.8804% | 7.0969% |
| | **S8*** | 0.1086 | - 0.0236 | 0.0977 | - 0.0230 | 0.0865 | - 0.0348 | 2.3176% | 4.5784% |
| | **S9*** | 0.1341 | +0.0019 | 0.0962 | - 0.0245 | 0.0979 | - 0.0234 | 8.4497% | 7.6157% |
| 0.20 | **S10*** | 0.0845 | - 0.0477 | 0.0754 | - 0.0453 | 0.0743 | - 0.0470 | 1.8784% | 2.0592% |
| 0.22 | **S11*** | 0.0821 | - 0.0501 | 0.0756 | - 0.0452 | 0.0692 | - 0.0521 | 1.3560% | 2.6373% |
| 0.23 | **S12*** | 0.0697 | - 0.0625 | 0.0670 | - 0.0538 | 0.0654 | - 0.0559 | 0.5567% | 0.8742% |
| 0.25 | **S13*** | 0.0672 | - 0.0650 | 0.0626 | - 0.0581 | 0.0581 | - 0.0632 | 0.9773% | 1.8561% |

Table 4.8: Profit rates and over-employment in the post-expansion lpp under HWP

Under the HWP scheme, scenarios 2 and 3 are the only two for which the agricultural profit rate differential is positive in the post-expansion long-period. This goes to show that the positive *uniform* and *actual* agricultural profit differentials in scenarios 2 and 3 are unrelated to the ability to lay-off workers. Instead, they are related to decreases in $\boldsymbol{l^{II}}$ and $\boldsymbol{l^{AI}}$ (for scenario 2), which off-set the downward pressure of $b^{I^*}$ on the uniform and agricultural rate of profit. When it comes to the industrial profit rate differential, however, it is negative as the result of over-employment.

Each of the scenarios under the HWP scheme are equal to their counterpart under the LWP scheme, except for scenarios 5, 6 and 9 where profit-rate differentials are driven by the ability to lay off workers.

Scenario 5 is characterized by stark adjustments to both $I^I$ and $I^A$ which feed back into the uniform profit rate and adjust it upwards. At the same time, over-employment rates are extremely high for both sectors but do not surpass the 40% requirement under the HWP scheme. This results in stark divergences from the uniform profit rate as well as a negative agricultural profit rate differential. Scenario 6 on the other hand, is characterized by overall negative profit rate differentials and this is driven by labour mobilization from the subsistence sector and its influence on $b^A$. Furthermore, the measure of over-employment in scenario 6 under the HWP scheme is lower than under the LWP scheme. This is related to the fact that the higher excess labour capacity in the agricultural sector allows the agricultural labour sector to meet its labour shortages in the face of an increase in $b^A$ and $\boldsymbol{a_S^A}$. Finally, scenario 9 is similar to scenario 5 in that it is characterized by a positive *uniform* profit rate differential and negative *actual* profit rate differentials. This is the result of over-employment in the face of adjustments to both $h$ and $I$ which were based on output targets under a coordination mechanism which does not take into account adjustments to $I$.

| $b^{I^*}$ | | $O^A_{cap}$ | $O^I_{cap+2}$ | $r$ | $r^A$ | $r^I$ | $O^A$ | $O^I$ |
|---|---|---|---|---|---|---|---|---|
| 0.12 | **S1** | 30.4315% | 14.0744% | 0.3924 | 0.3879 | 0.3850 | 1.7738% | 1.7461% |
| 0.14 | **S4** | 38.5834% | 17.6013% | 0.4145 | 0.4122 | 0.4094 | 0.9379% | 1.2221% |
| 0.18 | **S7** | 39.7627% | 16.0852% | 0.3783 | 0.3778 | 0.3734 | 0.2436% | 1.1697% |
| | **S8** | 33.7389% | 13.8654% | 0.3736 | 0.3732 | 0.3719 | 0.1907% | 0.3908% |
| 0.20 | **S10** | 35.6208% | 14.7738% | 0.3957 | 0.3926 | 0.3902 | 1.3468% | 1.3347% |
| 0.22 | **S11** | 37.2981% | 15.4320% | 0.3820 | 0.3806 | 0.3799 | 0.5974% | 0.4771% |
| 0.23 | **S12** | 37.2702% | 15.3094% | 0.3731 | 0.3731 | 0.3626 | 0.0255% | 2.4824% |
| 0.25 | **S13** | 39.1499% | 16.0817% | 0.3491 | 0.3489 | 0.3422 | 0.0865% | 1.5824% |

Table 4.9: Profit rates and over-employment in the post-capitalization lpp under LWP

Table 4.9 summarizes over-employment and profit rates in the post-capitalization long period position for each of the scenarios in which it takes place under the LWP scheme. The first column assesses the agricultural over-employment rate the moment the capitalization is adopted (indicated with subscript $_{cap}$). The second column assesses over-employment rates in the industrial sector 2 periods after the capitalization is adopted (indicated with subscript $_{cap+2}$), when the reduction in demand feeds into the industrial target output.

Under the LWP scheme, where over-employment rates must exceed 10%, it is clear that each of the scenarios induce lay-offs and increase unemployment. This feeds back into the uniform and agricultural profit rates which are significantly higher (compared to the post-expansion long-period) as the result of a decreased agricultural wage-basket. Comparing scenarios 1 and 4, we see that a higher rate of over-employment in the latter scenario results in higher profit rates, even if $b^{I^*}$ is higher under scenario 4. The higher profit rate for scenario 4 is also the result of higher adjustments to $I^A$ and $I^I$ due to fertilizer induced soil degradation. On the one hand, higher measures of over-employment drive post-capitalization long-period profit rates upwards due to stronger decreases in $b^A$. But it is also important to take into account subsequent adjustment of labour intensities which feed back into $\boldsymbol{l}^{AI}$ and $\boldsymbol{l}^{II}$ as well as the size of $b^{I^*}$. All in all, over-employment is massively reduced in the post-capitalization long-period which results in a lower divergence between actual and uniform rates of profit. Table 4.10 summarizes the same variables for the HWP scheme. In this case, scenarios indicated with an asterisk (*) are those that have not been subjected to capitalization under the LWP scheme.

| $b^{I*}$ | | $O^A_{cap}$ | $O^I_{cap+2}$ | $r$ | $r^A$ | $r^I$ | $O^A$ | $O^I$ |
|---|---|---|---|---|---|---|---|---|
| 0.12 | **S1** | 30.4315% | 6.2397% | 0.0728 | 0.0602 | 0.0689 | 3.3365% | 0.7782% |
| 0.14 | **S4** | 38.5834% | 11.3930% | 0.0883 | 0.0528 | 0.0867 | 9.7950% | 0.3422% |
| 0.18 | **S5*** | 50.8114% | 53.5825% | 0.3745 | 0.3556 | 0.3740 | 6.8714% | 0.1412% |
| | **S6*** | 34.8037% | 8.8412% | 0.0626 | 0.0395 | 0.0600 | 6.8005% | 0.5263% |
| | **S7** | 39.7627% | 12.2675% | 0.0751 | 0.0397 | 0.0701 | 10.7293% | 0.9941% |
| | **S8** | 33.7389% | 9.6313% | 0.0626 | 0.0423 | 0.0556 | 5.9569% | 1.4089% |
| | **S9*** | 42.3225% | 33.0237% | 0.2851 | 0.2708 | 0.2040 | 5.4818% | 18.8286% |
| 0.20 | **S10** | 35.6208% | 7.9398% | 0.0525 | 0.0258 | 0.0398 | 7.4479% | 2.5564% |
| 0.22 | **S11** | 37.2981% | 9.4538% | 0.0549 | 0.0237 | 0.0431 | 8.7767% | 2.3773% |
| 0.23 | **S12** | 37.2702% | 7.7304% | 0.0479 | 0.0169 | 0.0428 | 8.7546% | 1.0401% |
| 0.25 | **S13** | 39.1499% | 9.2018% | 0.0454 | 0.0098 | 0.0441 | 10.2439% | 0.2363% |

Table 4.10: Profit rates and over-employment in the post-capitalization lpp under HWP

The first noticeable difference between the LWP and HWP schemes is the near-absence of an increase in the profit rates as the result of capitalization. The only exceptions are scenarios 5 and 9, which are subject to over-employment rates $> 40\%$. Profit rates are higher under scenario 5 due to the fact that *both* sectors are able to engage in lay-offs while under scenario 9 only the agricultural sector is able to do so. Scenarios 7 and 13 illustrate that the over-employment rates are only slightly below what is required to engage in lay-offs. In scenarios where lay-offs are absent, over-employment rates nonetheless decrease because of soil degradation and the resulting increase in sectoral outputs. In sum, the near-absence of lay-offs under the HWP maintains keeps employment levels constant and wage-rates high even when capitalization takes place.

The aim of this section has been to show the interplay between the intensity of expansion, profit rates and over-employment *conditional* on the labour shortage strategies deployed by the agricultural and industrial sectors under LWP and HWP schemes. In the following section we reiterate these findings but from the worker's vantage point by addressing the development of unemployment and wages.

### Unemployment and wage-rates

As mentioned earlier, employment levels fluctuate according to the strategies deployed by each sector in the face of labour shortages. Increasing labour intensities drives over-employment and this may result in lay-offs if over-employment rates surpass 10% under the LWP scheme or 40% under the HWP scheme. While the previous section already engaged in a discussion of the repercussions of this interplay in terms of additional degradation of the agro-ecological system through capitalization, this sections serves to graphically depict the development of unemployment and wage-rates. This is done through Figure 4.5 which shows the development of unemployment for scenarios 1 and 2 under a LWP scheme and Figure 4.6 which depicts the development of wages for the same scenarios.

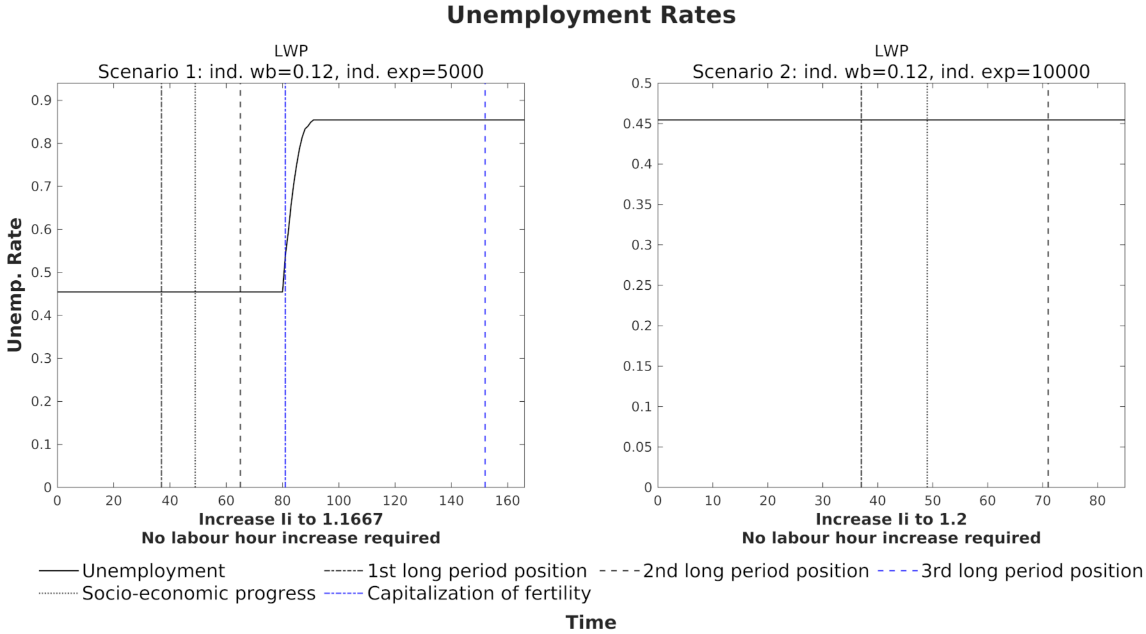



Figure 4.5: Development of unemployment for scenarios 1 and 2 under LWP


Figure 4.6: Development of wages for scenarios 1 and 2 under LWP

The initial level of unemployment is the result of arbitrary initial values of the respective labour forces (see Appendix C). The comparison between scenario 1 and 2 under the LWP scheme shows that the increase of $I^I$ under both scenarios is not sufficient to engage in lay-offs. Hence, the rate of unemployment remains constant in the post-expansion period. Scenario 1, however, is subject to capitalization which drives the over-employment rates to the point that lay-offs are possible. Recalling Table 4.7, for scenario 2 the increase in $I^I$ is such that the agricultural rate of profit is higher than it was under the first long-period. Since $I^I$ is not sufficient to engage in lay-offs, the unemployment rate is kept constant.

When it comes to wages, we see an equal increase in the post-expansion period as the result of the same magnitude of $b_I^{I^*}$ for both scenarios. Capitalization under scenario 1, however, decreases the wage-rate as the result of unemployment. The slight adjustments to the wage-rate in long-period positions are the result of new relative prices. When adjustments to intensity are high enough, scenarios under the LWP scheme result in increased unemployment associated with higher profit rates and the absence of capitalization. Under the HWP scheme however, this is not the case. Figures 4.7 and 4.8 depict the development of unemployment rates and wages for scenario 5 under the LWP and HWP schemes.

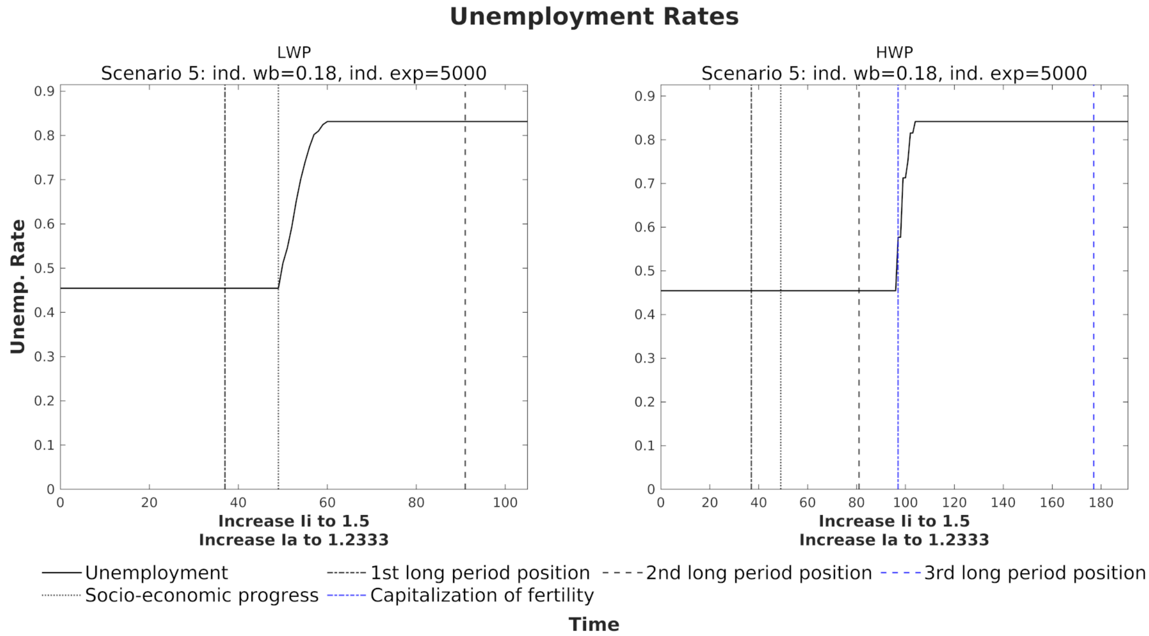



Figure 4.7: Development of unemployment for scenarios 5 under LWP and HWP

Under the HWP scheme, the inability to engage in lay-offs keeps the unemployment rate constant in the post-expansion period resulting in a negative agricultural profit rate differential. Subsequent capitalization allows lay-offs to take place — increasing unemployment. When it comes to wages, a close look at Figure 4.8 shows that wages under the HWP scheme are slightly lower than under the LWP scheme. In fact, unemployment under the HWP is higher at the end of the simulation run. This is related to the fact that capitalization decreases the labour-coefficient, where capitalization-induced lay-offs are higher than those driven by labour intensity increases. In scenarios where the industrial strategy is to increase the length of the working day, $h^I$, the development of unemployment, wages as well as the presence of capitalization depends on the adjustments to agricultural labour intensities and subsequent over-employment rates.

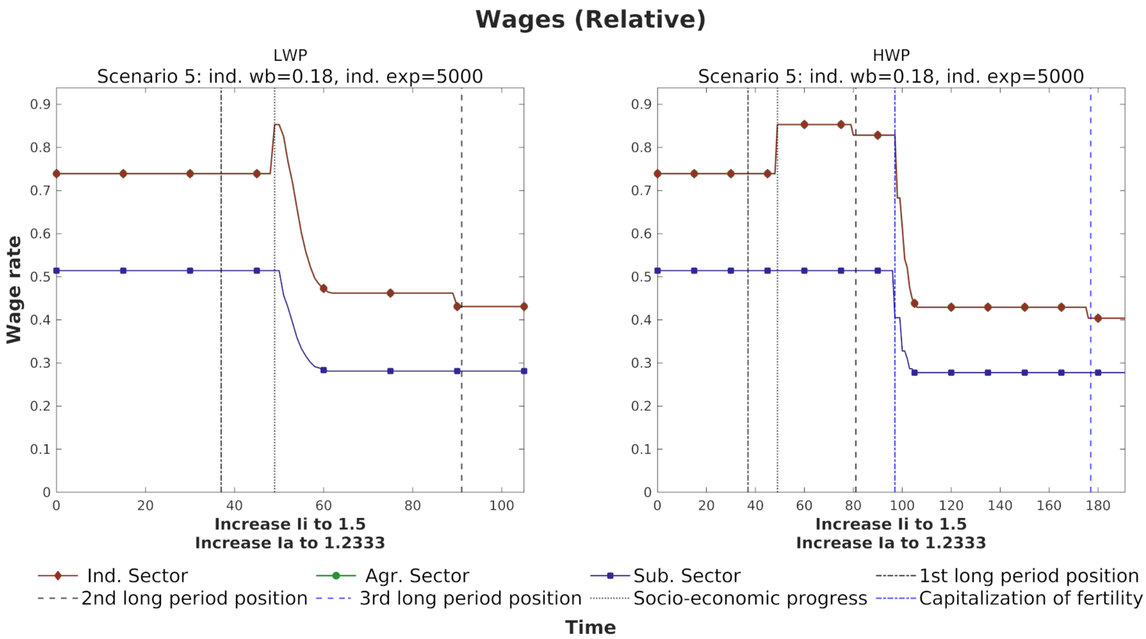



Figure 4.8: Development of wages for scenarios 5 under LWP and HWP

What happens in scenarios where the strategy is to draw on external labour forces? Figures 4.9 and 4.10 depict the development of unemployment and wage-rates for scenarios 6,10,12 and 13 under the LWP scheme. In the period of expansion, scenario 6 indicates a slight and temporary decrease in the unemployment rate as the result of labour mobilization from the subsistence sector into the industrial sector. The decrease is temporary given the ability of the agricultural sector to engage in lay-offs as the result of an increased $I^A$.

Scenario 10 is subject to a higher degree of labour mobilization from the subsistence sector given that *both* sectors require an expansion of their labour forces. Scenarios 12 and 13 are characterized by the fact that the industrial sector draws on the agricultural labour force. In the face of this labour shortage, the agricultural sector subsequently draws on the subsistence sector. In conclusion, in the post-expansion long-period unemployment rates are highest under scenario 6 and lowest under scenario 10. Capitalization under the LWP results in lay-offs which increases unemployment. In scenario 13 however, the initial increase is slightly offset as the agricultural labour force is forced to draw on the subsistence sector in the face of soil degradation. This is the result of the inability to further adjust $h^A$ and $I^A$ which are constrained by institutionally set limits, $h^{max}$ and $I^{max}$.

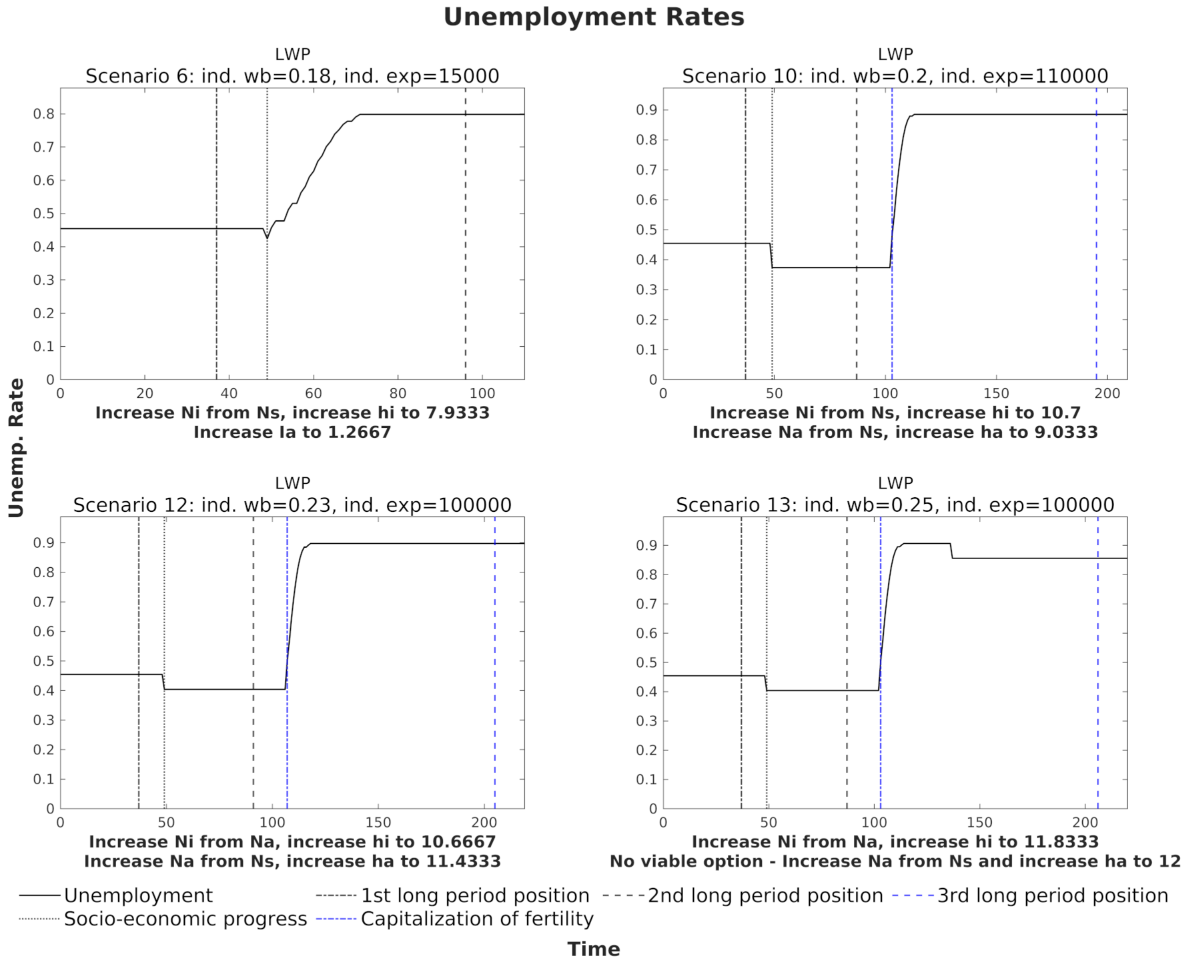



Figure 4.9: Development of unemployment for scenarios 6, 10 ,12 and 13 under LWP

Directing the attention to Figure 4.10, the development of wages follows the level of unemployment while additionally taking into account the addition of the industrial commodity to the wage-basket. Regardless of a higher $b^{I^*}$ under scenario 10, wages at the end of the simulation run are higher under scenario 6. This is because capitalization-induced unemployment is stronger than labour-intensity induced lay-offs. Scenarios 12 and 13 are characterized by a wage-differential between the agricultural and industrial sector. This is the result of the necessary wage-premium, $\epsilon^I$, which the industrial sector introduces in order to draw on the agricultural labour force. Both wages follow the same general trend in the period of expansion and in the period of post-capitalization. Namely, the wage increases upon the introduction of the industrial commodity and consequently decreases as the result of capitalization-induced unemployment.

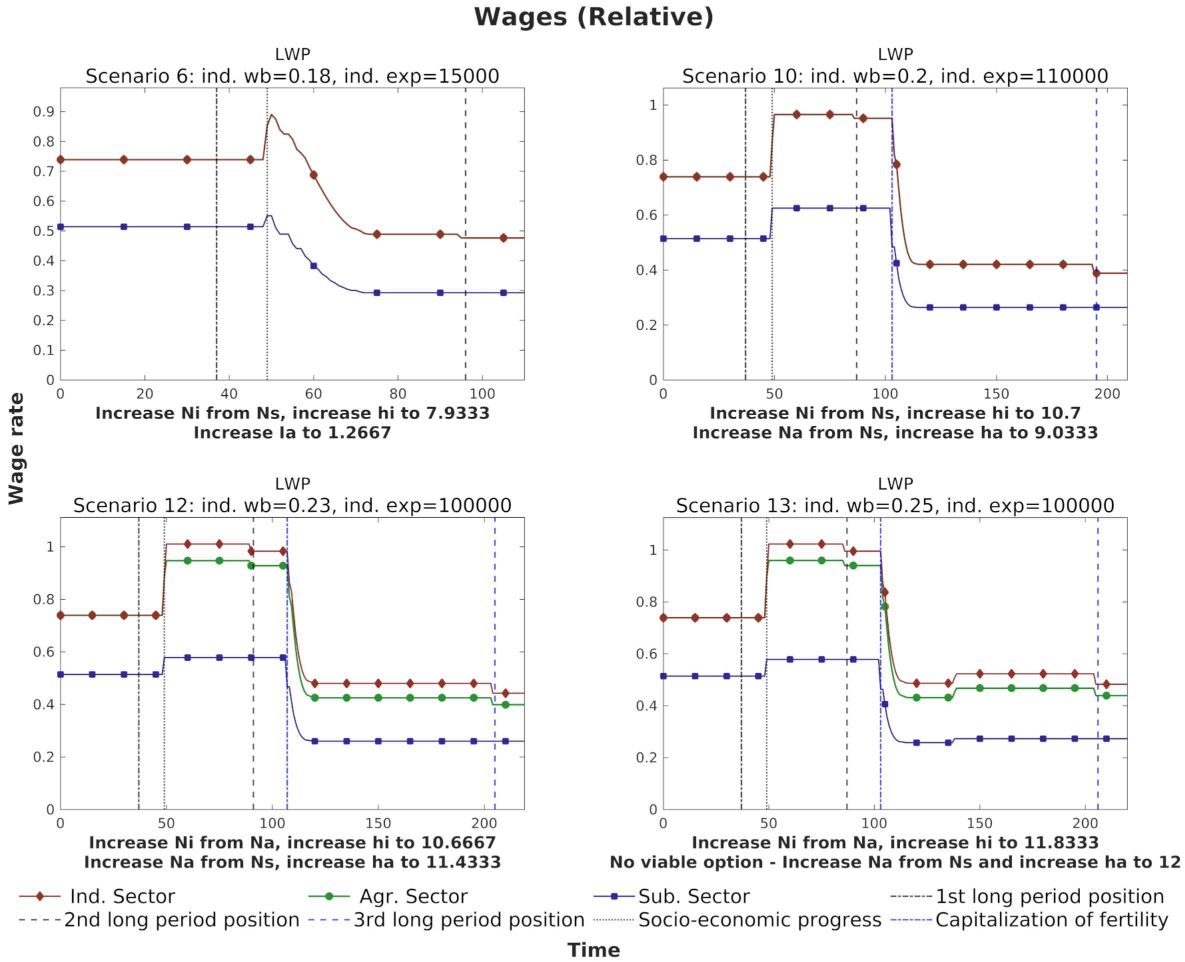



Figure 4.10: Development of wages for scenarios 6, 10, 12 and 13 under LWP

Evidently, drawing on either the subsistence or agricultural labour force under the HWP scheme results in lower unemployment and therefore higher wages due to the absence of capitalization induced lay-offs. Scenarios which are characterized by both sectors drawing on subsistence labour result in the lowest unemployment rates (scenario 10). This is followed by scenarios characterized by the agricultural sector drawing on the subsistence sector while the industrial sector draws on the agricultural labour force (scenarios 12 and 13). Finally, scenarios in which only the industrial sector draws on the subsistence labour force are subject to the lowest decrease in unemployment since $N^M_{S\to A} > N^M_{S\to I}$ (scenario 6).

For the sake of clarity, Figure 4.11 shows the development of wages for scenarios 10 and 12 for both the LWP and HWP schemes.

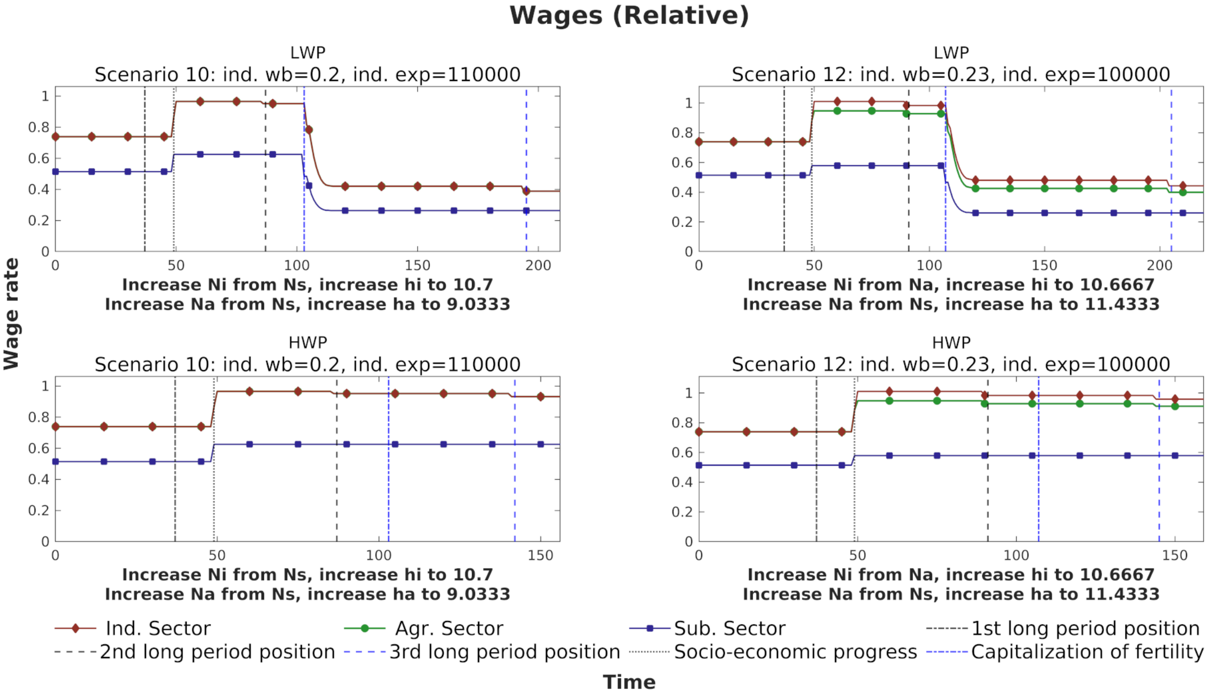



Figure 4.11: Development of wages for scenarios 10 and 12 under LWP and HWP

## The development of agricultural fertility

Having described the development of distributional variables; wages, profits and unemployment, we now turn to an assessment of agricultural fertility. As mentioned in Part I, the development of fertility is a function of a physiological component, $\frac{n^A}{n^{A*}}$ and a cognitive component related to working conditions in the agricultural sector, $\left(\frac{I^S \cdot h^S}{I^A \cdot h^A}\right)^\alpha$, relative to the prevailing working conditions in the subsistence sector. Changes in output and distributional variables influence the physiological component while the strategies deployed in the face labour shortages influence the working conditions component.

Changes in fertility feed back into the production processes since we assume that decreases in fertility increase the seed-coefficient, $\boldsymbol{a}_S^A$. This results in increased target and actual output levels for the agricultural and the industrial sector which provides the intermediate good. An important assumption in our simulation model is that capitalists are not aware of the physiological and working condition components that impact fertility, hence in response to fertility-induced labour shortages the response is to adjust either $h^A$ or $I^A$ upwards. The *capitalization* of the agro-ecological system, entails the use of fertilizers as means to artificially and more importantly *temporarily* increase fertility levels to their maximum level. This brings down the seed-coefficient, $\boldsymbol{a}_S^A$, to its minimum.

We coin capitalization as an instance of the *metabolic rift* since it involves a complete rupture between the agro-ecological process and the labour process: both the physiological and working conditions component seize to influence the development of fertility when fertilizers are used. When fertilizer residues are sufficiently high (see [4.123]), soil degradation takes place which gradually brings fertility to its baseline level. Given the metabolic rift, the development of fertility upon capitalization is equal across all scenarios under both the LWP and HWP schemes. The pre-capitalization development of fertility, however, varies according to expansion-intensities and the strategies adopted by the agricultural sector as a means to meet labour shortages. Figure 4.12 depicts this development for scenarios 1, 3, 5 and 7 under the LWP scheme:

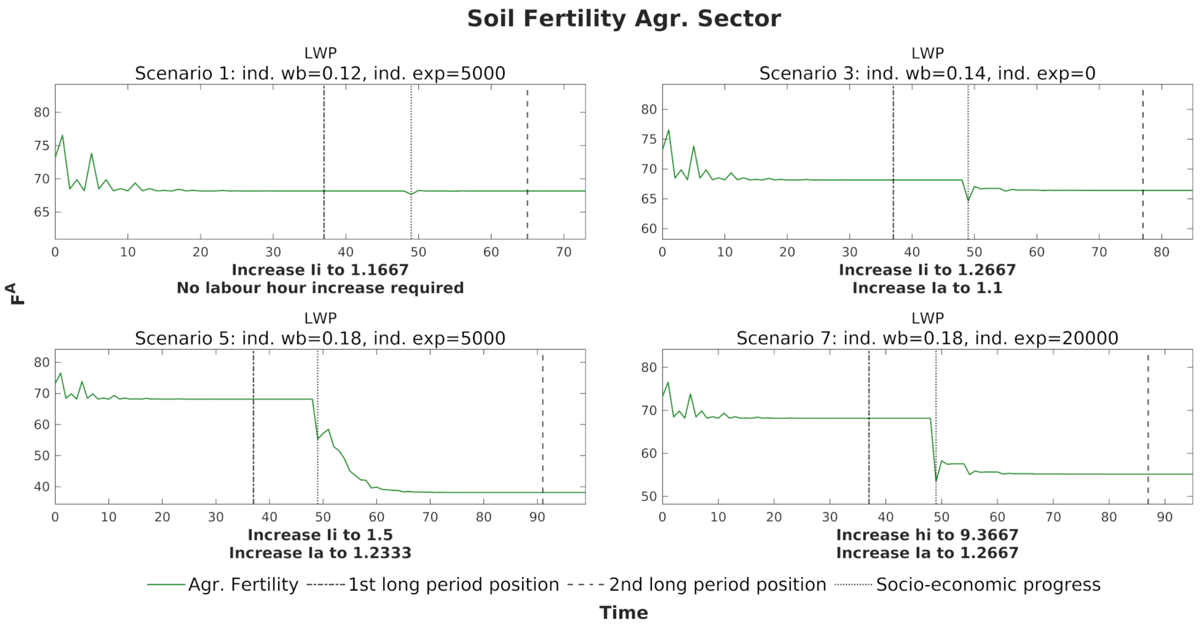



Figure 4.12: Development of fertility for scenarios 1, 3, 5 and 7 under the LWP scheme

Each scenario reveals the same fluctuation in what we call the *stabilizing* production period; before the first long-period position. The higher seed-coefficient as the result of $h^A > h^S$ causes adjustments in the agricultural organization of production which then proceed to impact $F^A$. Each scenario is characterized by the same increase in $I^A$ as a means to meet an increase in target output due to a decrease in fertility. Eventually this decreases fertility even more, but the graphs also indicate temporary increases. These are the consequence of fluctuations in $\frac{n^A}{n^{A^*}}$ due to the fact that it takes $R_a > 1$ periods for capitalists to take note of changes in the seed-coefficient. As a result there is a divergence between the agricultural target $(Y^{A^T})$ and realized output $(Y^A)$, where $Y^A < Y^{A^T}$ due to repercussions in the agro-ecological system.

A lower realized output however, reduces $n^{A^*}$ while $n^A$ stays constant, hence the physical determinant of fertility increases. In a way this can be seen as the agro-ecological system's intrinsic recovery mechanism, which is off-set or dampened as soon as capitalists re-organize production around the *actual* seed-coefficient. The moment of socio-economic expansion is characterized by the fact that the agricultural sector produces a target output which is not adjusted for the strategies actually deployed to meet labour shortages. Hence, fertility peaks downwards as the result of a higher $n^{A^*}$ while $n^A$ remains constant.

If the agricultural sector does not require to adjust its labour intensity, fertility stabilizes to its previous levels as soon as the agricultural sector adjusts its target output to consumption in the previous period (scenario 1). If $I^A$ is adjusted however, fertility will stabilize at a lower level (scenarios 2, 5 and 7). Comparing scenarios 5 and 7 we see that post-expansion levels of fertility are higher under scenario 7 than under 5, even if the latter is subject to a lower adjustment to $I^A$. This is because scenario 5 is characterized by lay-offs which decrease $b^A$ and therefore $n^A$. Figure 4.13 summarize the development of fertility for scenarios in which labour mobilization takes place.

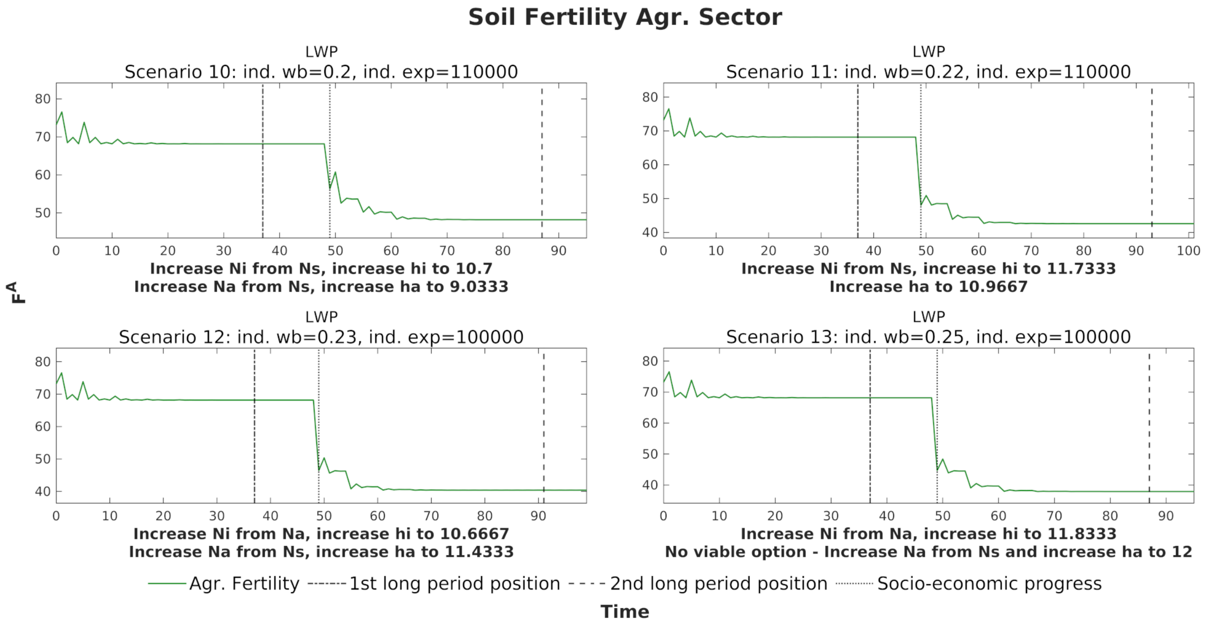



Figure 4.13: Development of fertility for scenarios 10, 11, 12 and 13 under the LWP scheme

Comparing scenarios 10 and 11, we see that the post-expansion period fertility level is lower under the former scenario. This is the result of a stronger adjustment to $h^A$ as well as the absence of labour mobilization under scenario 11. Labour mobilization dampens the negative effect of adjustments to working conditions as the result of a higher $b^A$ and therefore $n^A$. The difference in fertility levels under scenario 12 and 13 are also the result of stronger adjustments to $h^A$ and $I^A$ (see Table 4.6), though they are less pronounced as the result of the smaller difference between the adjustments.

Does higher worker protection translate to higher fertility levels? For scenarios in which lay-offs are prevented due to HWP this is indeed the case, as shown by Figure 4.14 which compares scenarios 5 under the LWP and HWP schemes:

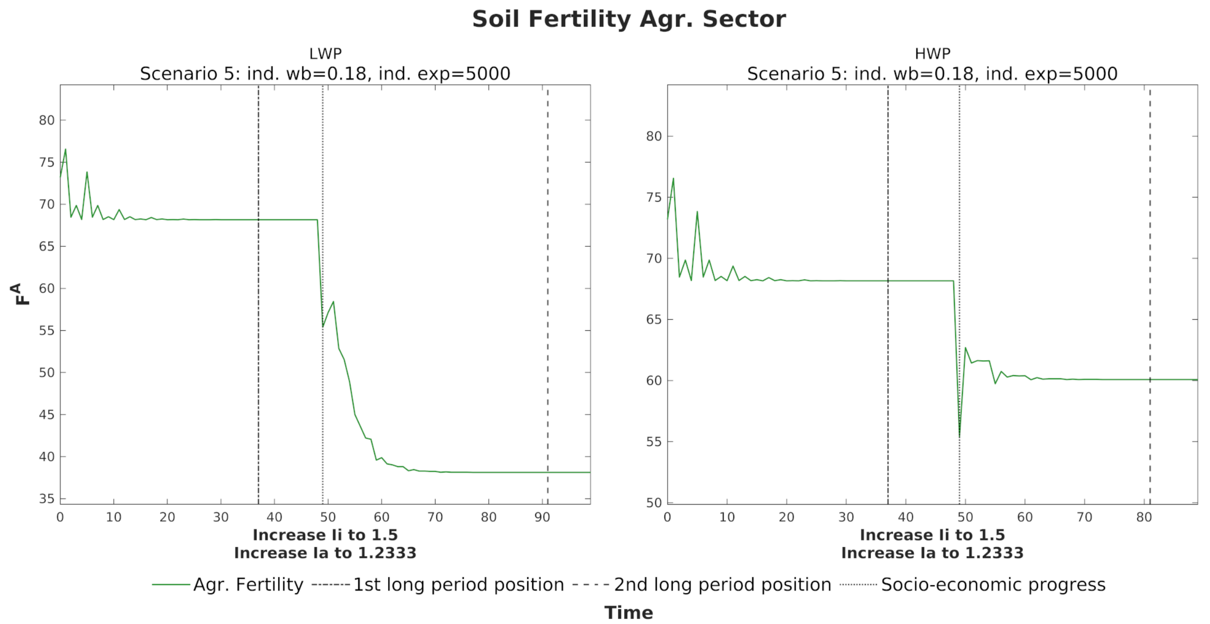



Figure 4.14: Development of fertility for scenario 5 under the LWP and HWP scheme

Such a difference between the LWP and HWP schemes holds for each of the scenarios in which lay-offs take place during the post-expansion period (scenarios 5, 6 and 9). Other scenarios however, are subject to the same development of fertility in both the LWP and HWP schemes. Thus, worker protection sustains the agro-ecological system due to a maintenance of $\frac{n^A}{n^{A*}}$ through $b^A$ and therefore the physiological component of fertility. Figure 4.15 displays the complete development of fertility for scenario 7. As mentioned before, each of the scenarios is subject to the same development if capitalization takes place:

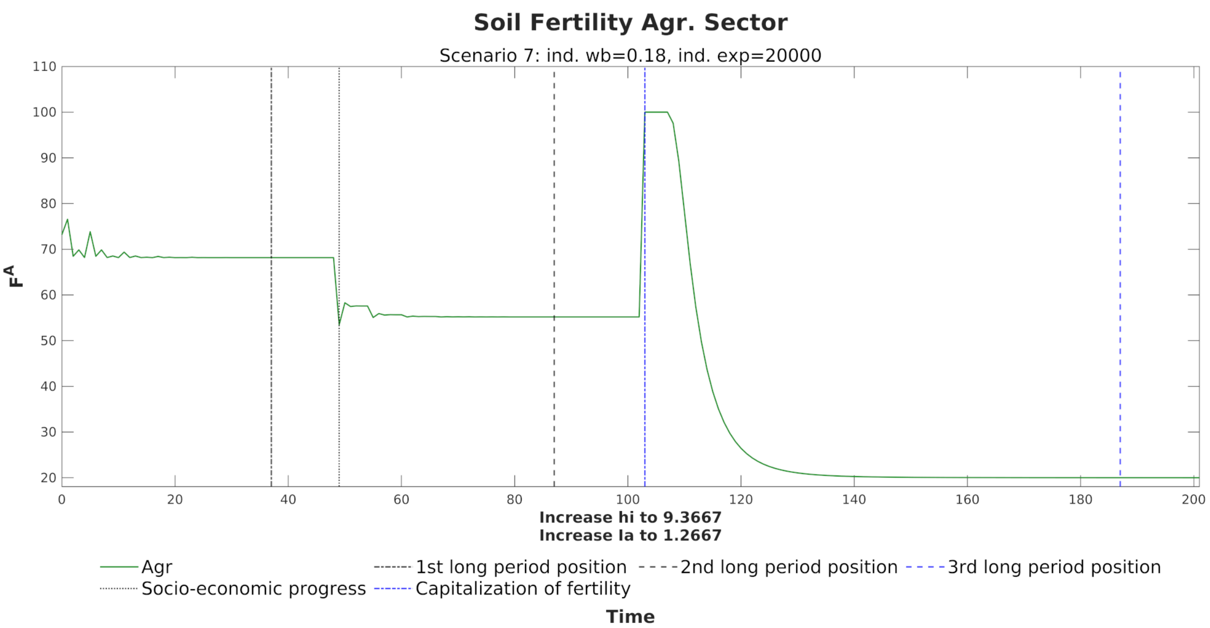



Figure 4.15: Full development of fertility for scenario 7 under both LWP and HWP

### The rates of exploitation

The agricultural rate of exploitation, which we deploy as a measure of alienation not of distribution, are positively correlated with the state of the agro-ecological system (measured through fertility) through variables $b^A$ (which determines $n^A$) and $l^A$. The industrial rate of exploitation also depends on the agro-ecological system since increases in $Y^A$, as the result of decreased fertility levels, result in increased demand for $Y^I$. Each of the scenarios in the selected set show that the industrial sector meets this increased demand by adjusting $l^I$ upwards. At the same time however, both the agricultural and industrial rates of exploitation are negatively correlated with the state of the agro-ecological system through $\boldsymbol{a}_S^A$. This is because a higher seed-coefficient results in a higher amount of indirect labour embodied in $b^A$. Figure 4.16 shows the development of exploitation rates $e^A$ and $e^I$ for scenarios 2, 4, 5 and 7 under the LWP scheme:

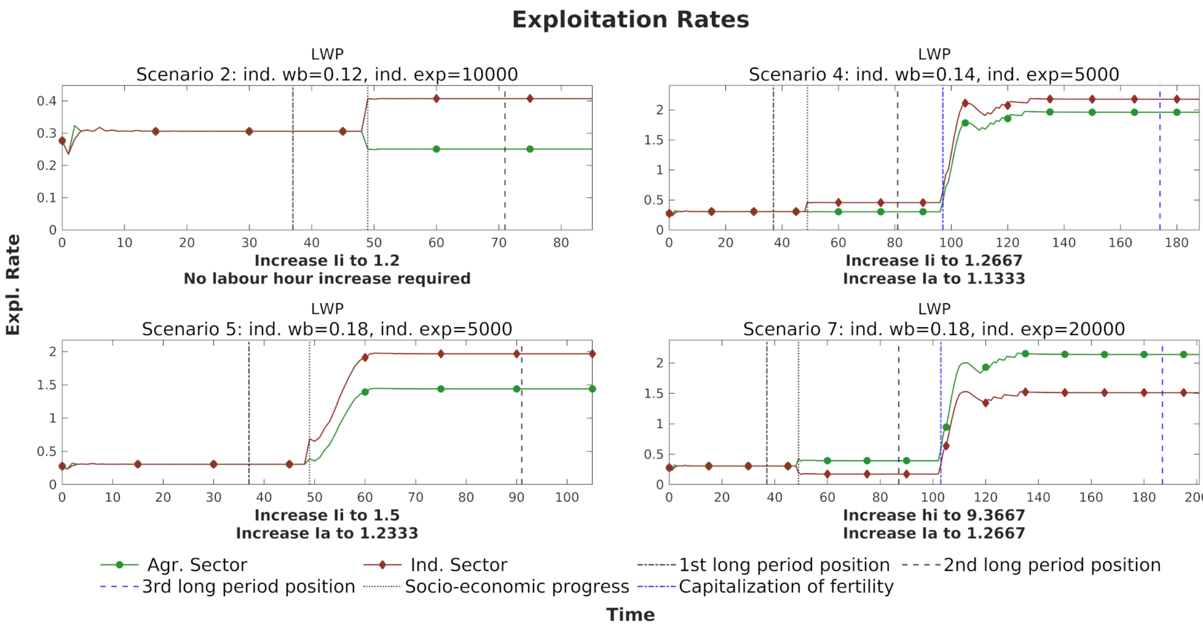



Figure 4.16: The rates of exploitation for scenarios 2, 4, 5 and 7 under LWP

Prior to expansion, both of the rates of exploitation experience a slight increase as the result of decreased fertility and adjustments to $l^A$ and $l^I$ as the result thereof. These adjustments compensate for the negative effect of a higher amount of labour embodied in the $b^A$ due to an increased $\boldsymbol{a}_S^A$. In the post-expansion period, the rates of exploitation either decrease or increase and this depends on the measure of the industrial wage-basket, $b^{I^*}$, and adjustments to $l$. In scenario 1 for example, we see that $e^A$ decreases while $e^I$ increases. This indicates that the adjustment to $l^I$ compensates for the effect of $b^{I^*}$. In scenario 2, the adjustment to $l^A$ results in a near-constant rate of exploitation for agricultural workers, whereas scenario 7 is characterized by an increase in $e^A$ and a decrease in $e^I$ due to the absence of adjustments to $l^I$.

Evidently, if adjustments to labour intensities are such that lay-offs take place, the rate of exploitation drastically increases as the result of lower agricultural wage-baskets (scenario

5). Capitalization results in an even higher increase of both $e^A$ and $e^I$ due to lay-offs and adjustments to $l^A$ and $l^I$ as the result of soil degradation. The first peak after capitalization is the result of lay-offs as well as the decrease of $\boldsymbol{l}^A$ due to the capitalization technique.[13] This is followed by a decrease due to the higher seed-coefficient and therefore the higher labour embodied in $b^A$. But as soon as sectors adjust $l$ to meet increased demand, $e^A$ and $e^I$ climb up again. Figure 4.17 illustrates the development of exploitation rates for scenarios 12 and 13 in order to illustrate the effects of labour mobilization:

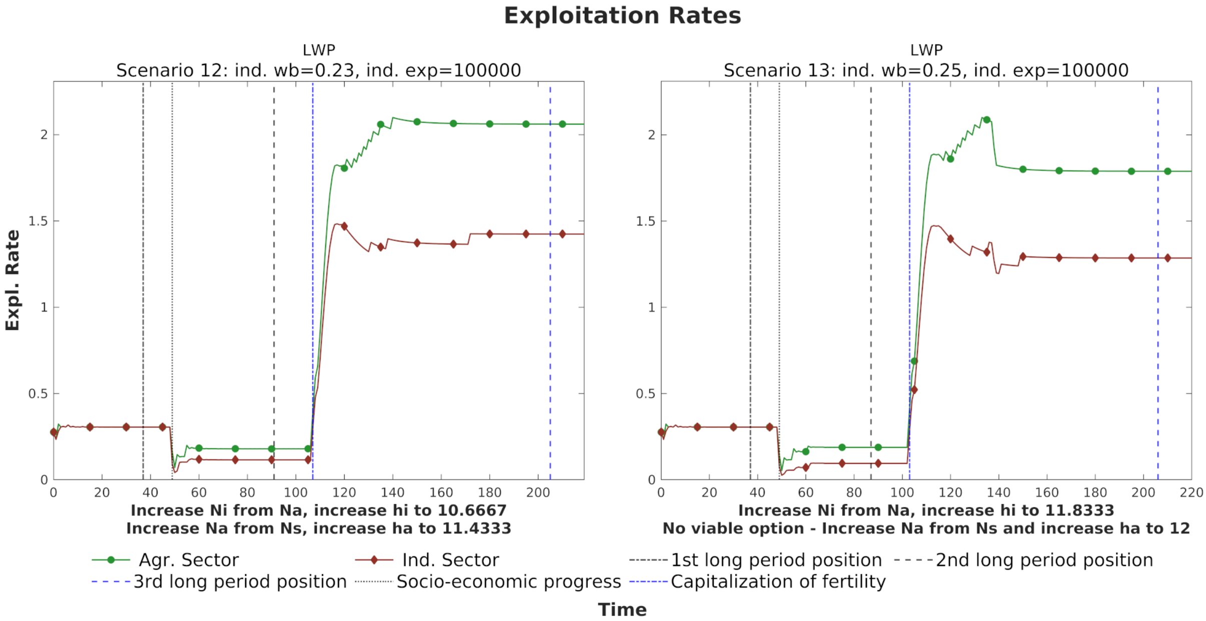



Figure 4.17: The rates of exploitation for scenarios 12 and 13 under LWP

As the result of labour mobilization and the addition of the industrial commodity to the the wage-basket, post-expansion exploitation rates experience a higher decrease than under previously discussed scenarios. However, due to the fact that the coordination mechanism is unable to take into account employment-induced increases in $b^A$, labour intensities are adjusted in order to meet the increased demand — subsequently increasing both $e^A$ and $e^I$. These adjustments are stronger under scenario 13 given the higher lengths of the working day for both sectors (resulting in higher demand). Additionally, the divergence between $e^A$ and $e^I$ is stronger compared to the previous set of scenarios given that drawing on the agricultural labour force results in a higher wage-rate for industrial workers.

Upon capitalization, both $e^A$ and $e^I$ increase as the result of lay-offs and the lower labour coefficient. When soil degradation kicks in, labour shortages arise and adjustments are required. The lower variability of $e^I$ compared to $e^A$ is the result of a higher rate of over-employment for the industrial sector compared to the agricultural sector. Scenario 13 differs

[13] A lower labour coefficient results in a lower amount of labour embodied in the agricultural commodity which increases the rates of exploitation (see eqs. [4.79]-[4.84]). This decrease in the labour coefficient compensates the negative effect on the rates of exploitation as the result labour embodied in the fertilizer input, $V^F$ (see eq. 4.125)

from scenario 12 in that adjustments to either $h^A$ or $I^A$ in the face of soil degradation become exhausted and the agricultural sector is forced to draw on the subsistence sector. This increases $b^A$ and therefore decreases both $e^I$ and $e^A$. Evidently the possible prevention of lay-offs under the HWP scheme places downward pressure on the rates of exploitation. Figure 4.18 compares scenarios 4 and 5 for the LWP and HWP schemes:

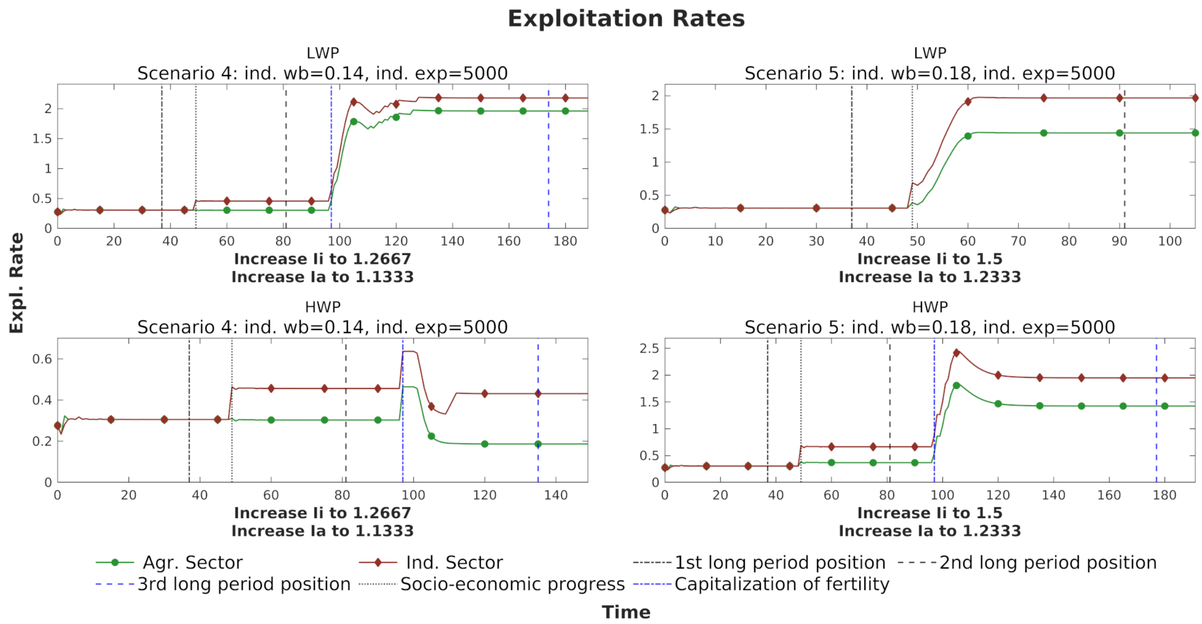



Figure 4.18: The rates of exploitation for scenarios 4 and 5 under LWP and HWP

Scenario 4 under the HWP scheme results in a slight increase of both $e^A$ and $e^I$ as the result of capitalization and the related decrease of $\boldsymbol{l}^A$. As soil degradation kicks in, the rates decrease due to the higher seed-coefficient. Finally $e^I$ experiences an increase due to adjustments of $I^I$ in the face of soil degradation. The reason why this increase is absent for agricultural workers is related to the higher rate of over-employment in the face of the downward adjustment to $\boldsymbol{l}^A$ and inability to lay-off workers (see Table 4.10).

Scenario 5 results in capitalization because lay-offs are not able to take place in the post-expansion period. Upon capitalization however, over-employment in the agricultural sector exceeds 40% and lay-offs take place. As the result of the higher seed-coefficient under soil degradation, both $e^A$ and $e^I$ experience a decrease. Characteristic of scenario 5 under the HWP scheme is the absence of adjustments to $I$ in the face of soil degradation. The lack thereof in the industrial sector is related to the fact that it has increased labour intensity to its maximum (see Appendix C) in the post-expansion period. Just as increases in $b^A$ as the result of employment are unforeseeable, so are decreases as the result of unemployment — resulting in over-employment. The higher measure of over-employment in the agricultural sector allows it to meet degradation-induced demand without any adjustments to its working conditions. All in all, the HWP scheme for scenario 4 results in significantly lower rates of exploitation compared to its LWP variant. The difference for scenario 5 is far less pronounced but is nonetheless negative. Figure 4.19 draws a similar comparison but for scenarios 12 and 13:

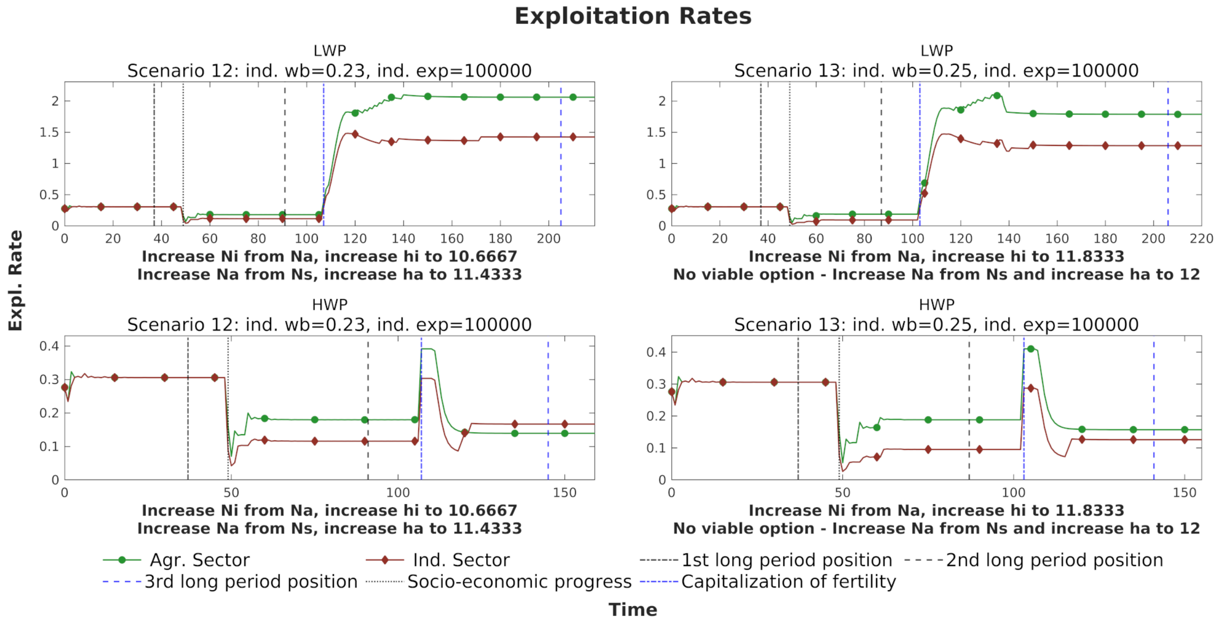



Figure 4.19: The rates of exploitation for scenarios 12 and 13 under LWP and HWP

For scenario 12, under HWP we see that capitalization temporarily increases $e^I$ and $e^A$ as the result of the lower labour coefficient. The higher seed-coefficient related to soil degradation, however, brings the rates of exploitation down again. Due to higher over-employment in the agricultural sector, adjustments to working conditions are absent. In contrast, the industrial sector adjusts $I^I$ which leads to an increase of $e^I$ and $e^I > e^A$ even if industrial workers are subject to higher wages. Scenario 13 under the HWP shows a similar development and in fact, compared to its LWP variant we can see that the inability to lay-off workers under capitalization results in an absence of labour mobilization in the post-capitalization period. Furthermore we see that $e^I < e^A$ at the end of the simulation run, due to lower adjustments to $I^I$.

### The treatment of phases as techniques

So far, we have provided a discussion of distribution, agro-ecological degradation and exploitation based on a selected set of scenarios which are each characterized by a different expansion intensity measure. Each scenario was subject to at least 2 long-period positions. The presence of a third long-period position was conditional on a negative agricultural profit-rate differential between the first and second long-period position. Another way to treat these long-period positions is by means of w(r)-curves, since each long-period position is characterized by a different set of technical coefficients. At reigning wages and relative prices, one is able to assess whether a technique is profitable or not.

**Three iterations of the expansion technique.** A comparison of the first long-period w(r)-curve against two different iterations of the expansion technique is equal under both the LWP and HWP schemes. The first iteration of the expansion technique only takes into account $l^{II^*}$ as the result of $l^{I*}$ and is therefore equal across all scenarios. The second iteration of the expansion technique additionally takes into account $l^{II^*}$ and/or $l^{AI*}$ as the result of upward adjustments to $I^I$ and/or $I^A$ *at the moment of expansion*.[14] If such adjustments are absent the first iteration and second iteration expansion technique w(r)-curves overlap. Figure 4.19 illustrates the 3 different w(r)-curves for scenarios 2, 5, 7 and 12.

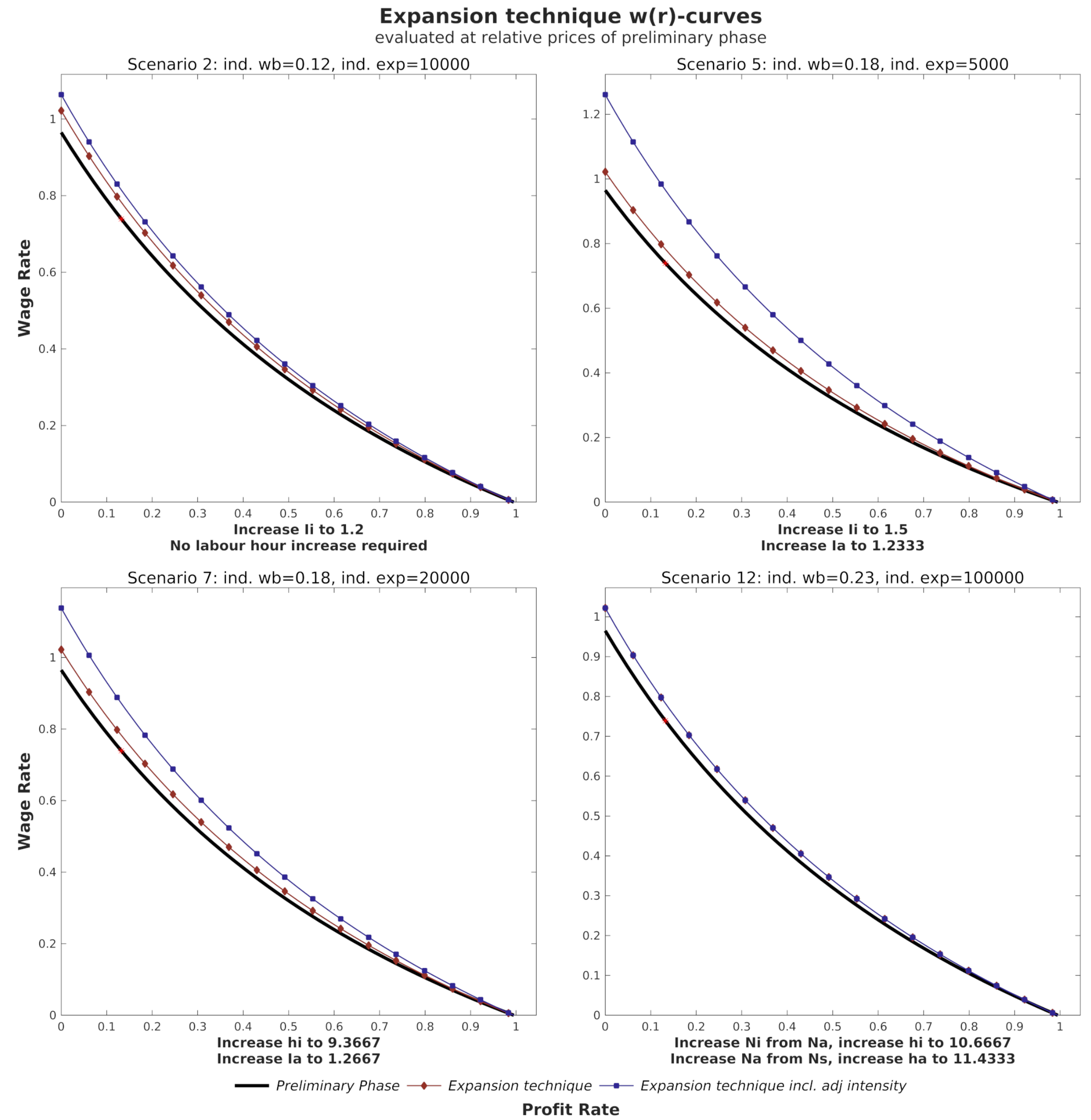



Figure 4.19: w(r)-curves 2 iterations expansion technique w.r.t. preliminary phase

Both iterations of the expansion technique lie above the w(r)-curve for the preliminary phase, which indicates that at prevailing wage-rates and relative prices it is profitable to deploy the expansion technique. In fact, it is profitable to deploy the expansion technique for all wage-rates under the preliminary phase apart from $w = 0$. At a zero wage-rate, the

[14] This is to say that we only take into account the adjustments in reaction to new coordinated target outputs, not those as the result of increased agricultural wage-baskets or agro-ecological degradation.

w(r)-curves intersect and this means that they each share an equal maximum rate of profit, $r^{max}$. Evidently, the w(r)-curve for the iteration of the expansion technique which takes into account adjustments to labour intensities lies above that of the first iteration. The higher the adjustments to $I$, the higher the profitability of deploying the second iteration of the expansion technique at prevailing wage-rates and relative prices (scenario 5 vs scenarios 2 and 7). As mentioned before, the absence of adjustments to $I$ results in the same w(r)-curve for the first and second iteration of the expansion technique (scenario 12).

What if capitalists could somehow *foresee* agro-ecological repercussions? This brings us to a third iteration of the expansion technique which takes into account adjustments to labour intensities *at the moment of expansion* as well as the seed-coefficient in the post-expansion long-period position. Figure 4.20 compares the w(r)-curve in the preliminary phase to that of the third iteration of the expansion technique for scenarios 2, 5, 7 and 12 under the LWP scheme.

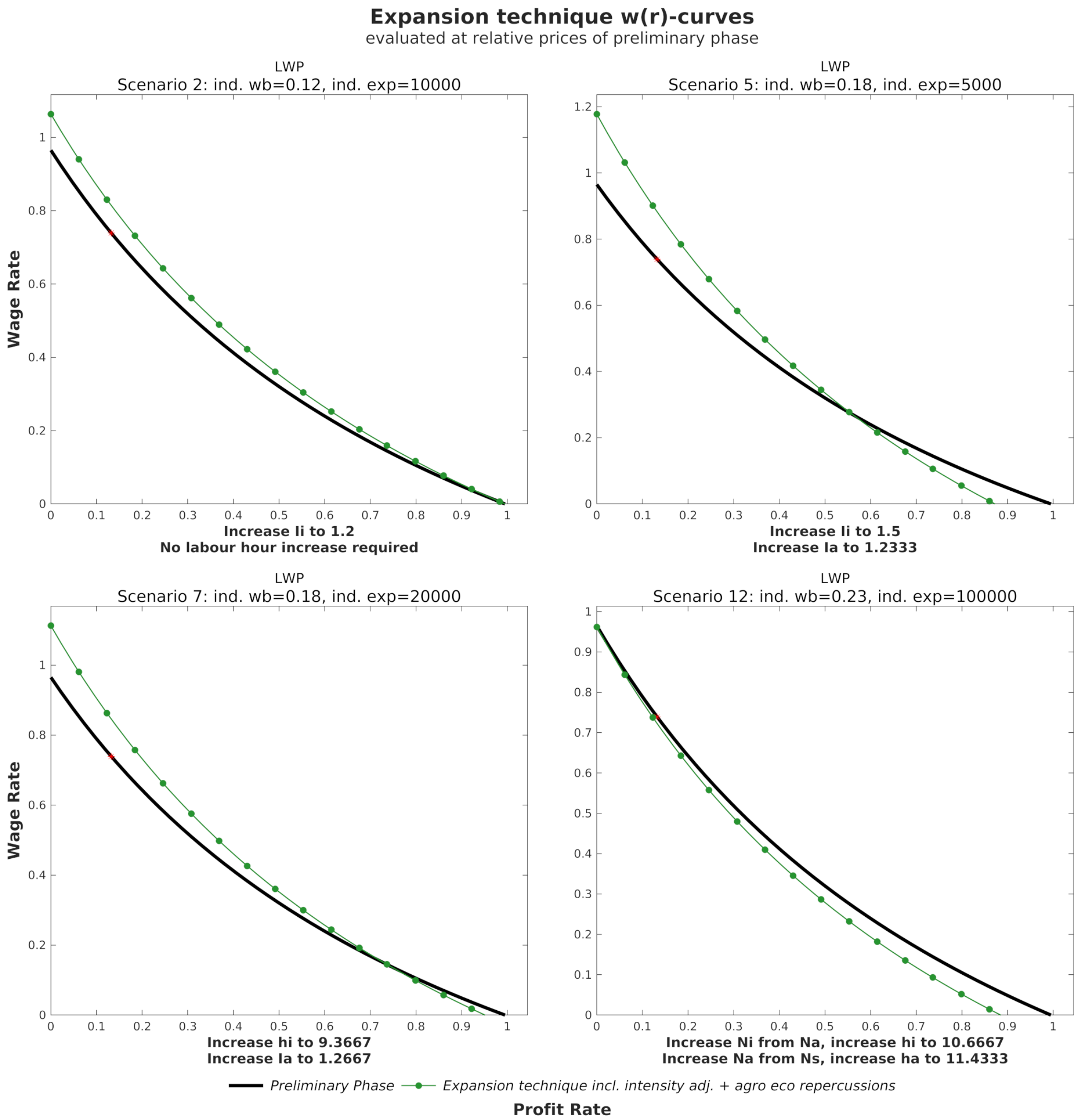



Figure 4.20: w(r)-curves 3rd iteration expansion technique w.r.t. preliminary phase

In absence of agro-ecological repercussions, the w(r)-curve related to the third iteration of the expansion technique is equal to the second iteration w(r)-curve. This is the case for scenario 2, where it is profitable to deploy the expansion technique for all wages at the prevailing relative prices (except for $w = 0$). Scenarios 5, 7 and 12 illustrate how the third iteration w(r)-curve changes as the result of agro-ecological degradation.

For scenarios 5 and 7 and at prevailing wages and relative prices, it is still profitable to deploy the expansion technique regardless of a higher seed-coefficient as the result of agro-ecological degradation. However, the third iteration w(r)-curve now intersects with that of preliminary phase for wages other than 0. This intersection is also referred to as a *switching point*, indicating the wage for which capitalists would be indifferent between deploying and not deploying the expansion technique. For scenario 5, the *switching point* is given by $w \approx 0.2710$ and allows us to conclude that deploying the expansion technique is only profitable for $w \gtrsim 0.2710$. One can easily see that the *switching point* for scenario 7 is lower than that of scenario 5. Indeed, it is given by $w \approx 0.1434$ and results in a larger wage-rate range for which the expansion technique is profitable to deploy. Evidently, this is the result of the higher post-expansion level of fertility under scenario 7 compared to scenario 5 (see Figure 4.12).

Finally, scenario 12 is characterized by the absence of a *switching point*. This means that, at prevailing wages and relative prices, it is *not* profitable to deploy the expansion technique (since the third iteration w(r)-curve lies below that of the preliminary phase). This is the result of the absence of adjustments to either $I^I$ or $I^A$ as well as lower levels of fertility in the post-expansion period (see Figure 4.13). As mentioned in the subsection discussing the development of the agro-ecological system, fertility levels are only higher under the HWP scheme for scenarios in which lay-offs are prevented. Figure 4.21 draws a comparison between scenario 5 under the LWP and under the HWP scheme.

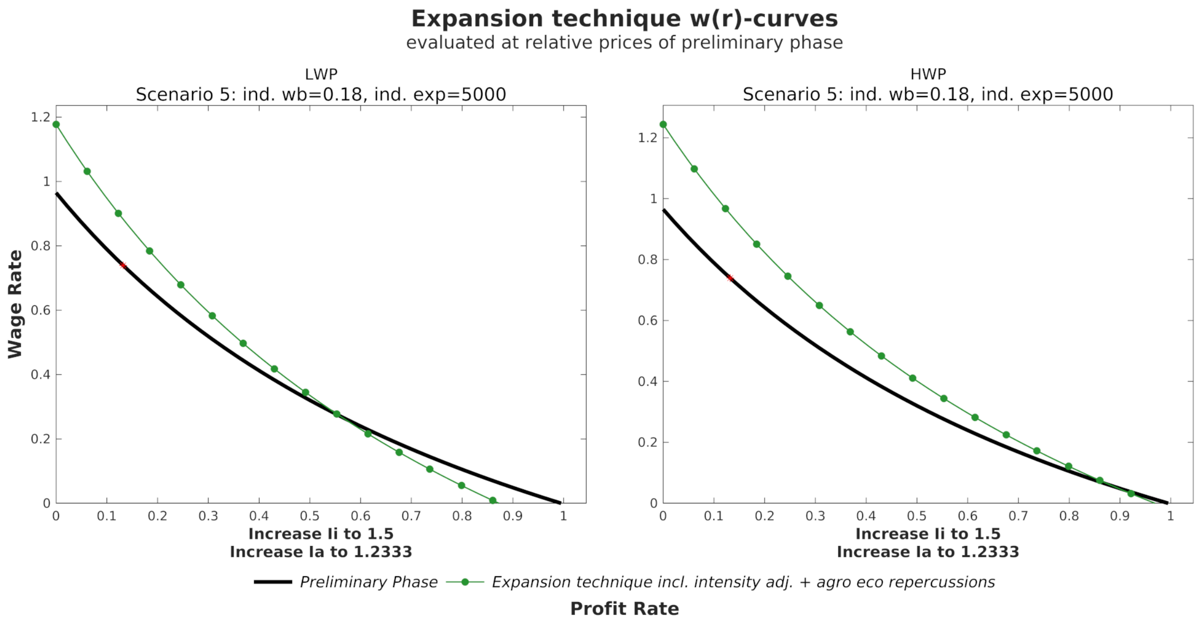



Figure 4.21: w(r)-curves 3$^{\text{rd}}$ iteration expansion technique: scenario 5 (LWP/HWP)

The higher level of fertility under the HWP scheme increases the range of wages for which it is profitable to deploy the expansion technique. More specifically, the *switching point* is given by $w \approx 0.0546$. In sum, for most of the scenarios in our selected set, each of the expansion technique iterations are profitable to deploy at the prevailing wages and relative prices. Exceptions are scenarios in which adjustments to the labour intensities are absent, *at the moment of expansion*, and agro-ecological repercussions are such that the benefit of $\boldsymbol{l}^{I^*}$ is outweighed by the higher seed-coefficient.

While expansion bears negative implications for the agro-ecological system fertility levels in the post-expansion period are still relatively high compared to the post-capitalization period. In the following subsection we will discuss various iterations of the capitalization w(r)-curve against the post-expansion long-period w(r)-curve in order to assess the profitability of capitalization from a *choice of technique* perspective.

**Three iterations of the capitalization technique.** The first iteration of the capitalization technique only takes into account the new labour coefficient, $\boldsymbol{l}^{A^*}$, and seed coefficient, $\boldsymbol{a}_S^{A^*} = \boldsymbol{a}_S^S$ which is based on the maximum level of fertility. For this iteration of the capitalization technique, we'll have that the w(r)-curve *always* lies above that of the post-expansion long-period w(r)-curve — for both the LWP and HWP schemes. An example hereof is shown in Figure 4.22 for scenario 5 in the LWP and HWP scheme.

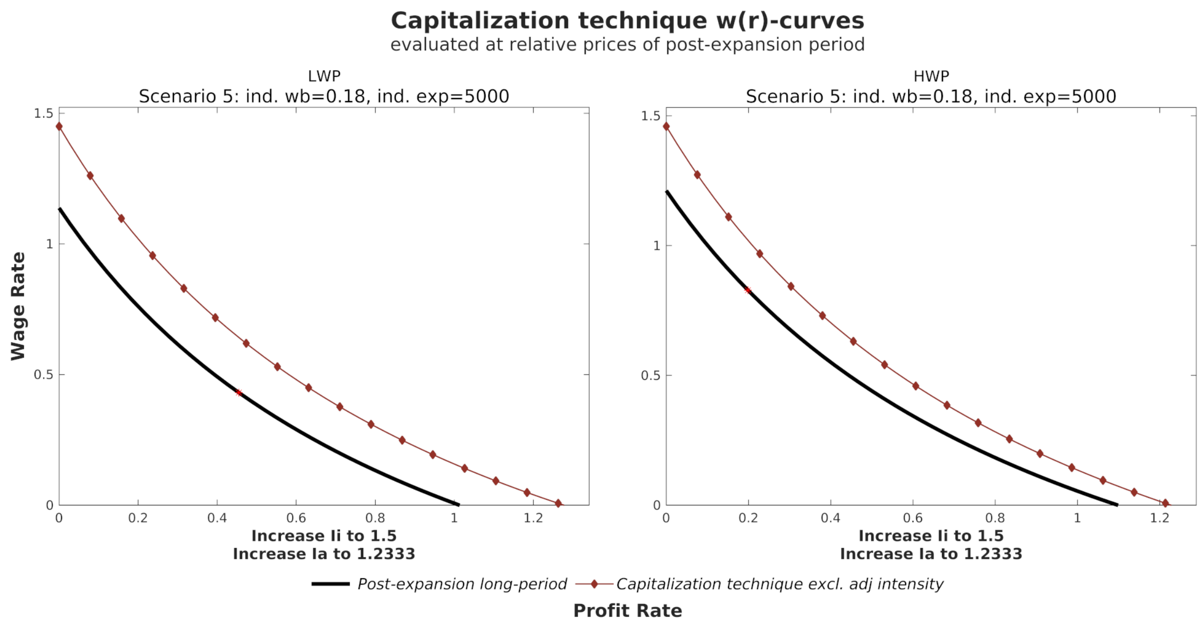



Figure 4.22: w(r)-curves 1$^{\text{st}}$ iteration capitalization technique: scenario 5 (LWP/HWP)

Even if the post-expansion long-period curves differ across the LWP and HWP schemes due to the absence of lay-offs, we see that the first iteration of the capitalization technique is profitable for *all* wage-rates at post-expansion long-period prices.

The second iteration of the capitalization technique is based on the assumption that capitalists can somehow foresee the soil degradation as the result of fertilizer use. Hence the technique is characterized by $l^{A^*}$ and $a_S^{A^-} < a_S^A < a_S^{A^*}$. Figure 4.23 displays the w(r)-curve for the second iteration of the capitalization technique for scenarios 2, 5, 10 and 13 under the LWP scheme.

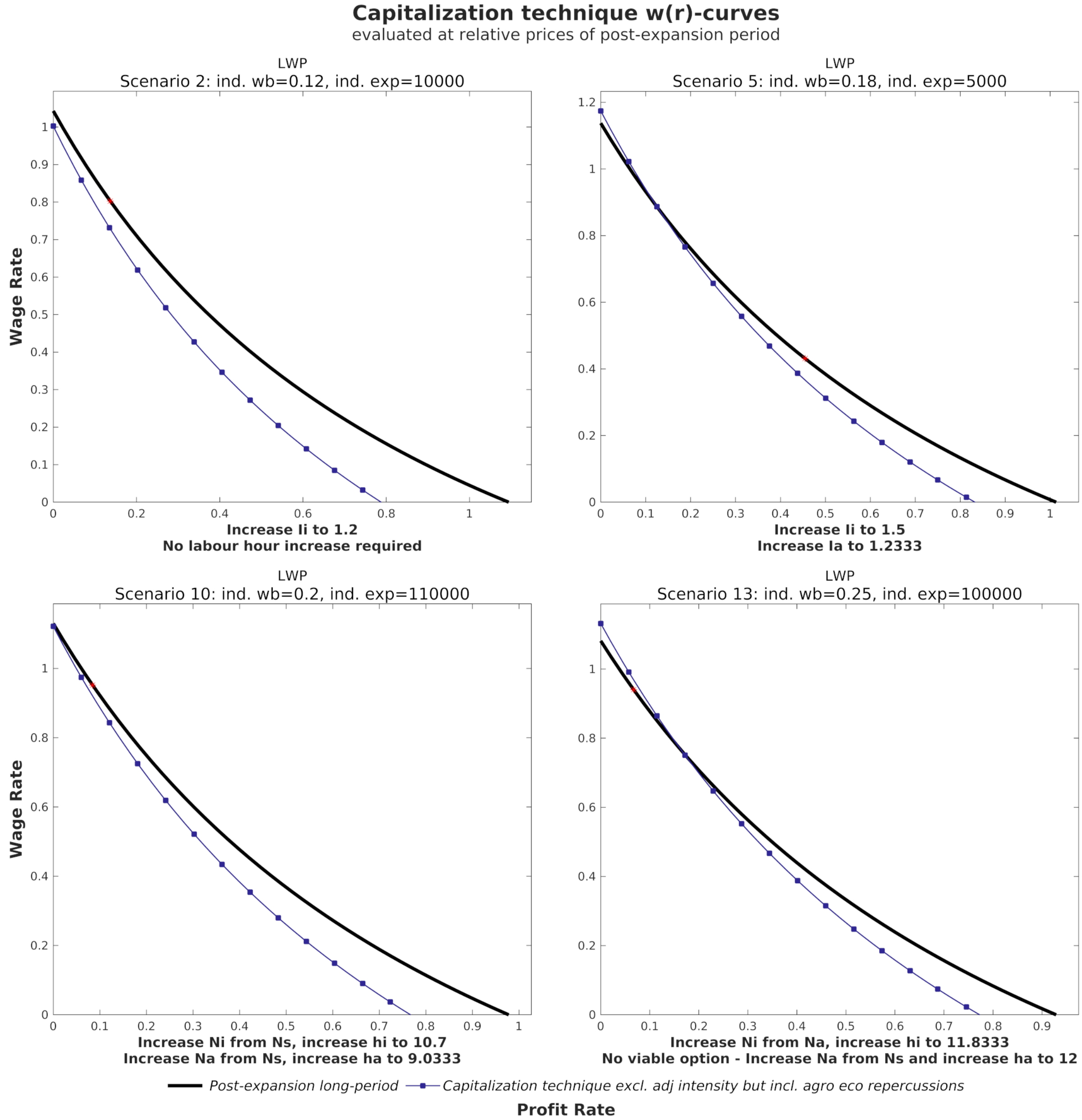



Figure 4.23: w(r)-curves 2$^{\text{nd}}$ iteration capitalization technique w.r.t. post-exp. period

Scenario 2 is characterized by the absence of adjustments in the agricultural sector and is therefore subject to constant fertility throughout the preliminary phase and post-expansion period. This is why the capitalization technique w(r)-curve lies strictly below that of the post-expansion period. Across all wages at the prevailing relative prices, it is *not* profitable to deploy the capitalization technique. For scenario 5 however, there exists a *switching point* above which it is profitable to deploy the capitalization technique. The *switching point* is given by $w \approx 0.8818$ but at the prevailing wages, however, we see that it is nevertheless not profitable to deploy the capitalization technique. Scenario 10 is similar to scenario 2, in that the w(r)-curve for the capitalization technique lies below that of the post-expansion long-period. The reason why the gap is wider under scenario 2 compared to scenario 10 is related to the fact that fertility levels are higher under scenario 2 due to the absence of adjustments in agricultural working conditions. Finally, scenario 13 indicates the existence of a *switching point* for $w = 0.7600$ which lies slightly below the prevailing wages showing that is profitable to deploy the capitalization technique. In sum, the closer the fertility level in the post-expansion period is to the baseline level of fertility, the more likely it is that the capitalization technique which exacerbates soil degradation is profitable at the prevailing wages and relative prices. Under the HWP scheme, the w(r)-curves for the post-expansion long-period are obviously different for scenarios in which lay-offs are prevented. This results in higher levels of fertility and therefore either the absence of *switching points* or lower wage ranges for which the capitalization technique is profitable at the prevailing relative prices.

The third iteration of the capitalization technique additionally considers the adjustments to $I^A$ and $I^I$ as the result of soil degradation. Hence, the technique is characterized by the higher seed-coefficient as well as lower intensity-adjusted labour coefficients. The derivation of the third iteration w(r)-curve is only possible for scenarios in which capitalization actually takes place, since adjustments to $I^I$ and $I^A$ are taken from the post-capitalization long-period. Figure 4.24 summarizes the w(r)-curves for scenarios 4, 7, 10 and 13 under the LWP scheme.

For each of the scenarios, at prevailing wages and relative prices in the post-expansion long-period, it is profitable to deploy the capitalization technique if soil degradation leads to adjustments in labour intensities which decrease the labour coefficients. A comparison between scenario 4 and 7 shows us that the switching points are $w \approx 0.6415$ and $w \approx 0.6455$ respectively. Hence, the range of wages for which the capitalization technique is more profitable is *slightly* higher under scenario 4. This is not only related to the higher levels of fertility under scenario 7 in the post-expansion long-period, but also to the higher adjustments to both $I^A$ and $I^I$ in its post-capitalization period.

The second iteration of the capitalization technique was not profitable under scenario 10 for *any* wage (see Figure 4.23), but the third iteration of the capitalization technique is characterized by a *switching point* for $w \approx 0.6188$. For the third iteration of the capitalization technique, the *switching point* for scenario 13 is now lower than it was for the second iteration of the capitalization technique, namely: $w \approx 0.4115$. The divergences with respect to the second iteration are evidently related to labour intensity adjustments. The higher range of wages for scenario 13 is driven by the lower level of fertility in the post-expansion period compared to scenario 10.

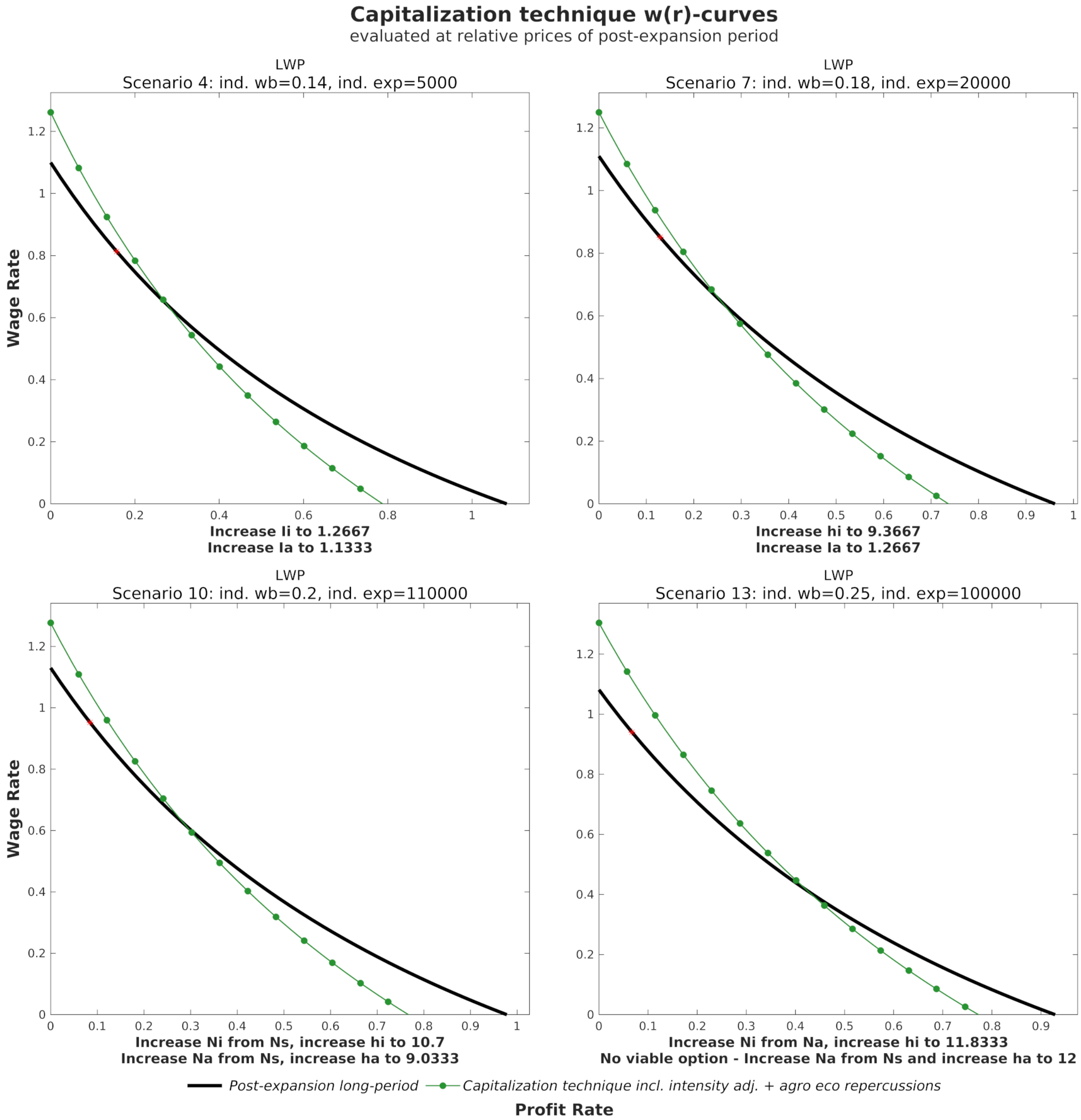



Figure 4.24: w(r)-curves 3[rd] iteration capitalization technique w.r.t. post-exp. period

As mentioned in Section 4.2.1, the inability to lay-off workers upon capitalization under the HWP scheme can result in the lack of adjustments to $I^I$ and $I^A$ as the result of over-employment. Figure 4.25 draws a comparison between the scenarios 4 and 13 under the LWP and HWP schemes.

Scenario 4 shows that the reduced amount of adjustments to intensity under HWP, results in a w(r)-curve which lies strictly below that of the post-expansion long-period. Hence, the capitalization technique is not profitable to deploy. For scenario 13 however, the reduced amount of adjustments under HWP results in a *switching point* which is far above that of the LWP variant, namely: $w \approx 0.6713$.

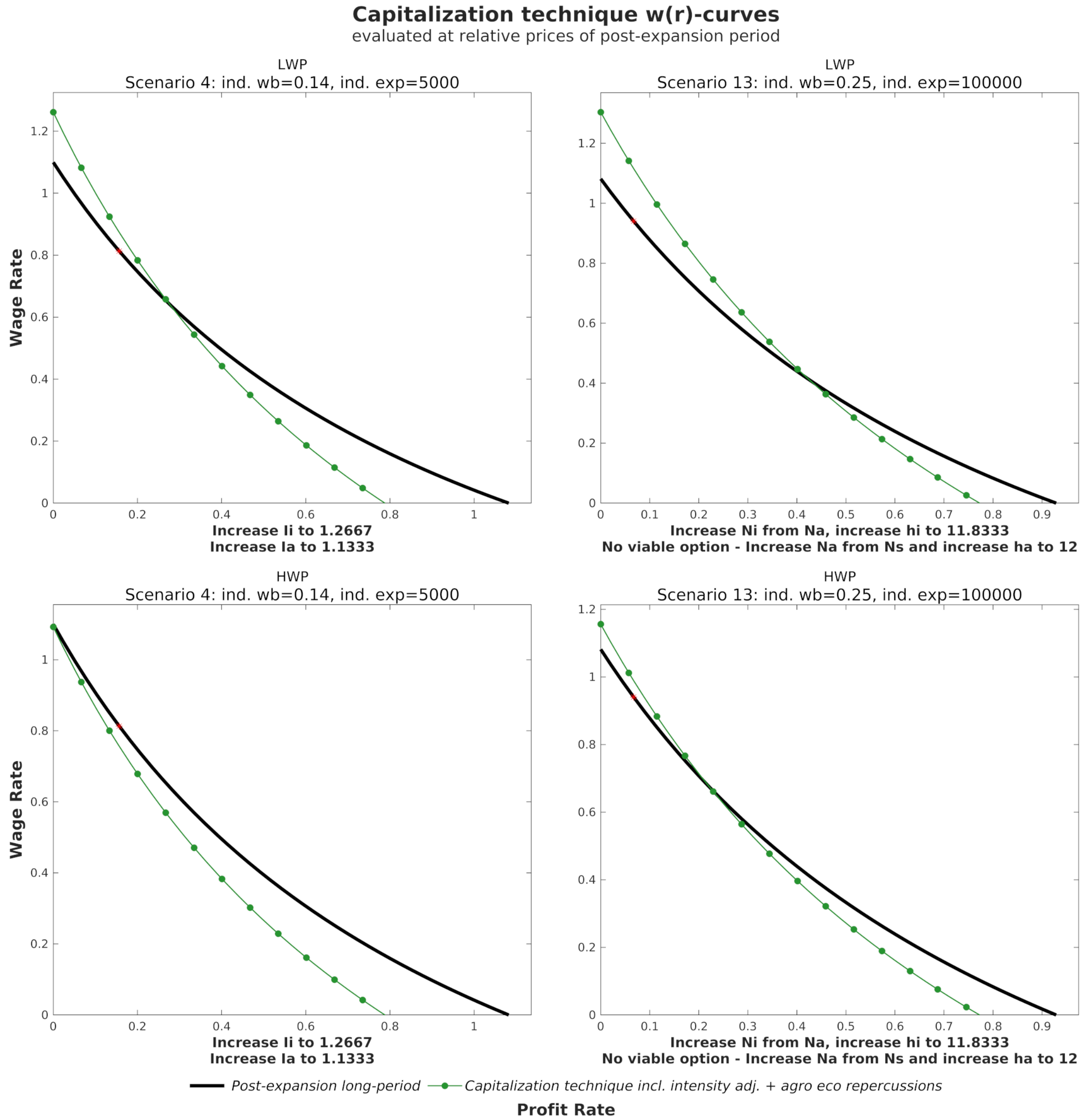



Figure 4.25: w(r)-curves 3rd iteration capitalization technique: scenarios 4 & 13 (LWP/HWP)

**Preventing capitalization at the expense of worker's income.** While the *actual* simulation runs are not based on the above-mentioned *choice of technique* considerations on profitability, the exercise can still be used to assess a hypothetical situation where workers would be able to prevent capitalization. Such an obstruction would prevent soil degradation as well as the eradication of the metabolic relationship between labour and ecological processes. Let's consider scenarios 5 and 13 and the second iteration of the capitalization technique (see Figure 4.23). Under the LWP variant of scenario 5, a prevention of capitalization would require an *increase* in the wage-rate from $\approx$ 0.4310 to a wage-rate greater than $\approx$ 0.8818. Under the HWP variant, there is no *switching point* and hence no incentive to deploy the capitalization technique. Hence for scenario 5, one is able to conclude that higher worker protection and therefore higher wages and levels of fertility in the post-expansion period, automatically stave off further degradation of the agro-ecological process. But this is purely the result of its profitability-decreasing characteristic.

On the other hand, *both* the LWP and HWP variants of scenario 13 would require a *decrease* of the wage-rate from $\approx 0.9402$ to a wage-rate below $\approx 0.7600$ to prevent capitalization. For these scenarios one is able to argue that a trade-off exists between *additional* ecological degradation and a more favourable distribution between workers and capitalists vis-a-vis workers. This is to say that if workers were to give up part of their material benefits ecological degradation could be prevented. The net benefit of such a prevention however, will be higher under the HWP scheme. Assuming that an income reduction takes the shape of a reduced industrial wage-basket then in the *short-run* fertility levels remain constant. But if in the *long-run* the reduced demand for the industrial commodity results in the ability to lay-off workers, this increases unemployment and thereby reduces $b^A$, which negatively impacts soil fertility. To the extent that $I^{max}$ and $h^{max}$ are not met, the reaction of agricultural capitalists will be to face this soil degradation in terms of adjustments to working conditions — placing even more downward pressure on fertility levels. Obviously, if worker's income is reduced through a decrease of the agricultural wage basket, the aforementioned repercussions on agro-ecological fertility are stronger, since the channel through which they operate is a direct one, $\frac{n^A}{n^{A*}}$.

This concludes our discussion on the scenario-specific simulation results regarding the development of output, profit-rates, unemployment, wages, soil fertility, exploitation and w(r)-curves. In the section below, we will discuss some general implications of these results regarding distribution, exploitation and agro-ecological degradation.

### 4.2.2. Distribution, exploitation and agro-ecological degradation

In the following paragraphs we aim to summarize the inter-dependency between distribution, exploitation and agro-ecological degradation as it appears across scenarios 1 to 13. We treat this inter-dependency as our main result which, to the best of our knowledge, has not been previously considered in the field of Ecological Economics. In doing so, we abstract from the various dynamic repercussions discussed at the end of Section 4.2.1. This is to say that when we assume changes in for example, a co-determinant of profit rates, we assume that all other variables remain constant.

Given that we are operating in a Sraffian/neo-Ricardian framework, our reference to distribution concerns the distribution of the physical surplus between workers and capitalists. All else constant, an increase in wage-rates must necessarily be accompanied by a decrease in the profit rates. This relationship is exemplified by the w(r)-curves presented at the end of Section 4.2.1. Wage-rates in the industrial and agricultural sectors are a positive function of employment, $\frac{N^{WC}}{N^T}$, and the average product in the subsistence sector, $b^S$. Thus, if we assume the emergence of a third sector which increases employment then the wage-rate would increase and profit rates would fall. Apart from the wage-rate, the profit-rate additionally depends on technical coefficients, $\boldsymbol{a}_I^A, \boldsymbol{a}_I^I$ and $\boldsymbol{a}_S^A$, and labour-intensity adjusted labour coefficients, $\boldsymbol{l}^{AI} = (\boldsymbol{l}^A / I^A)$ and $\boldsymbol{l}^{II} = (\boldsymbol{l}^I / I^I)$. Technological change or a different organization of production which decrease technical and/or labour intensity adjusted coefficients result in higher rates of profit if all else were to remain constant.

Exploitation, a measure which aims to characterize capitalist *social relations of production* and hence worker well-being, is determined by the same set of variables as distribution. All else constant, the higher the wage-rate, the higher the amount of $b^A$ and/or $b^I$ contained in the wage-basket. This entails an increase of the labour embodied in wages and hence a decrease in the rates of exploitation. Positive technological changes operate in an opposite way. A decrease in either the capital or labour inputs while output and wages remain constant results in a lower amount of labour embodied in wages — increasing the rate of exploitation. Changes in the organization of production which increase labour intensities, $I^A$ or $I^I$, also result in higher rates of exploitation as the amount of labour expended per hour of production increases (see [4.79] - [4.86]). In the end we'll have that, all else constant, higher employment results in lower profit-rates, higher wage-rates and lower rates of exploitation. On the other hand, technological or organizational changes increase profit-rates as well as exploitation rates while the wage-rate remains unaffected.

The state of the agro-ecological system is expressed through a measure of fertility, $F^A$, which depends on a physiological as well as a cognitive component. In our view, these two components fall in line with Marx's description of material metabolism and purpose realisation as elements of the labour process. When it comes to material metabolism, an increase in the physical wage-basket, $b^A$, while all else remains constant, improves fertility through the impact on $n^A$. The same applies for an increase in agricultural employment (see Section 4.1.2). Following the way we abstract purpose realisation, its measure depends on the working conditions in the agricultural sector *relative* to the subsistence sector. Hence, all other variables held constant, upward adjustments to $h^A$ or $I^A$ negatively impact fertility levels. In sum, the state of the agro-ecological system, or fertility levels, stand in relationship to distribution in the following way:

- Rates of profit are higher when levels of fertility are high due to the impact of lower seed-coefficients, $\boldsymbol{a}_S^A$.
- The higher the employment rate, the higher the agricultural wage-basket, the higher the wage-rate and the higher the levels of fertility.[15]

[15] This positive relationship is conditional on a higher rate of change in $n^A$ compared to $n^{A^*}$. If output remains constant and the agricultural wage-basket *for agricultural workers* increases exogenously (without an increase of employment), $n^A$ increases while $n^{A^*}$ remains constant — increasing the material metabolism parameter. When

- Rates of profit are also higher when production is more efficiently organized, which impacts intensity-adjusted labour coefficients. Upward adjustments in $I^A$, however, decrease fertility levels, and lower the rate of profit through upward adjustments in $\boldsymbol{a}_S^A$.

When the agro-ecological system is in a state of appropriation, high employment, distribution which is more favourable to workers and less alienating production organization methods result in a better state of the agro-ecological system. While higher wage-baskets and the absence of labour intensity adjustments negatively impact the rate of profit, a lower $\boldsymbol{a}_S^A$ positively impacts the rate of profit. As iterated many times before, this positive impact of a higher wage-basket on the rate of profit does not take part of capitalist decision-making; it appears as a coincidental improvement of the appropriated agro-ecological process.

### A world-ecology digression

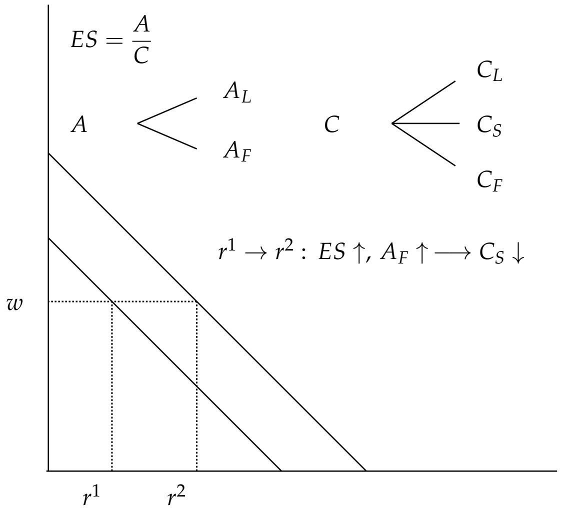
The insight on agro-ecological degradation and distribution can also be framed in terms of the ecological surplus: the ratio between appropriated (unpaid) and capitalized (paid) production inputs or processes. Higher levels of fertility coincide with a more profitable technique because of the impact of fertility on the seed coefficient and therefore the necessary seed input.[16] This resonates with the world-ecology idea that higher contributions of appropriated processes to the production process result in higher profit rates as the result of the increased productivity of capitalized inputs. More specifically, fertility levels can be characterized as appropriated *ecological* or extra-human processes. At the same time, labour-saving production organization methods, which increase the labour intensity, can be seen as appropriated labour or human processes. This is because workers expend more labour per hour of production but are left unpaid for the additional amount. All in all, increases in either appropriated process tends to result in higher rates of profit. An important complexity, however, is related to the fact that i) increases in human labour appropriation render ecological appropriation less efficient and ii) increases in labour capitalization render ecological appropriation more efficient. It is important to note that increases in labour capitalization, or any type of capitalization for that matter, are both a function of quantity and price. Hence, both a higher labour coefficient and higher wage-rate are treated as instances which increase capitalization.

Upon capitalization of the ecological process or soil fertility, labour capitalization is rendered more efficient while the efficiency of capitalized fertility is dramatically decreased in the long-run. Hence, in the post-capitalization long-period, appropriation is solely determined by unpaid labour as the result of increases in labour intensity. Whether this results in a lower or higher ecological surplus and thereby a lower or higher profit rate, depends on the degree of decreased reliance on capitalization due to lower labour coefficients vis-a-vis the absence

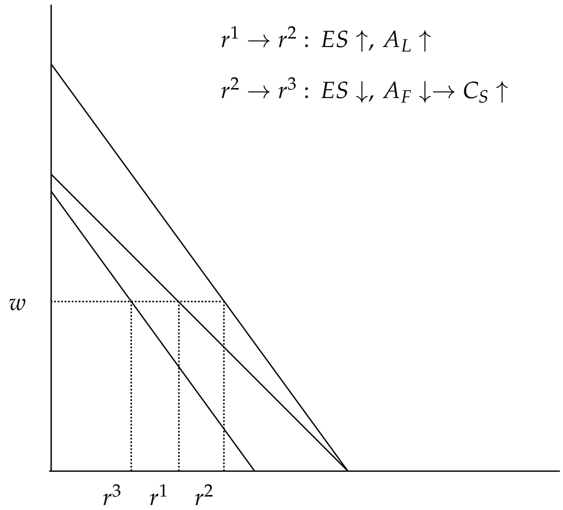
increases in the agricultural wage-basket are endogenously determined by employment, the increase in $n^A$ must outweigh the increase in $n^{A^*}$ as the result of demand-driven increases in output.

[16] Seed *enters* the production process and is therefore considered to be a capitalized input.

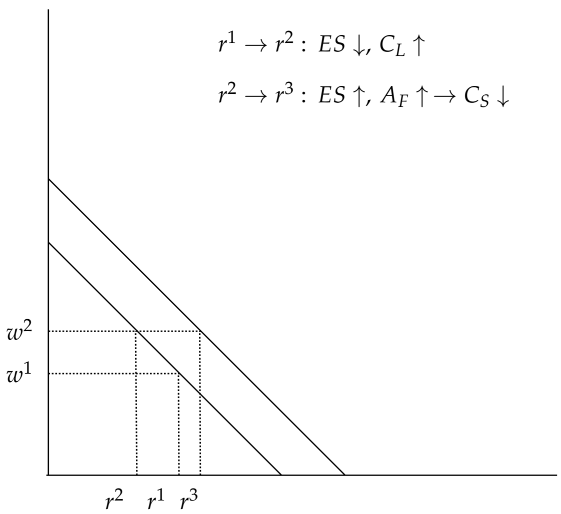
of ecological appropriation. Under the LWP scheme, lower labour coefficients result in lay-offs which translates to a decreased reliance on capitalization in terms of the quantity of necessary labour hours. In addition, we'll have a decreased reliance on capitalization in terms price due to the effect of unemployment on the wage-rate. Soil degradation increases the reliance of capitalization as it renders the seed-input less efficient. But an increased reliance on human labour appropriation as the result of soil degradation together with a decreased reliance on labour capitalization ultimately results in a higher ecological surplus and therefore a higher rate of profit. This is not the case under the HWP scheme, where the lack of increased unemployment does not allow for an increased ecological surplus and hence profit rate. Interestingly, these considerations on the ecological surplus and rates of profit can be graphically illustrated by means of generalized instead of scenario-specific w(r)-curves. This is done in Figure 4.26:



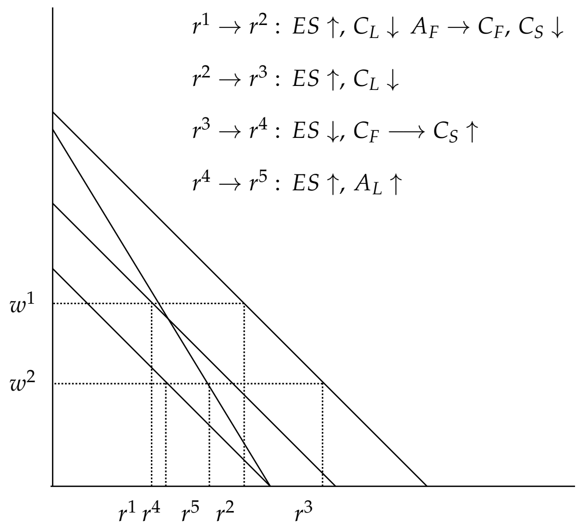

(a) Appropriation: Increase in $F^A$




(b) Appropriation: Increase in $I^A$




(c) Appropriation: Increase in $w$




(d) Capitalization under LWP

Figure 4.26: Considerations on the ecological surplus in w(r)-curves

$ES$ represents the ecological surplus, $A$ captures appropriated processes, labour and soil fertility $(A_L, A_F)$ and $C$ represents capitalized inputs, labour, seed and fertilizers $(C_L, C_S, C_F)$. The short text next to each diagram summarizes the variation in the rate of profit as the result of changes in either appropriated processes or capitalized inputs. The take-away message is that variations in the rate of profit correspond with variations in the ecological surplus.

Retreating from the above digression on the world-ecology ecological surplus, we now turn to the discussion of the exploitation rates. In a nutshell, the state of the *appropriated* agro-ecological system stands in relationship to exploitation in the following fashion:

- The improvement of material metabolism through an increase in $b^A$, and therefore $n^A$, simultaneously results in decreased rates of exploitation.
- The degradation of the purpose realisation through an increase in $I^A$, simultaneously results in increased rates of exploitation.
- At the same time, a worse-off agro-ecological system increases $\boldsymbol{a}_S^A$ and thereby increases the amount of labour embodied in the agricultural wage-basket, $b^A$ — ultimately decreasing the rates of exploitation.

Apart from the higher amount of labour embodied in one unit of the agricultural commodity as the result of agro-ecological degradation, a better state of the agro-ecological system goes hand in hand with "more bearable" rates of exploitation. Furthermore, our scenario-specific discussion of exploitation rates indicates that decreases in labour exploitation as the result of higher seed-coefficients are minimal compared the increases induced by adjustments to labour intensity and unemployment (see Figures 4.16 - 4.19).
So far, this discussion aimed to summarize the intricate relationship between distribution, exploitation and agro-ecological degradation as the result of the various assumption pertaining to our simulation model. Its take-away message is that favourable conditions for workers, through higher employment and less adjustments to labour intensity, result in higher levels of fertility and a lower degree of exploitation. Particularly with respect to the relationship between employment and fertility, this is clear in the comparison we make between the LWP and HWP schemes for scenario 5 in Figure 4.14. All things considered, agro-ecological well-being shares a two-way relationship with worker well-being in a material and cognitive sense. Such an evaluation holds throughout the first and post-expansion long-period positions, when the agro-ecological system is still appropriated. Given that capitalists are ignorant of the relationship between agro-ecological and worker well-being, they perceive the well-being of workers to stand in direct opposition to the profit-motive. If workers were to demand less labour intensive organization methods ($I^A \downarrow$) and/or shorter working days ($h^A \downarrow$) accompanied by higher wages ($b^A \uparrow$), this would place downward pressure on the rates of

profit. Even if the eventual lower seed-coefficient would ultimately result in higher profit rates. Instead, reckless adjustments to working conditions (together with over-employment) result in a negative profit differentials which incentivize the capitalization of the agro-ecological system. Capitalization not only results in long-run soil degradation but additionally eradicates the relationship between the well-being of workers and the agro-ecological system. As a result, improvements in worker well-being no longer impact the state of the agro-ecological system. Once capitalization takes place, workers are indeed better off if worker protection is higher but this is merely through the maintenance of sufficiently high material gains. Higher worker protection does not prevent capitalists from adopting labour intensity increasing production organization methods. The reason why further adjustments to intensity are less present in capitalization under the HWP scheme is only the result of over-employment.

### Expansion intensities and agro-ecological degradation

Our contribution provides a reformulation of the idea that industrial development and the additional provision of use-values is doomed to result in agro-ecological degradation. Aspects of industrial development which are often highlighted are its *scale* and *intensity*. While the issue of scale is absent in our modelling approach, variations in intensity are what distinguish the various scenarios. Our modelling approach and the various assumptions therein suggest that higher intensities *do* result in lower fertility levels in the post-expansion long-period for both the HWP and LWP schemes. Figure 4.27 captures the development of fertility for scenarios 3 to 13 under the HWP scheme.[17]

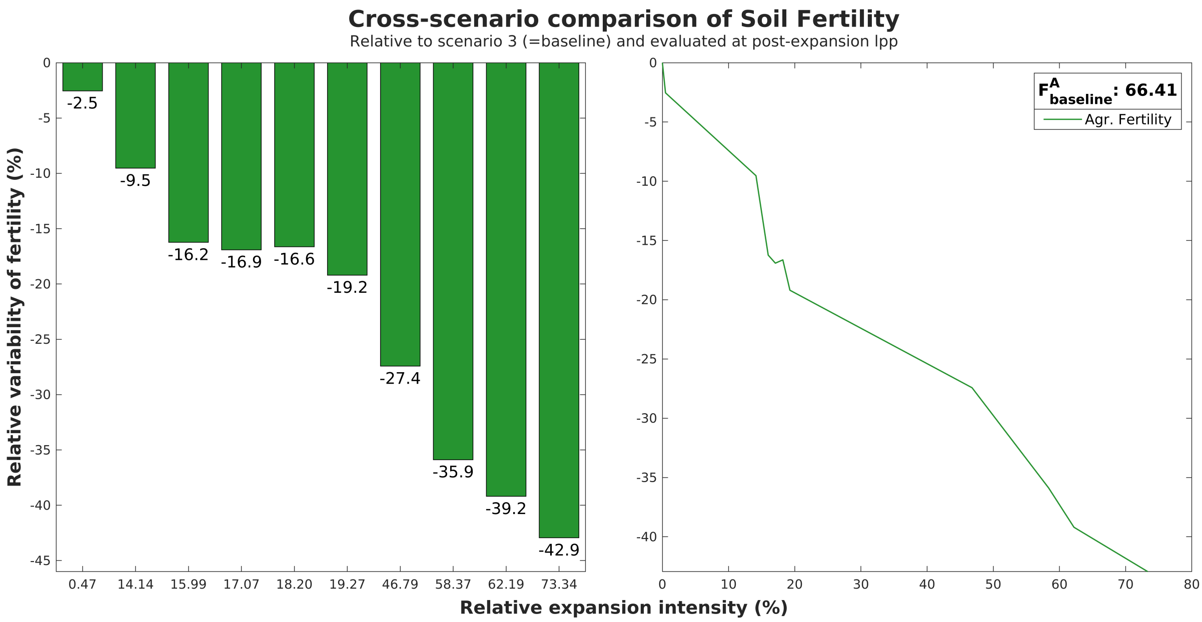



Figure 4.27: Cross-scenario comparison of agricultural fertility

[17] Scenarios 1 and 2 are excluded because they are subject to a zero variability of fertility with respect to the first long-period position. Furthermore, a discussion of scenarios under the LWP scheme results in outliers related to the presence of lay-offs in the post-expansion long-period as the result of over-employment.

The subplot on the left portrays a bar-chart which displays the relative variability of fertility against the relative variability of expansion with respect to baseline scenario 3. As mentioned before, the expansion intensity is determined by variables $b_I^{I^*}$ and $E^{I^*}$. Our measure is based on the difference between total output *at the moment of expansion* and one period *before* expansion: $\Delta Y = Y_{se} - Y_{se-1}$. Hence we'll have that, for an expansion intensity which is 15.99% higher than the expansion intensity in scenario 3, the level of fertility in the post-expansion long-period is 16.2% lower than under scenario 3. On the other hand, for an expansion intensity which is 58.37% higher than the baseline, the level of fertility in the post-expansion long-period is 35.9% lower. The subplot on the right portrays a line-plot with the relative variability of the expansion intensity on the x-axis and relative variability of fertility on the y-axis. This is just to show, that were we to assume that expansion intensity is continuous, the estimated relationship between relative expansion intensity and the relative variability of fertility is approximately linear and generally decreasing.

The specific mechanism through which the intensity of agro-ecological degradation is positively related to the expansion intensity is far more nuanced than simply higher levels of output. On the one hand, higher expansion intensities result in higher amounts of necessary labour inputs for both the industrial and agricultural sector. If the industrial sector meets the labour increase through increases in the working day or the labour force, demand for the agricultural commodity increases. A higher fraction of agricultural output exported to, let's say urban industrial centres, results in a reduction of the material metabolism parameter which determines fertility levels. This is precisely how Marx formulated the metabolic rift with respect to industrialization, agricultural intensification and the increasing divide between town and country. That which we additionally consider in our modelling approach is purpose realisation which is proxied by the relative working conditions of the agricultural sector with respect to the subsistence sector. Variability thereof is as much of a determinant of soil fertility. Within the confines of our simulated model, the question then becomes which component, material metabolism or purpose realisation, is the strongest driver of agro-ecological degradation as expansion intensity increases. Figure 4.28 depicts the relative variability of material metabolism for scenarios 3 to 13 under the HWP scheme:

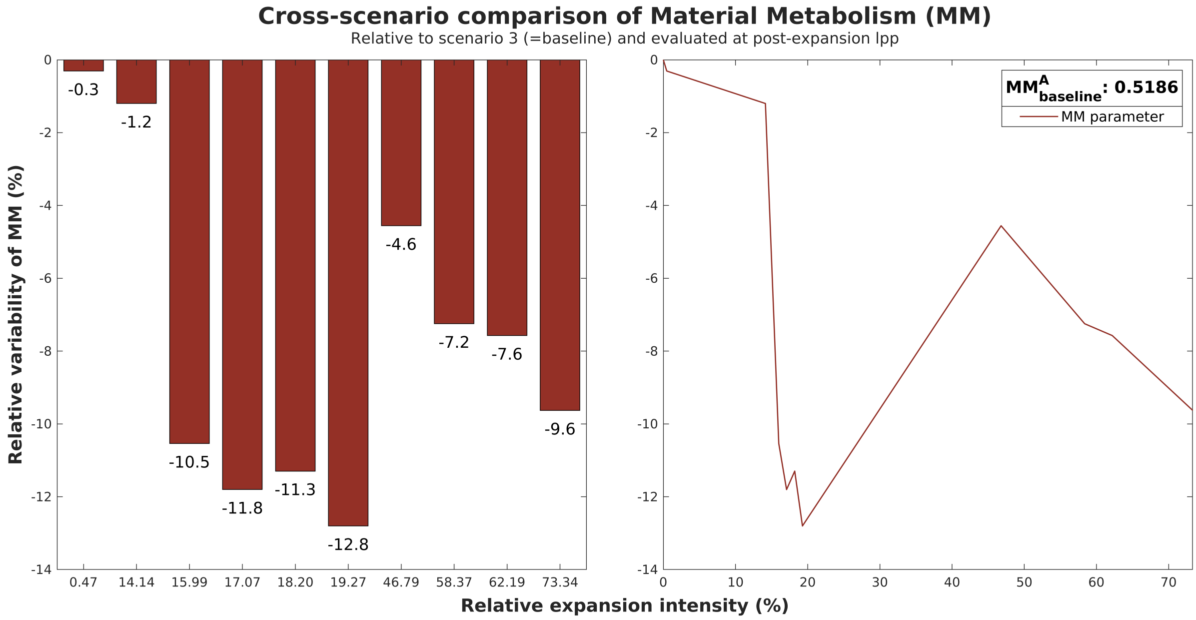



Figure 4.28: Cross-scenario comparison of material metabolism

The figure clearly indicates that the relationship between expansion intensity and material metabolism is still negative but less linear than the relationship between expansion intensity and fertility levels. For example, we see that for an expansion intensity which is 14.14% higher than the baseline, the material metabolism parameter decreases by 1.2%. A percentage differential of 1.85% (from 14.14% to 15.99%) in terms of the expansion intensity, however, results in a 10.5% decrease of the material metabolism. Obviously, this is related to the stark increase of demand for the agricultural commodity in the city as the result of labour mobilization and/or additional adjustments made to $h^I$ in order to meet necessary labour inputs. The reason why an expansion intensity which is 46.79% higher than the baseline translates to a decrease of the material metabolism parameter by merely 4.6% is the result of the fact that such expansion intensities require labour mobilization into the agricultural sector as well. This is able to off-set the effect of an increased industrial labour force on $\frac{n^A}{n^{A*}}$. Finally, the increasingly negative relationship for the highest relative expansion intensities (last 4 bars) is related to the higher adjustments to $h^I$ and ultimately the fact that labour mobilizes from the agricultural sector to the industrial sector in the last two scenarios.

The slight decrease in the metabolic parameter variability with respect to the baseline would lead one to think that variability in the measure of fertility must decrease (become less negative) as well. But Figure 4.27, clearly indicates that this is not the case. This must mean that the increasingly negative relationship between the relative expansion intensity and relative variability of fertility is driven by purpose realisation. Figure 4.29 displays the development of purpose realisation across scenarios 3 to 13:

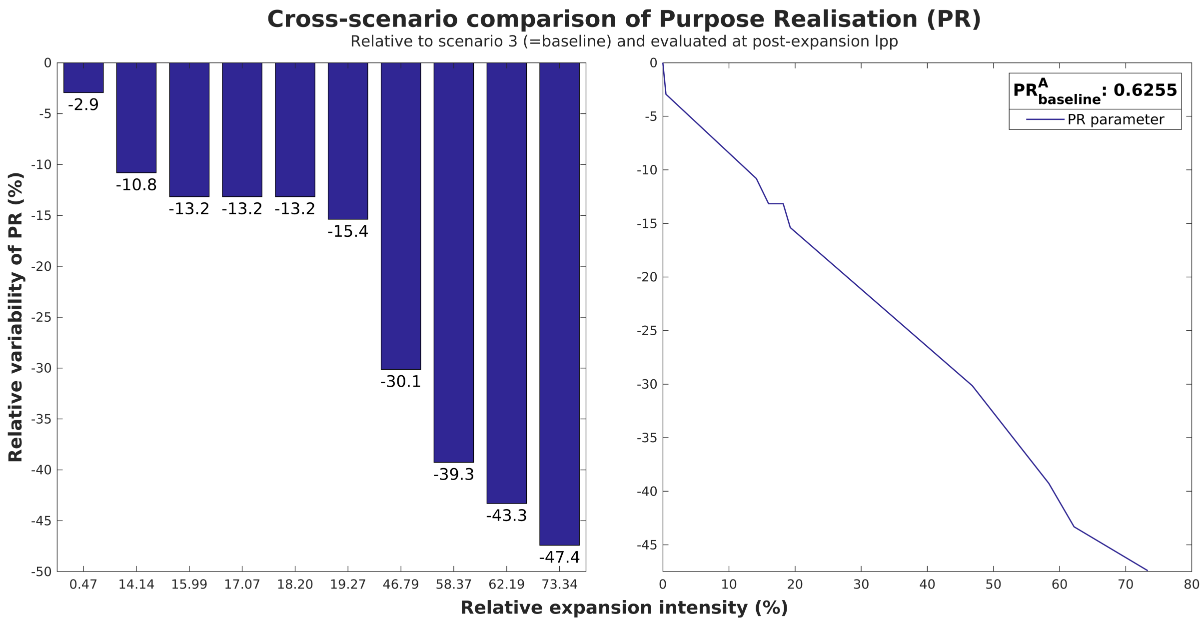



Figure 4.29: Cross-scenario comparison of purpose realisation

From the figure it is clear that for the range of relative expansion intensities between 46.79% and 73.34% the relative variability of fertility levels, which is negative and increasing, is mainly driven by purpose realisation and not material metabolism. For relative expansion intensities 15.99%, 17.07% and 18.20% we see that the variability of purpose realisation is constant while the variability of fertility levels in Figure 4.27 *slightly* fluctuates. This fluctuation is the result of modest fluctuations in material metabolism indicated in Figure 4.28. Overall, the range of relative variability of purpose realisation (2.9% - 47.4%) is wider than the range of variability for material metabolism (0.3% - 12.8%), which indicates that the main driver of agro-ecological degradation until the post-expansion period is purpose realisation.

The above exposition of relative fertility, material metabolism and purpose realisation measures aimed to capture an often overlooked aspect of industrial development with respect to ecological degradation. Namely, that it is not only the physiological components (material metabolism) of ecological processes which become deteriorated as the result of industrial development. Purpose realisation, also plays a significant role and it has less to do with the physical characteristics of what is produced and more to do with *how* labour is organized in order to produce.

In sum, when it comes to relationship between the *intensity* of industrial development and ecological degradation, the *organization* of production plays an equally (if not more) significant role. Capitalistically organized production which is governed by the profit-motive and accumulation is based on production organization methods which are exploitative and therefore alienating. While higher wage-rates as the result of worker protection and the effect thereof on employment is able to off-set some of this alienation and increase worker well-being, it is not sufficient to guarantee an improvement in the metabolic relationship between workers and the ecological processes they depend on.

As indicated by Figure 4.24, capitalization and therefore *extreme* agro-ecological degradation is prevented, or *can* be prevented at the expense of higher exploitation rates (scenarios 5, 6 and 9 under LWP) in terms of lower wage-baskets and/or higher labour intensities. Then, in the face of the negative relationship between wages and profit-rates, higher worker protection and therefore higher levels of worker well-being, incentivize capitalization due to lower profit rates. The only difference between LWP and HWP, once capitalization has taken place, is a higher level of worker well-being under the latter — an attainment which no longer stands in relationship with the well-being of the agro-ecological system.

### Implications for climate change

The following subsection is dedicated to the implications of our modelled insights for other contemporary ecological problems, particularly climate change.[18] One of our insights described a link between agricultural worker and agro-ecological well-being by means of the agricultural wage-basket. The higher the agricultural wage-basket, the higher the amount of nutrients returned to the soil; enhancing the state of the agro-ecological system. Climate change concerns the emission of greenhouse gasses through a variety of energy-dependent activities that are considered to be essential to human life. If the increased agricultural wage-basket is extrapolated to signify increased consumption, it is hard to imagine how higher consumption levels can lead to decreased greenhouse gas emissions in absence of increased energy efficiencies. But there's a reason an increase in agricultural commodity consumption, not industrial commodity consumption, results in a synergistic effect on ecological and human well-being. Furthermore, it is agricultural commodity consumption by *agricultural workers* which results in the aforementioned synergy. This is all to point out that our insight does not simply suppose that absolute increases in consumption levels are beneficial for ecological processes. It is crucial to consider the *type* of consumption as well as the *recipients* of increased consumption possibilities.

When it comes to the type of consumption, one can argue that this reflects the necessity to engage in the consumption of low-carbon intensity goods vs. high-carbon intensity goods. For example, organic vs. processed food, electric vs. fossil-fuel powered vehicles etc. Such goods are not only said to be better for the biophysical environment but are subject to various health effects as well. Organic food is often a better source of essential nutrients (for humans) compared to processed food. The exhaust of electric vehicles is null compared to that of a vehicle which combusts diesel. By and large, the relationship between planetary and human well-being through an increase of the consumption of one "green" good over its "brown" counterpart is well-documented across scientific fields.

[18] It should be noted that our implications are mainly oriented towards the Global North/Western societies. Considerations on the Global South (emerging and developing economies) are crucial but extend beyond the scope of the current contribution.

When it comes to the recipients of consumption, our insight suggests that the state of an ecological process improves when workers, whose labour stands in a direct relationship to an ecological process, receive a higher fraction of the produced surplus. In our model, the agricultural wage-basket was considered as the component of a minimum wage-basket, capable of fulfilling a basic human need. Zooming out of the specificity of agricultural production and the importance of nutrient cycles, the aforementioned can be extrapolated to assert that ecological sustainability requires that the labours involved in the appropriation of ecological processes must have their basic needs met. This, precisely in order to provide the rest of society with use-values that are produced under circumstances of human and planetary well-being. Specifically with respect to climate change, the majority of society is an indirect appropriator of earth system's ecological and biophysical processes through reliance on food and fossil fuel combustion for the provision of basic needs. Seen in this way, our insight seems to argue that the guaranteed satisfaction of human needs for each and every worker is a precondition for ecologically sustainable production. This too, accommodates exemplar studies on the debated inverted-U relationship between human development and "eco-friendly" technological change. In contrast to most of these studies, however, we consider it to be a necessary but not a sufficient condition.

Considerations on the consumption of one good over the other as well as the fulfilment of basic needs can be seen as the 'material metabolism' channel through which human and planetary well-being fortify each other. What about the 'purpose realisation' element of the labour process? Reducing the length of the working day, nowadays referred to as working-time reduction, carries the possibility to reduce occupational health problems while simultaneously allowing the substitution of short-term high-carbon consumption for long-term low-carbon consumption. For example, workers could take a 3-day holiday to Ibiza by flight vs. a 7-day trip to Amsterdam by train. Alternatively, they could do groceries at a local market and enjoy a moment of cooking instead of having fast-food delivered at home on a fossil fuel powered motorbike. Again, there is an upcoming stream of literature addressing how a reduction in working-time bears the potential to dampen climate change impacts by means of leisure-induced consumption substitution from low-carbon to high carbon goods. Much like the earlier considerations on consumption, the substitution of labour for leisure is assumed to lead to "eco-friendly" adjustments in society's consumption composition. Therefore, it can be seen as another way to arrive at the material metabolism channel through which the synergy between planetary and human well-being becomes a reality.

Ultimately, the main novelty of our contribution lies with its emphasis on the alienating character of capitalist social relations. In our model, the organization of production for the purpose of profit grants capitalists the opportunity to organize labour to ever-alienating extents. This process is captured through the measure of labour intensity and its partial determination of both worker and agro-ecological well-being. In our view, this consideration captures the necessity to incorporate measures which address *how* by *who* and *for what purpose* production is *organized* in addition to measures that dictate *how* a given production process proceeds and *what* share of the surplus is distributed to labourers post-factum. As argued by Barca (2019a): "the alienation of producers from the products of their work is what leads to the reinvestment of surplus into increased production" (Ibid, 2019a: pp. 209). We find it important to highlight the purpose of increased production since the reinvestment of surplus into the expansion of basic needs such as housing, care, health and education is essential. The crux of Barca's consideration lies with the decision-making over the re-investment of surplus and the auxiliary importance of surplus re-investment for the purpose of conserving biophysical, ecological and social reproduction. This type of decision-making should be undertaken collectively and democratically by both waged and non-waged labour. Alternatives to the dominant organization of production are particularly present in the field of agricultural production. Scholarly work largely indicate that the cooperative form of agricultural production can play a positive role when it comes to farm sustainability (Candemir et al., 2021) but still face serious challenges when it comes to the provision of economic security in emerging and developing countries (Tschopp et al., 2020).

In essence, we contend that the alienating character of contemporary social relations in the sphere of production is a co-determinant of the divergence between planetary and human well-being. Or, in other words, that the maintenance of capitalist relations of production is a previously unconsidered aspect of wicked economy-ecology configurations. The absence of democratic and collective decision-making over the reinvestment of surplus, another characteristic of alienated social relations, forms an obstacle for the synergistic impact of the previously highlighted channels concerning consumption. In our model, all of this is trivially captured through the measure of labour intensity and some may argue that this mechanistic approach to alienating social relations is quixotic or out-dated. But we beg to differ. For example, with respect to food delivery it is worth noting the susceptibility of riders to algorithmically orchestrated increases in labour time intensity. In China for example, the algorithms that run the gig-economy are constantly squeezing the maximum time in which a delivery should reach final customers. Failure to abide by the dictated time results in decreased compensation. The introduction of algorithmically estimated delivery times is a form of technological change, but the continued reduction of this time is nothing more than a capital-led adjustment to labour intensity. Consequently, various riders have been forced to disobey traffic laws some of them even ended up in serious accidents. If this is what the "triumph of technology" entails, then we can comfortably proceed to affirm the significance of labour intensity adjustments for ecological processes. The algorithms that orchestrate these adjustments operate on energy and water consuming servers as they rift and alienate the workers they control from themselves, their labour and ecological processes.

## Conclusion

The aim of this paper was to expose the reader to an attempt at formally representing eco-Marxist insights. This was done through the introduction of various equations pertaining to a 3-sector open economy. The main innovation of our theoretical depiction of a 3-sector economy is related to the incorporation of a natural entity, the agro-ecological system, which supports the production process in a *hidden* way. Instead of abiding by the dominant representation of economy-ecology configurations, which assumes that natural resources or ecological processes *enter* the production process, we allow ecological processes to interact with the technical coefficient of the production process.

On the one hand, this interaction is determined by exogenously given parameters. On the other hand, and most importantly, the interaction is additionally modelled as a function of i) the material return of nutrients to the soil by the agricultural labour force and ii) *relative* working conditions in capitalistically organized agriculture. The reason why we characterize this interaction as *hidden*, is because we assume that capitalists, who own the means of production and thereby hold the right to *organize* the participation of labour in the production process, are not aware of this interaction. They only witness variations in the technical coefficients as the result of supply shortages.

Since our theoretical model operates in a Sraffian/neo-Ricardian (physicalist) framework, distribution in our 3-sector economy is based on the division of the physical surplus between capitalists and workers. Curiously, we nevertheless operationalize an adapted measure of labour exploitation based on the labour embodied in the wage-basket and labour intensity measures. The latter is additionally a determinant of the relative working conditions which feed back into the state of the agro-ecological system. The purpose of our exploitation rate variable is not to capture a measure of distribution but rather to reflect the subordination/alienation/estrangement of workers under capitalist production processes. In a way, it serves as a measure of worker well-being, which is a function of a material component and more of a psychological or cognitive component.

Ultimately, the aim of this contribution was to draw some insights on the relationship between distribution, exploitation and agro-ecological degradation through a computational analysis derived from the constructed set of equations. Remaining within the scope of the 3-sector economy and the simulation thereof, the main result can be summarized as follows:

- Positive variations in distribution, in favour of workers and as the result of higher employment, positively contribute to the state of the agro-ecological system and increase worker well-being through a decrease of exploitation rates, and *vice versa*. This relationship holds for both agricultural and industrial workers.

- Positive variations in the agricultural rate of exploitation, as the result of upward adjustments to the agricultural labour intensity, go hand in hand with negative variations in the state of the agro-ecological system. The magnitude of this relationship is stronger than that between employment and the agro-ecological system.

- Higher seed-coefficients result in an increased demand for the industrial intermediate good often causing upward adjustments to the industrial labour intensity as a means to meet necessary labour inputs. In this way, negative variations in the state of the agro-ecological system indirectly result in positive variations in the industrial rate of exploitation.

- Finally, negative variations in the state of the agro-ecological system result in subsequent positive variations in the rates of exploitation as the result of a higher amount of labour embodied in the wage-basket. The magnitude of this relationship is far weaker than the instantaneous relationship through adjustments in agricultural labour intensity.

Apart from the above, we have also illustrated the aptitude of the Sraffian/neo-Ricardian framework for the purpose of describing the relationship between the ecological surplus and uniform rates of profit. This was achieved through a comparison of generalized (instead of scenario-specific) w(r)-curves and the assessment of variations in the reliance of production on appropriated and capitalized ecological and labour processes.

There are many limitations to our computational analysis and they are related to the various abstractions which were necessary for a manageable representation of economy-ecology configurations. One particular limitation is related to the rather static and most importantly, semi-idealized role of the subsistence sector. In our modelling approach, the subsistence sector remains unaffected by capitalist development and related labour mobilization. As an example, the negative change in the average product of the subsistence sector when unemployment increases, is not considered to be a problem. In reality however, migration from rural areas to urban centres, is not a process without complex consequences. More than often, rural-urban migration creates a financial dependency (through remittances) between rural households and household members who have migrated. This sometimes results in the mismanagement of the farm as the result of the geographical distance between the person in charge of the farm (mostly men) and the household members who are still labouring the farm. At the same time, mass migration from rural to urban areas could leave previously cultivated lands abandoned; transforming the agro-ecological system into a more efficient carbon sink. Though capitalist agricultural sectors would likely engage in further intensification to meet increased urban demand.

Another interaction between the subsistence and capitalist sectors we failed to touch upon, is related to the phenomenon of land-grabbings. This is because considerations on expansion, beyond that which we've coined as socio-economic progress, were absent. Subsistence farmers have historically faced and, unfortunately, continue to face loss of livelihoods as the result of large-scale land acquisitions by multinational corporations interested in the extraction of natural resources. Finally, we idealized subsistence agricultural production in assuming that it operates on the basis of zero profits and maintains a healthy/desired/optimal rapport with the agro-ecological system. In reality, subsistence farmers are increasingly participating in the market-place (or incentivized to do so). In order to compete with intensive agriculture, they too start relying on the use of external inputs such as fertilizers, herbicides and pesticides. The intent of our contribution should not be read as a repudiation of small-holder farm commercialization nor its heightened reliance of external inputs. Such a development is but only a logical outcome in a socio-economic system in which abiding by the market-logic is the easiest way to guarantee survival and a better future.

Apart from the above, the consequences of fertilizer use are not always as devastating as depicted in our model. In the end, the method of abstraction followed in the construction of our model is based on the isolation of extremes. First, a production method and organization which is agro-ecologically sustainable (the subsistence sector), second, a production method and organization which is agro-ecologically sub-optimal (capitalist appropriation of the agro-ecological process) and third, a production method and organization which is dismal (capitalist capitalization of the agro-ecological process). What distinguishes these methods however is not the existence of an optimal allocation of capitalized resources. Instead, the *key* distinction among them is the way in which labour is organized. This distinction is made evident through the absence of the profit-logic and assumed co-existence and sustainable rapport between the activity of labouring and the appropriation of sustenance.

Other limitations of our modelling approach are related to the fact that trade-openness is entirely exogenous (e.g. import prices and comparative advantages of the economy with respect to the rest of the world). In addition, a government sector is absent and while debts are incurred, we do not take into account interest rates nor a separate banking sector. We leave it up to the reader to point out the remainder of this contribution's limitations (we are aware that they are many).

In an attempt to extrapolate the insights of our model to the broader issue of climate change, the final section discussed the relevance of consumption in relationship to their carbon intensity and as a means to meet basic human needs. We argued that in conjunction with reduced working days, consumption oriented measures are a necessary but not a sufficient condition for the desired convergence between human and planetary well-being. The same goes for the transformation of production processes into those which are less dependent on ecological degradation. By drawing attention on a proxy measure for alienation, labour intensity, we argue that a *fundamental* necessary condition for ecological sustainability is the alternative *organization* of production and collective decision-making on the reinvestment of the surplus. For all one knows, this could be a democratically planned economy based on the production of use-values and the maintenance of value which sustains social, ecological and biophysical reproduction. This would not only require the inclusion of labours beyond that which is considered to be wage-labour but an alternative organization of science and technology; one which is less technocratic and more democratic.

All together, we hope that this paper's alternative process of abstraction has pointed out the ability to arrive at distinct insights on economy-ecology considerations. Our process of abstraction aimed to lay a bit more emphasis on the economy-ecology interactions from the perspective of *how* and by *who* production is organized with reference to labour, rather than merely discussing the ecological/biophysical implications of physical quantities that go in and come out of a production process. Ultimately, this is what we consider to be one of the unique insights provided by eco-Marxism *for* Ecological Economics.

## Appendix C

# Initial conditions, exogenous variables and parameters

Parameters/variables that remain constant over time

| Variable | Description | Restriction | in MATLAB | Value |
|---|---|---|---|---|
| $Y^S$ | Output in subs. sector | $Y^S > 0$ | `Ys` | 60000 |
| $\boldsymbol{a}_S^S$ | Seed coefficient subs. sector | $\boldsymbol{a}_S^S \in (0, 1)$ | `ss` | 0.25 |
| $\boldsymbol{l}^S$ | Labour coefficient subs. sector | $\boldsymbol{l}^S > 0$ | `ls` | 0.8 |
| $h^S$ | Length of working day subs. sector | $h^S \leq h^{A,I}$ | `hs` | 5 |
| $I^S$ | Intensity of the working day subs. sector | $I^S = 1$ | `Is` | 1 |
| $\boldsymbol{l}^A$ | Labour coefficient agr. sector | $\boldsymbol{l}^A < \boldsymbol{l}^S$ | `laa` | 0.55 |
| $\boldsymbol{l}^I$ | Labour coefficient ind. sector | $\boldsymbol{l}^I < \boldsymbol{l}^A$ | `lii` | 0.35 |
| $\boldsymbol{l}^{I*}$ | Labour coefficient ind. sector in periods after expansion | $\boldsymbol{l}^{I*} < \boldsymbol{l}^I$ | `lii_n` | 0.3 |
| $\boldsymbol{a}_I^A$ | ind. good coefficient agr. sector | $\boldsymbol{a}_I^A \in (0, 1)$ | `ai` | 0.35 |
| $\boldsymbol{a}_I^I$ | ind. good coefficient ind. sector | $\boldsymbol{a}_I^I > \boldsymbol{a}_I^A$ | `ii` | 0.5 |
| $z$ | Production period | $z > 0$ | `z` | 35 |
| $F^*$ | Optimal fertility | $F^* > F_b$ | `F_` | 100 |
| $F_b$ | Baseline fertility | $F_b < 0$ | `Fb` | 20 |
| $k$ | Fertility curve steepness | $k > 0$ | `k` | 5.0814 |
| $\alpha$ | Working condition parameter | $\alpha > 0$ | `aw` | 1.5 |

| Variable | Description | Restriction | in MATLAB | Value |
|---|---|---|---|---|
| $m$ | Seed coefficient parameter | $m > 0$ | `m` | 0.30103 |
| $R_a$ | Periods it takes for capitalists to react to change in $a_S^A$ | $R_a \geq 1$ | `rpf` | 5 |
| $R_x$ | Periods of stability required for expansion | $R_x \geq 1$ | `se_p` | 10 |
| $m_A$ | Mobilization parameter agr. labour force | $m_A \in (0, 1)$ | `a_max` | 0.16 |
| $m_A^S$ | Mobilization parameter subs. labour force to agr. sector | $m_A^S \in (0, 1)$ | `sa_max` | $\frac{1}{9}$ |
| $m_I^S$ | Mobilization parameter subs. labour force to ind. sector | $m_I^S \in (0, 1), m_I^S < m_A^S$ | `si_max` | $\frac{1}{15}$ |
| $N_{min}^A$ | Minimum labour force in agr. sector | $0 < N_{min}^A < N_0^A$ | `Na_min` | 150 |
| $h^{max}$ | Institutionally determined maximum length of the working day | $h^{max} > h^S$ | `hmax_p` | 12 |
| $I^{max}$ | Institutionally determined maximum intensity of the working day | $I^{max} > 1$ | `Imax_p` | 1.5 |
| $E^A$ | agr. good exports | $E^A > 0$ | `exa` | 300000 |
| $E^I$ | ind. good exports | $E^I \geq 0$ | `exi` | 0 |
| $E^{I^*}$ | Autonomous consumption ind. good in periods after expansion | $E^{I^*} > E^I$ | `exi_n` | *sim* |
| $b_I^I$ | Wage basket ind. good for ind. labour force | $b_I^I \geq 0$ | `bi` | 0 |
| $b_I^A$ | Wage basket ind. good for agr. labour force | $b_I^A = b_I^I$ | `bi` | 0 |
| $b_{I^*}^I$ | Wage basket ind. good in periods after expansion for ind. labour force | $b_{I^*}^I > b_I^I$ | `bi_n` | *sim* |
| $b_{I^*}^A$ | Wage basket ind. good in periods after expansion for agr. labour force | $b_{I^*}^A = b_{I^*}^I$ | `bi_n` | *sim* |
| $b_A^\epsilon$ | Wage basket premium agr. good when ind. sector draws on agr. labour force | $b_A^\epsilon + b_A^I > b_A^A$ | `ba_e` | 0.1 |
| $b_I^\epsilon$ | Wage basket premium ind. good when ind. sector draws on agr. labour force | $b_I^\epsilon + b_{I^*}^I > b_{I^*}^A$ | `bi_e` | 0.1 |
| $m^R$ | Mark-up rate on imported goods | $m^R > 1$ | `m_r` | 1.2 |
| $p^F$ | Relative price of fertilizer | $0 < p^F < p^A$ | `p_f` | 0.25 |
| $\boldsymbol{a_F^A}$ | Fertilizer use coefficient in agr. sector | $\boldsymbol{a_F^A} \in (0, 1)$ | `af` | 0.2 |
| $\boldsymbol{a_F^I}$ | Fertilizer use coefficient in ind. sector | $\boldsymbol{a_F^I} = 0$ | `iff` | 0 |
| $\boldsymbol{l^{A^*}}$ | Labour coefficient with the use of fertilizer | $\boldsymbol{l^{A^*}} < \boldsymbol{l^A}$ | `la_n` | 0.45 |
| $V^F$ | Labour embodied per unit of fertilizer | $0 < V^F < V^A, V^F < V^I$ | `vf` | 0.2 |

| Variable | Description | Restriction | in MATLAB | Value |
|---|---|---|---|---|
| $\gamma$ | Fertility responsiveness to accumulated fertilizer | $\gamma \geq 1$ | `fres` | 5 |
| $\sigma$ | Fraction of fertilizer accumulated in soil | $\sigma \in (0, 1]$ | `res` | 0.4 |
| $\omega$ | Measure of worker protection (likelihood of lay-offs) | $\omega > 1$ | `l_sen` | 1.1/1.4 |
| | | Initial values specified at $t = 0$ | | |
| **Variable** | **Description** | **Restriction** | **in MATLAB** | |
| $N_0^S$ | Population subs. sector | $N_0^S > 0$ | `Ns` | 5000 |
| $N_0^A$ | Population agr. sector | $N_0^A > 0$ | `Na` | 4000 |
| $N_0^I$ | Population ind. sector | $N_0^I > 0$ | `Ni` | 2000 |
| $I_0^A$ | Intensity of the working day agr. sector | $I_0^A = 1$ | `Ia` | 1 |
| $I_0^I$ | Intensity of the working day ind. sector | $I_0^I = 1$ | `Ii` | 1 |

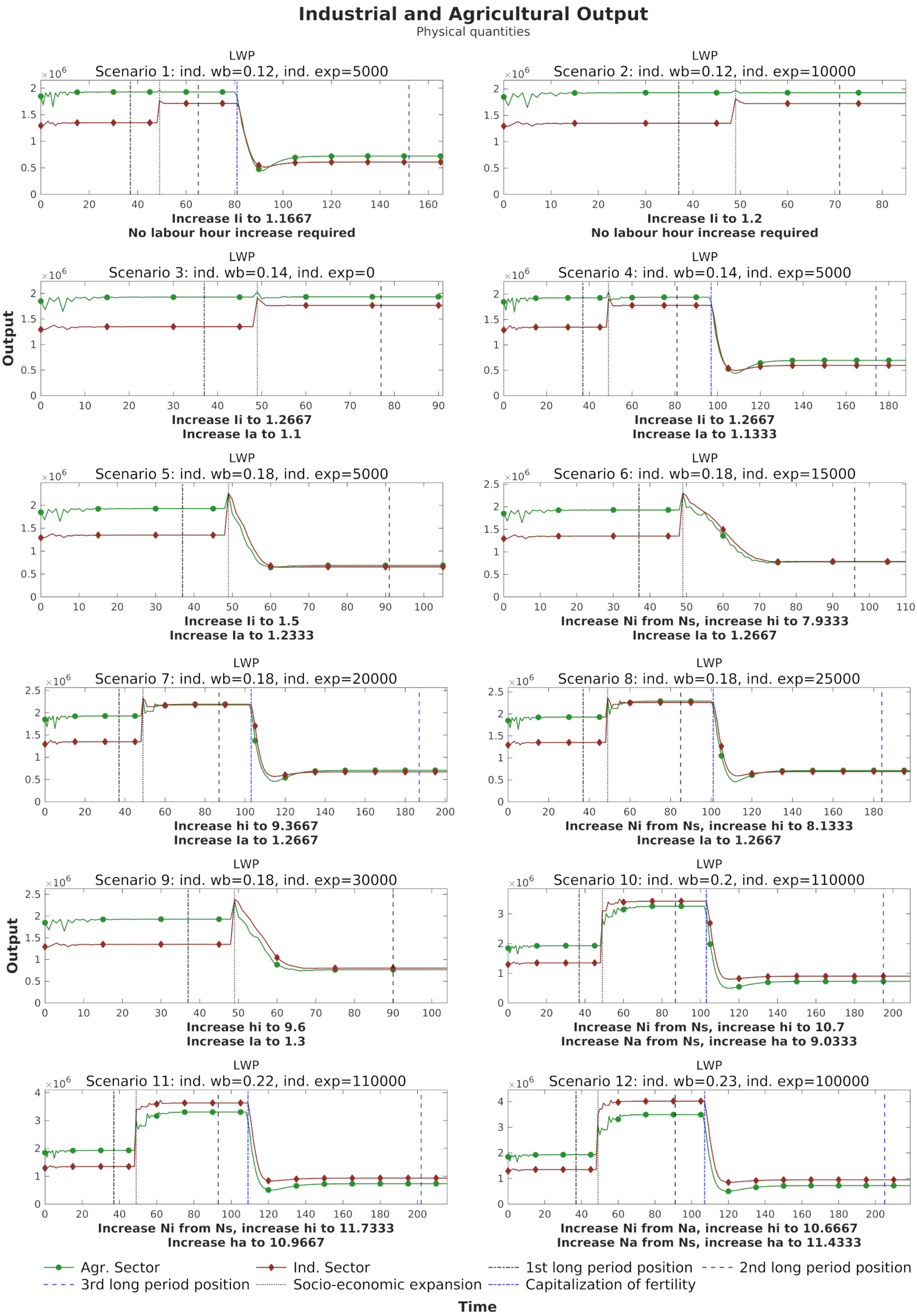
Table C.1: Initial conditions, exogenous variables and parameters

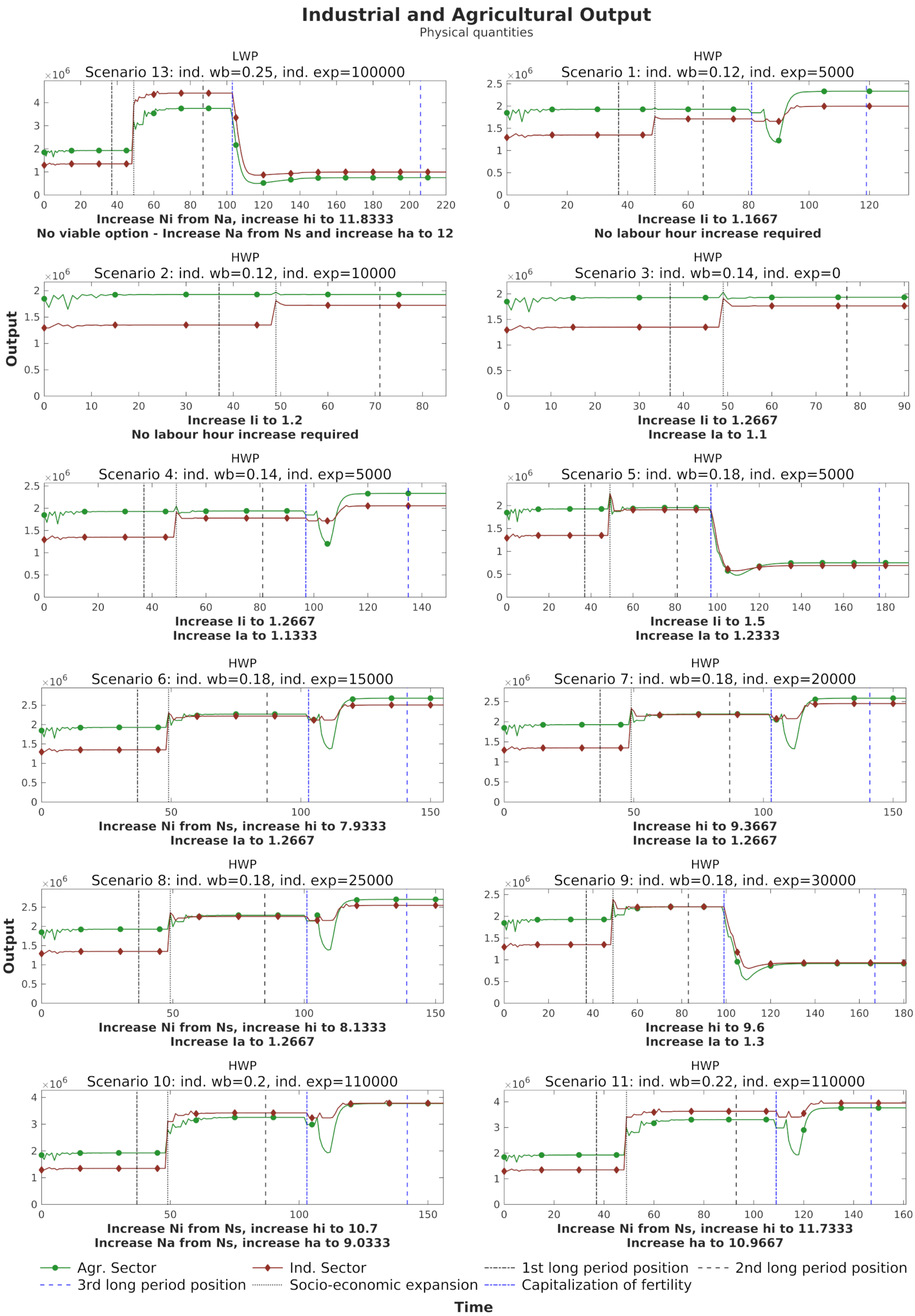
## Appendix D

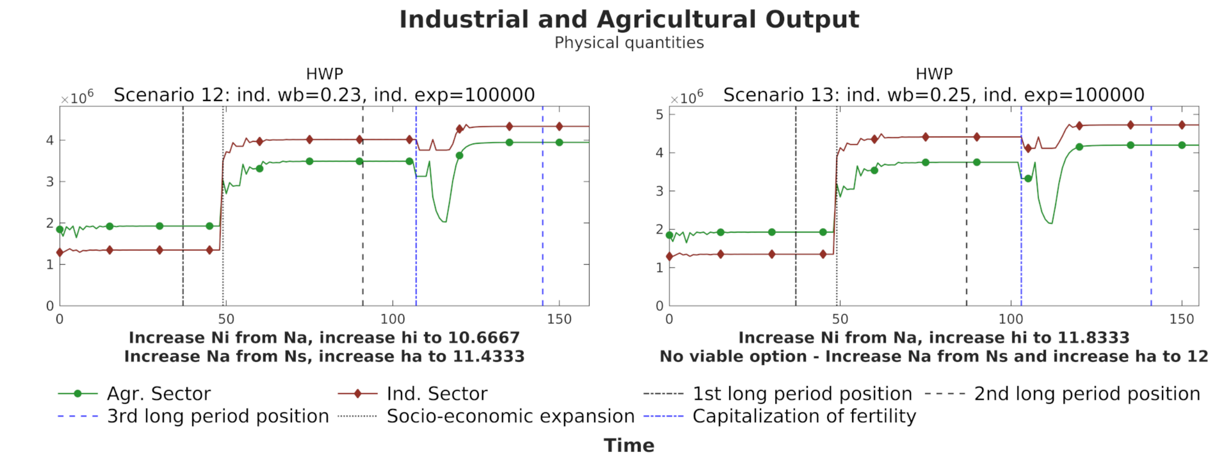
# Simulation result figures for scenarios 1-13

In this Appendix we provide a graphical overview of output, unemployment, wages, agro-ecological fertility and exploitation rates for every selected scenario under both the high worker and low worker protection schemes.

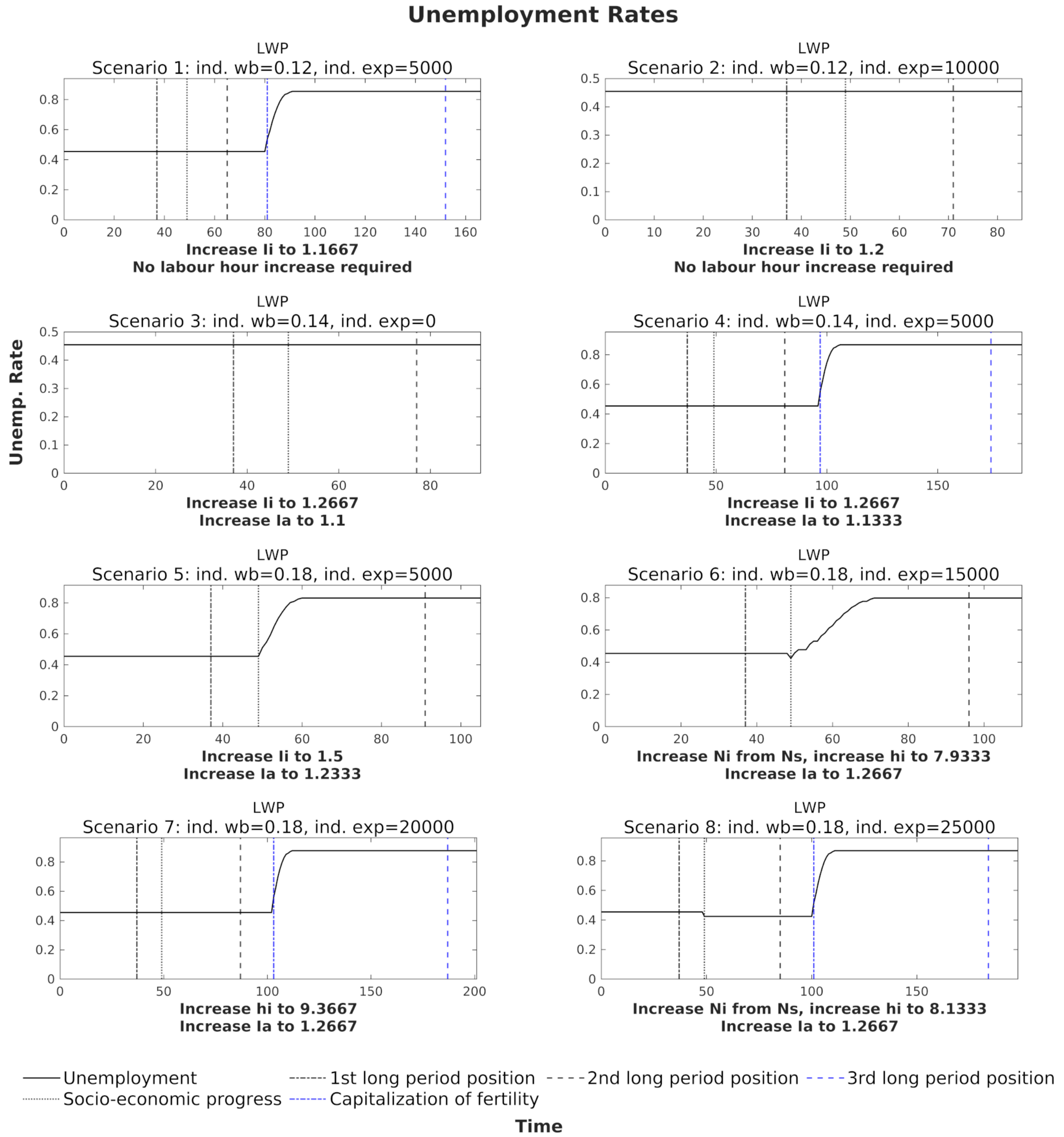
## D.1. Output

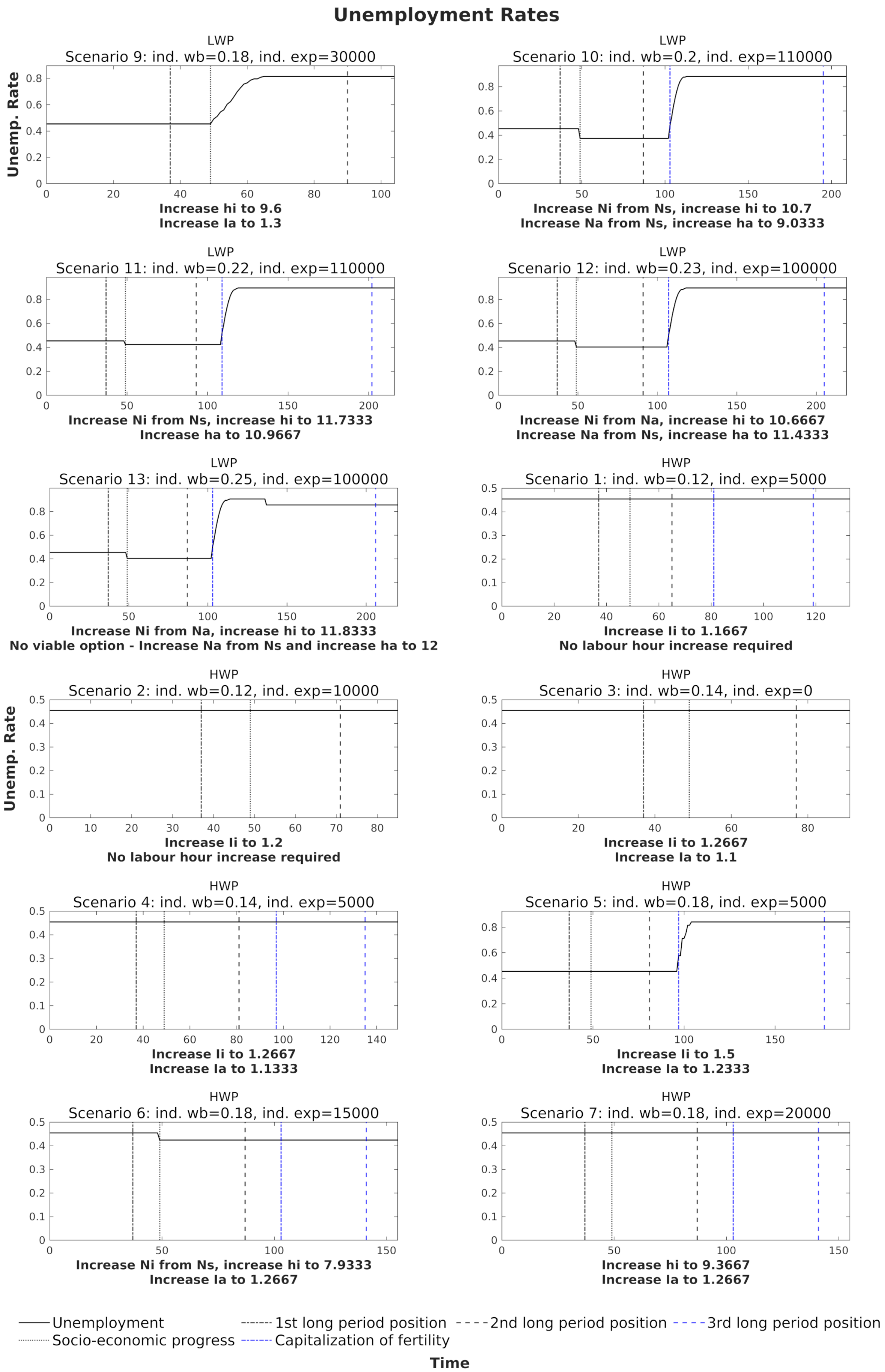

Industrial and Agricultural Output
Physical quantities
LWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase li to 1.1667
No labour hour increase required
LWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase li to 1.2
No labour hour increase required
LWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase li to 1.2667
Increase la to 1.1
LWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase li to 1.2667
Increase la to 1.1333
LWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
Increase la to 1.2333
LWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
LWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
LWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase la to 1.2667
LWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
LWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
LWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
LWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
Output
Output
Agr. Sector
Ind. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic expansion
Capitalization of fertility
Time

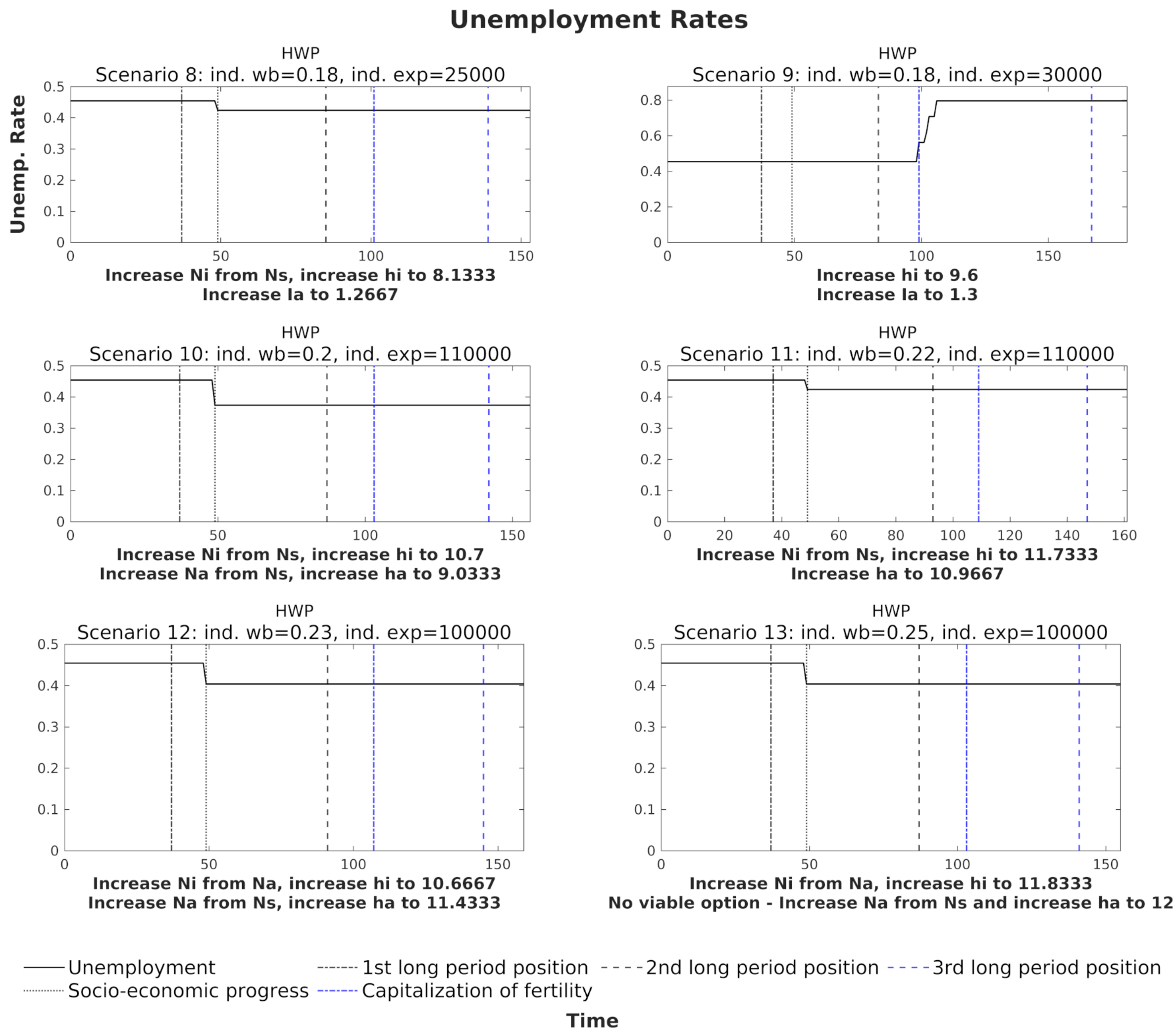

Industrial and Agricultural Output
Physical quantities
LWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
HWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase li to 1.1667
No labour hour increase required
HWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase li to 1.2
No labour hour increase required
HWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase li to 1.2667
Increase la to 1.1
HWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase li to 1.2667
Increase la to 1.1333
HWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
Increase la to 1.2333
HWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
HWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
HWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase la to 1.2667
HWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
HWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
HWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
Output
Output
Agr. Sector
Ind. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic expansion
Capitalization of fertility
Time



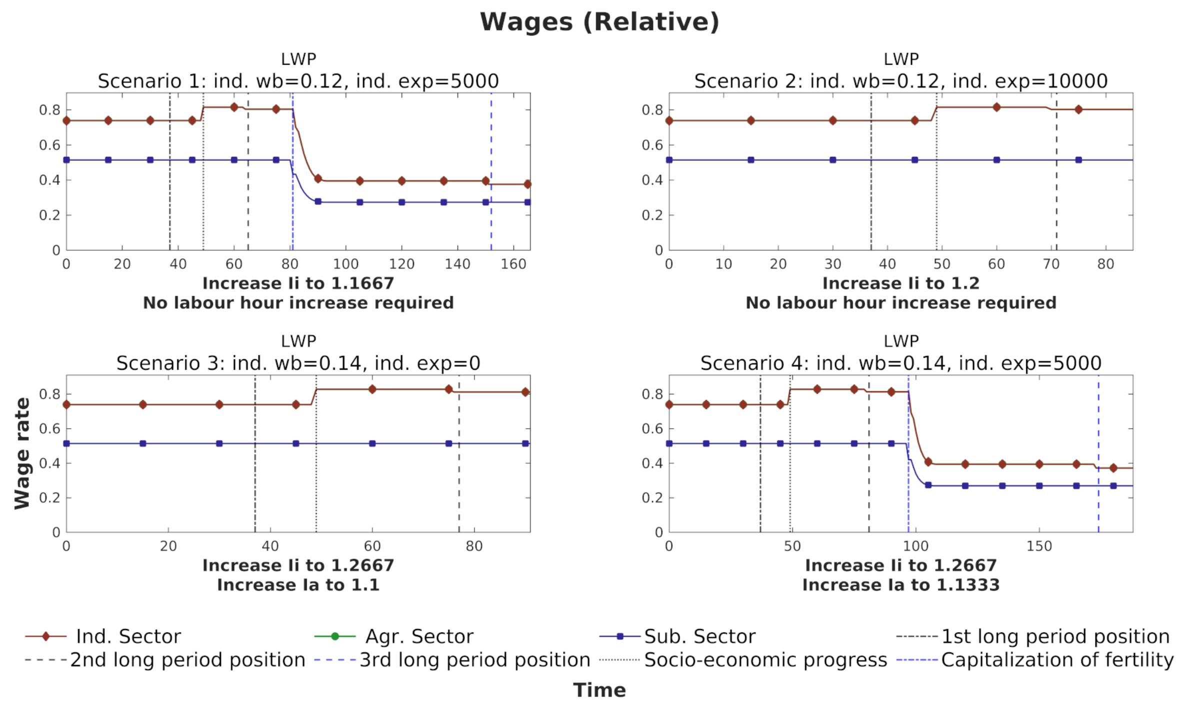

## D.2. Unemployment

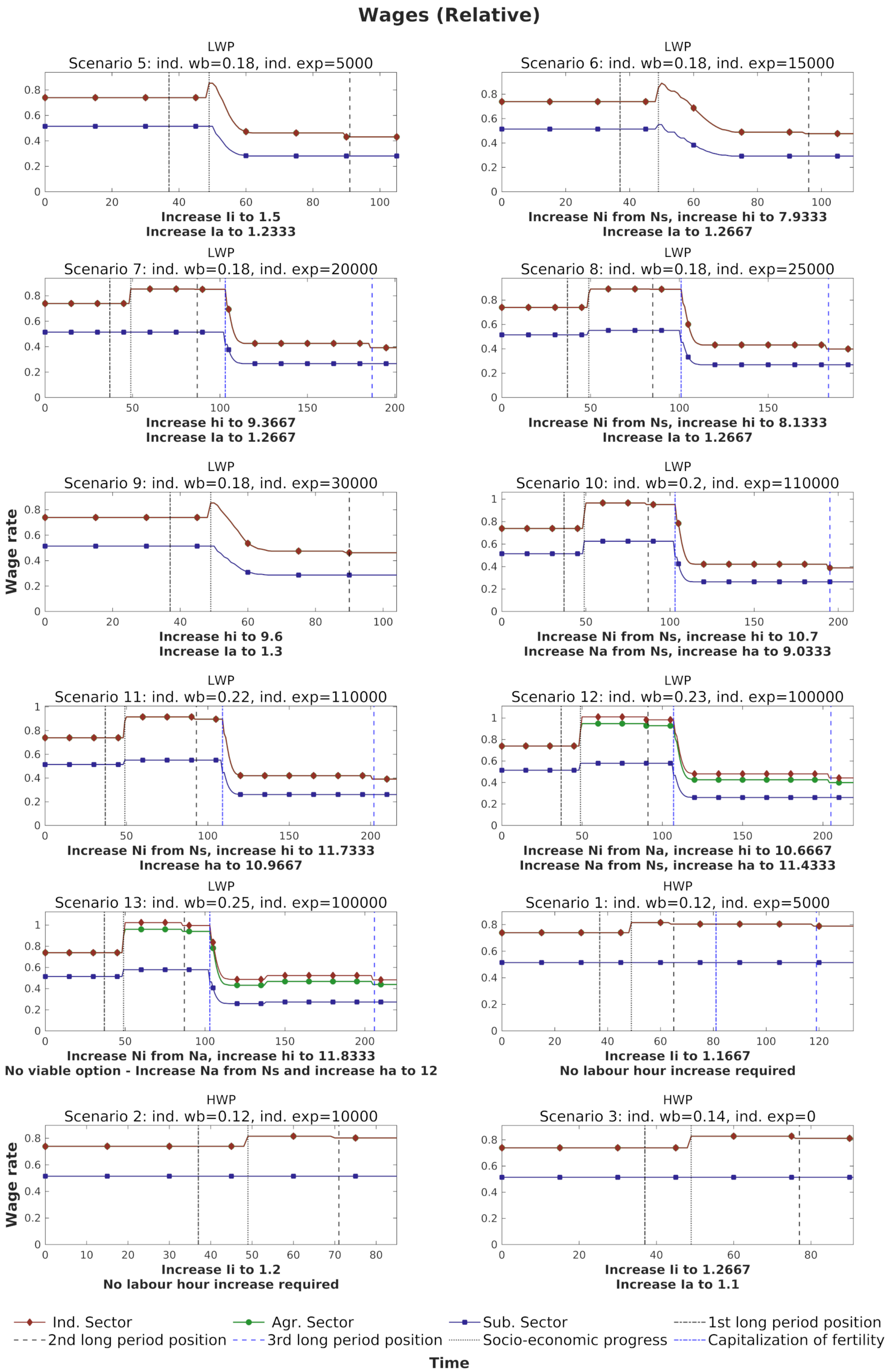


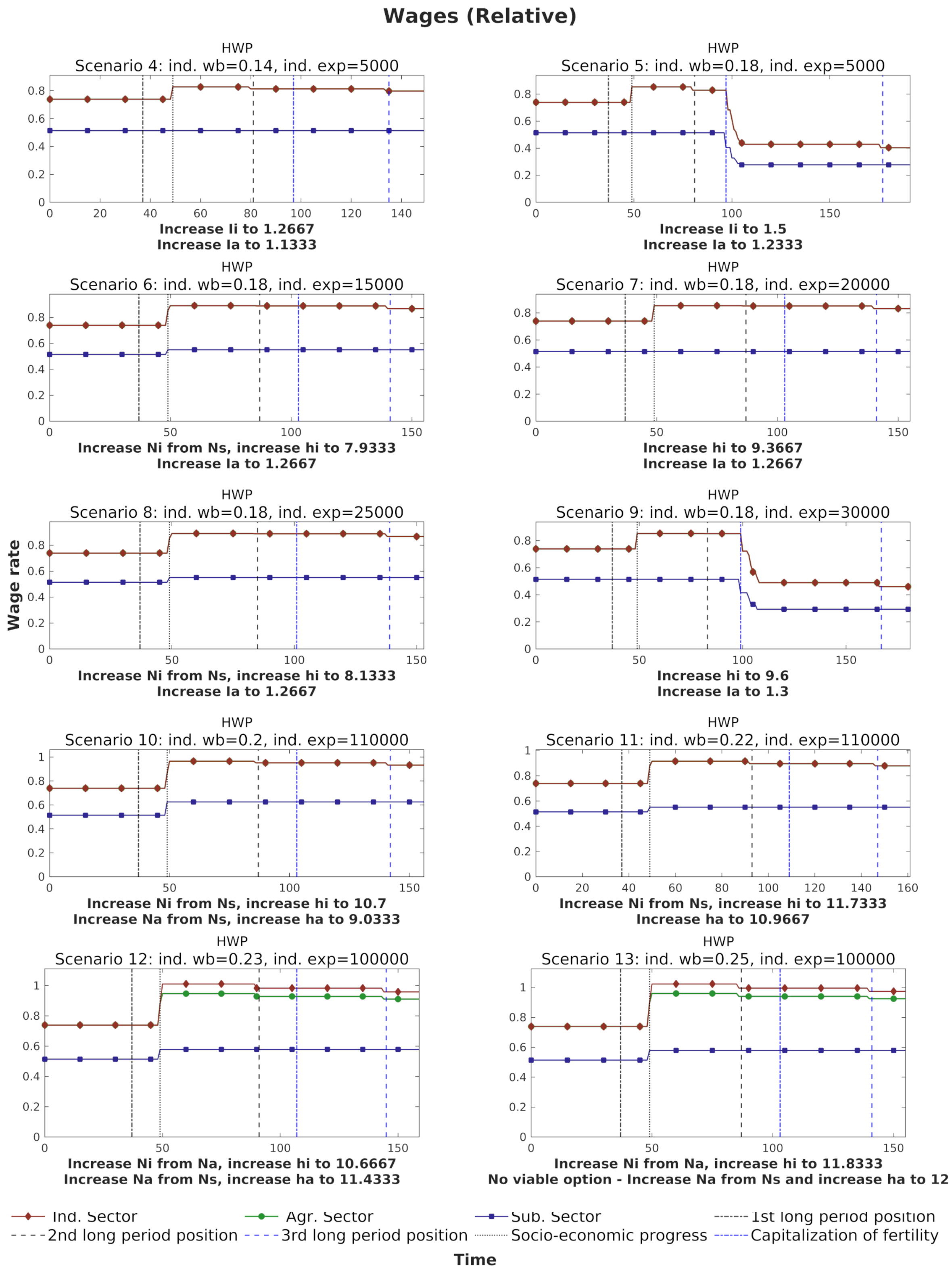

Unemployment Rates
Unemp. Rate
LWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
LWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
LWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
LWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
LWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
HWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase li to 1.1667
No labour hour increase required
HWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase li to 1.2
No labour hour increase required
HWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase li to 1.2667
Increase la to 1.1
HWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase li to 1.2667
Increase la to 1.1333
HWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
Increase la to 1.2333
HWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
HWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
Unemployment
1st long period position
2nd long period position
3rd long period position
Socio-economic progress
Capitalization of fertility
Time


Unemployment Rates
Unemp. Rate
HWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase Ia to 1.2667
HWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase Ia to 1.3
HWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
HWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
HWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
HWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
Unemployment
Socio-economic progress
1st long period position
Capitalization of fertility
2nd long period position
3rd long period position
Time

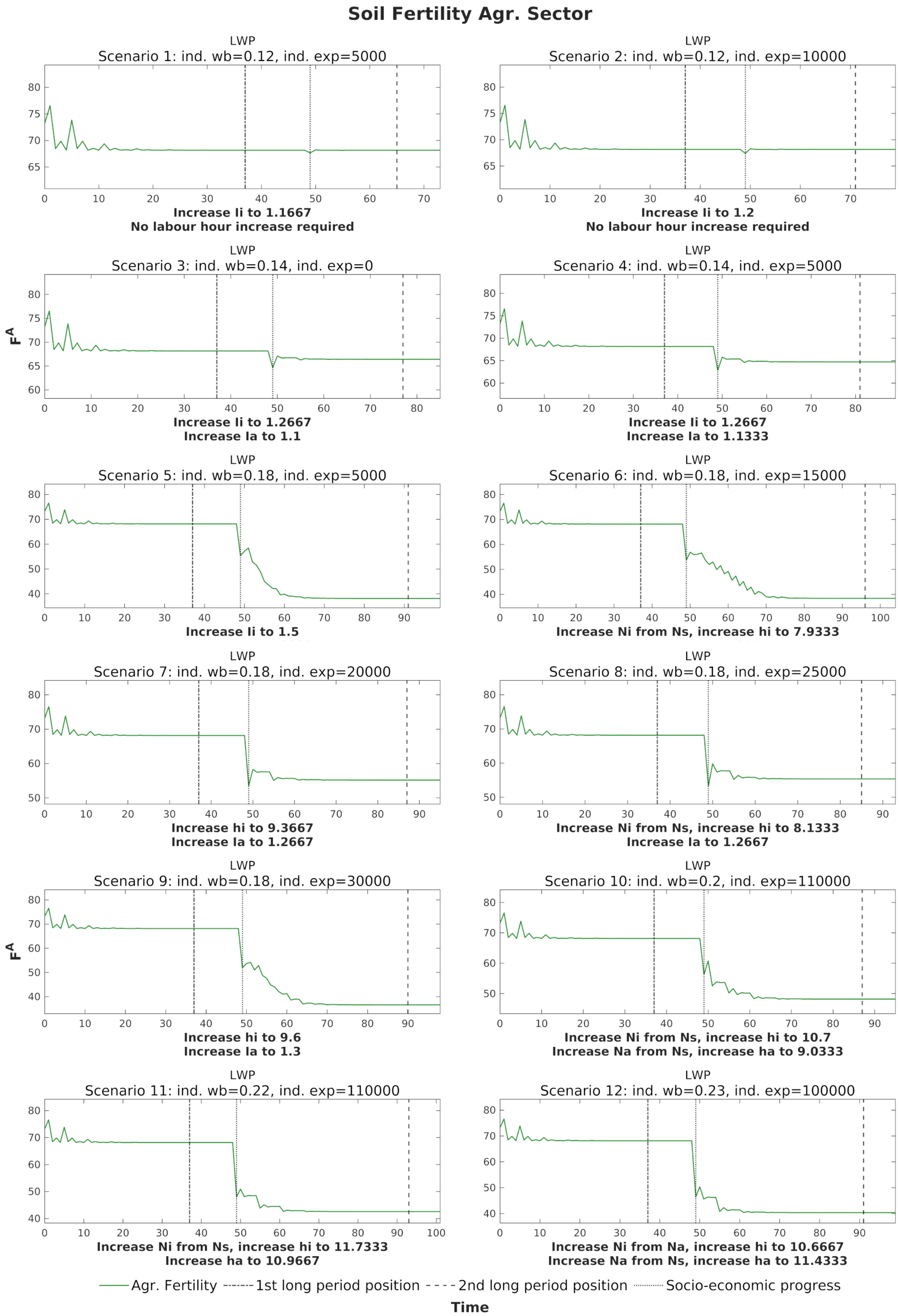
## D.3. Wages

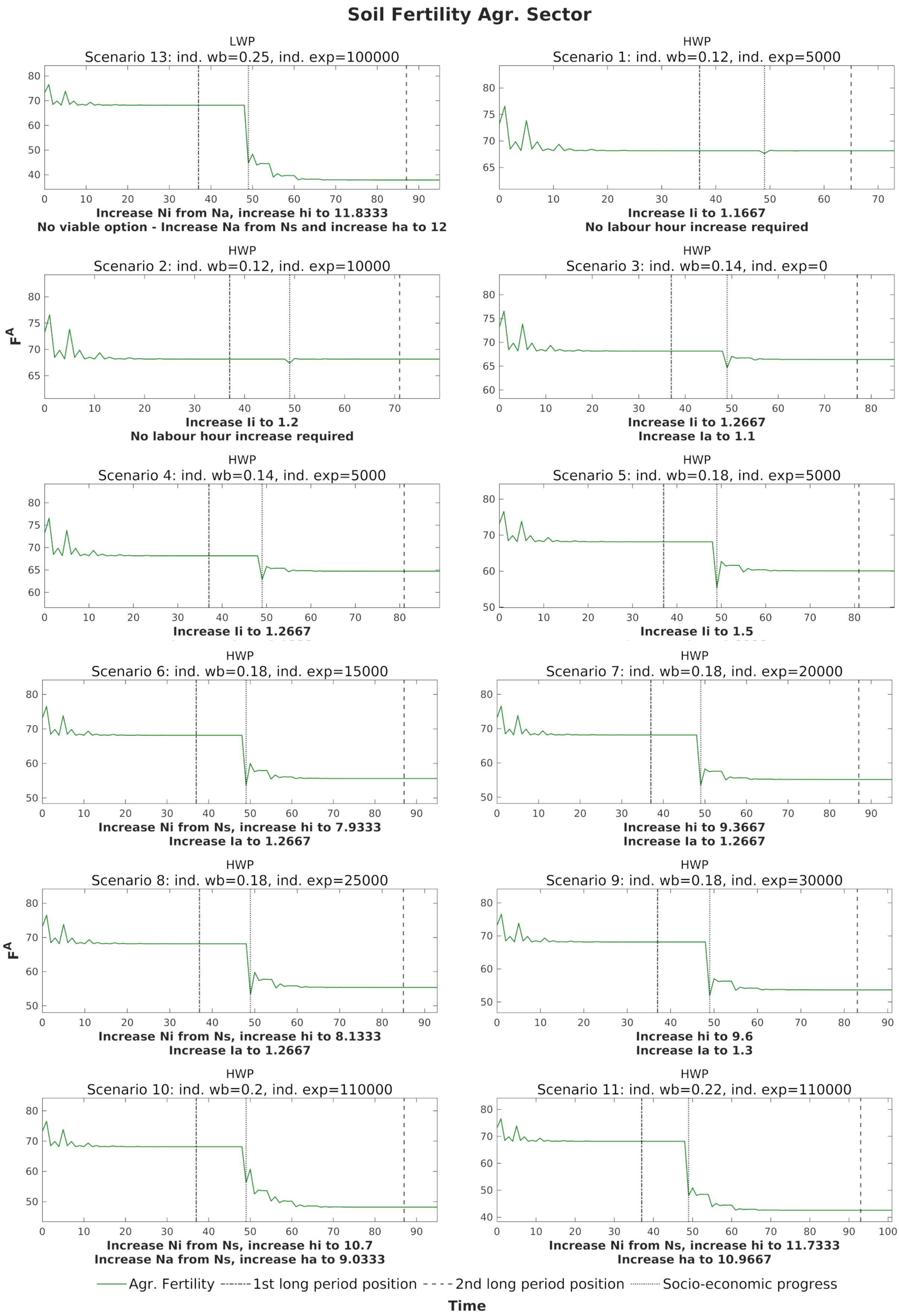

Wages (Relative)
Wage rate
LWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase Ii to 1.1667
No labour hour increase required
LWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase Ii to 1.2
No labour hour increase required
LWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase Ii to 1.2667
Increase Ia to 1.1
LWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase Ii to 1.2667
Increase Ia to 1.1333
Ind. Sector
Agr. Sector
Sub. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic progress
Capitalization of fertility
Time

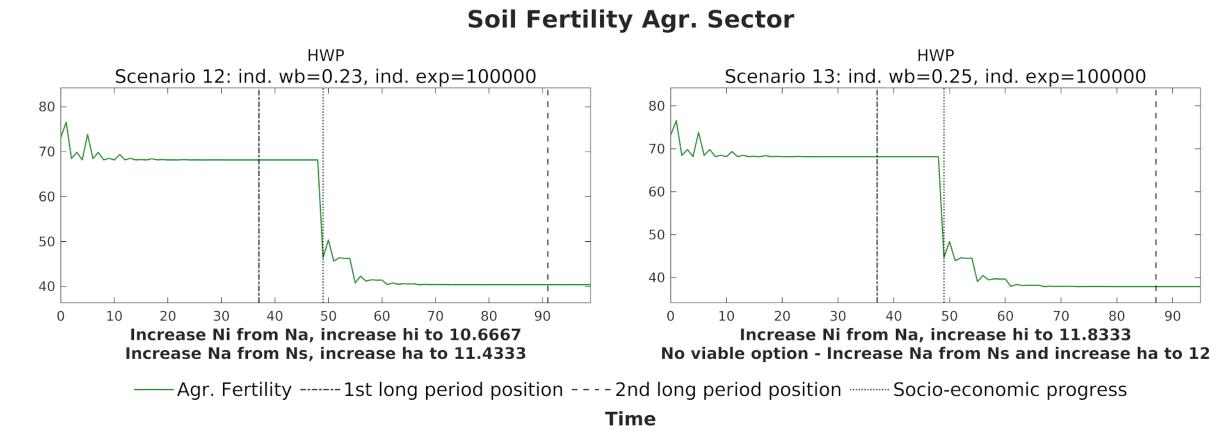

Wages (Relative)
LWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
Increase la to 1.2333
LWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
LWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
LWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase la to 1.2667
LWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
LWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
LWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
LWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
LWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
HWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase li to 1.1667
No labour hour increase required
HWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase li to 1.2
No labour hour increase required
HWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase li to 1.2667
Increase la to 1.1
Wage rate
Ind. Sector
Agr. Sector
Sub. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic progress
Capitalization of fertility
Time


Wages (Relative)
Wage rate
HWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase li to 1.2667
Increase la to 1.1333
HWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
Increase la to 1.2333
HWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
HWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
HWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase la to 1.2667
HWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
HWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
HWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
HWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
HWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
Ind. Sector
Agr. Sector
Sub. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic progress
Capitalization of fertility
Time

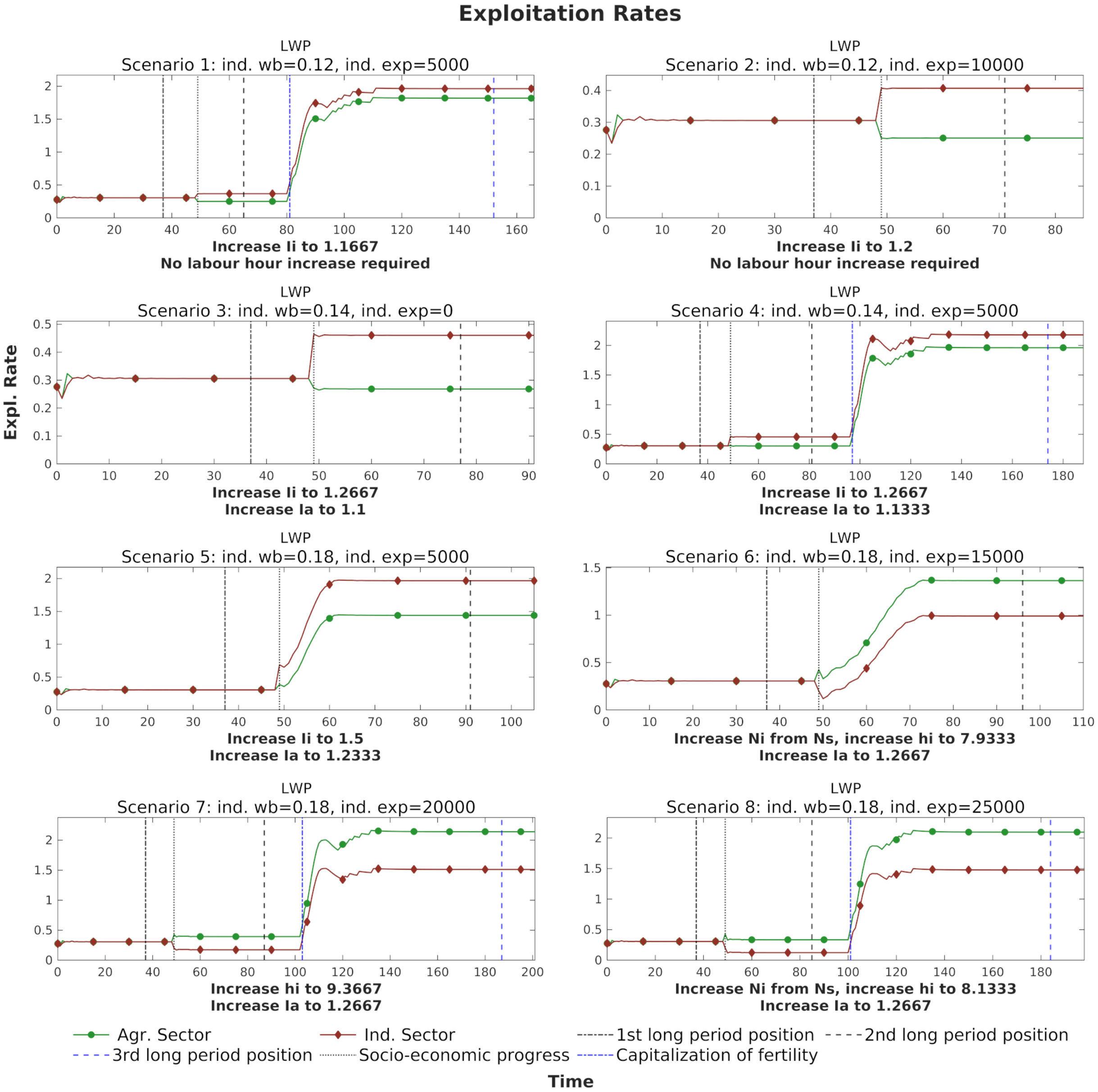
## D.4. Agro-ecological fertility

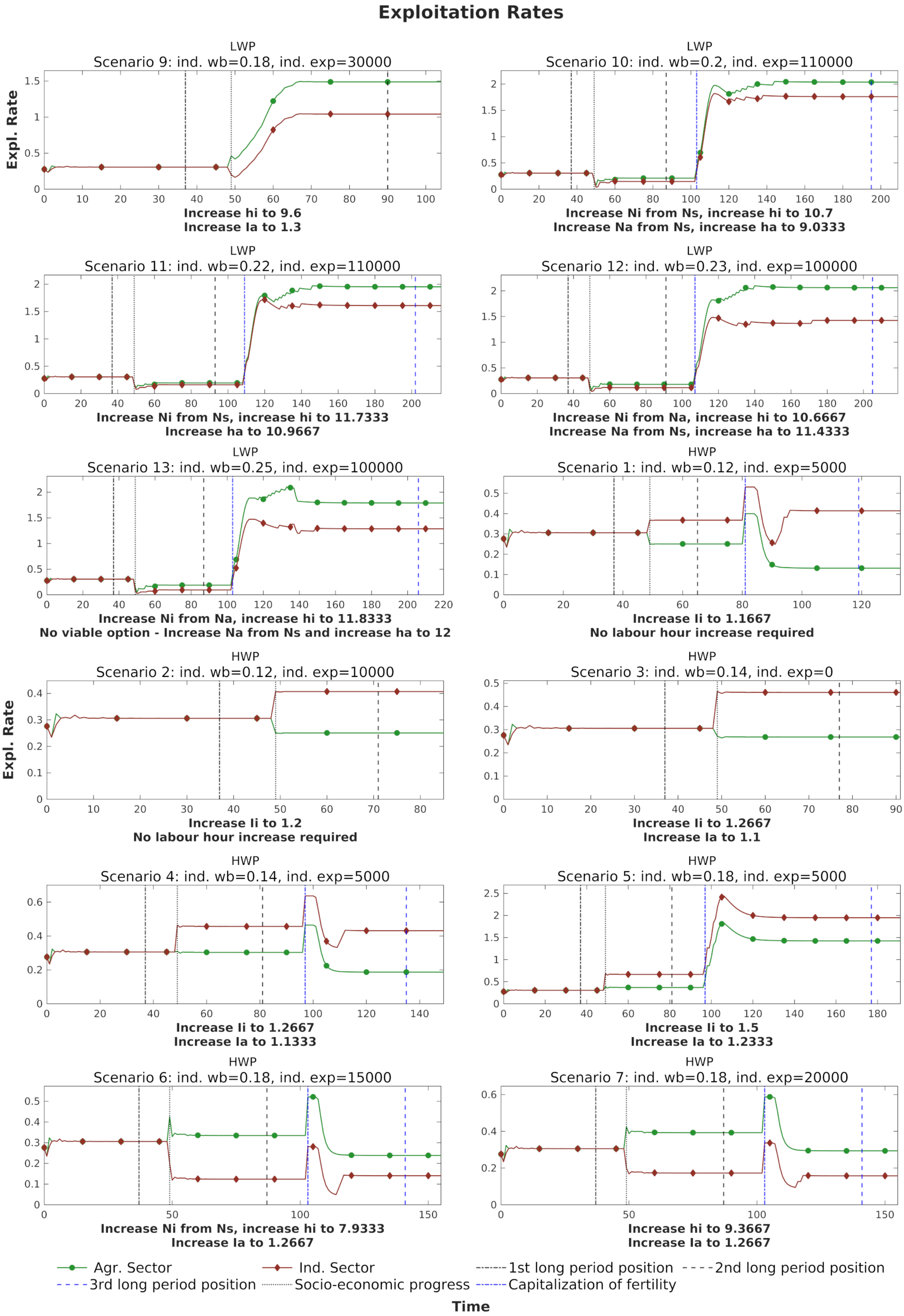


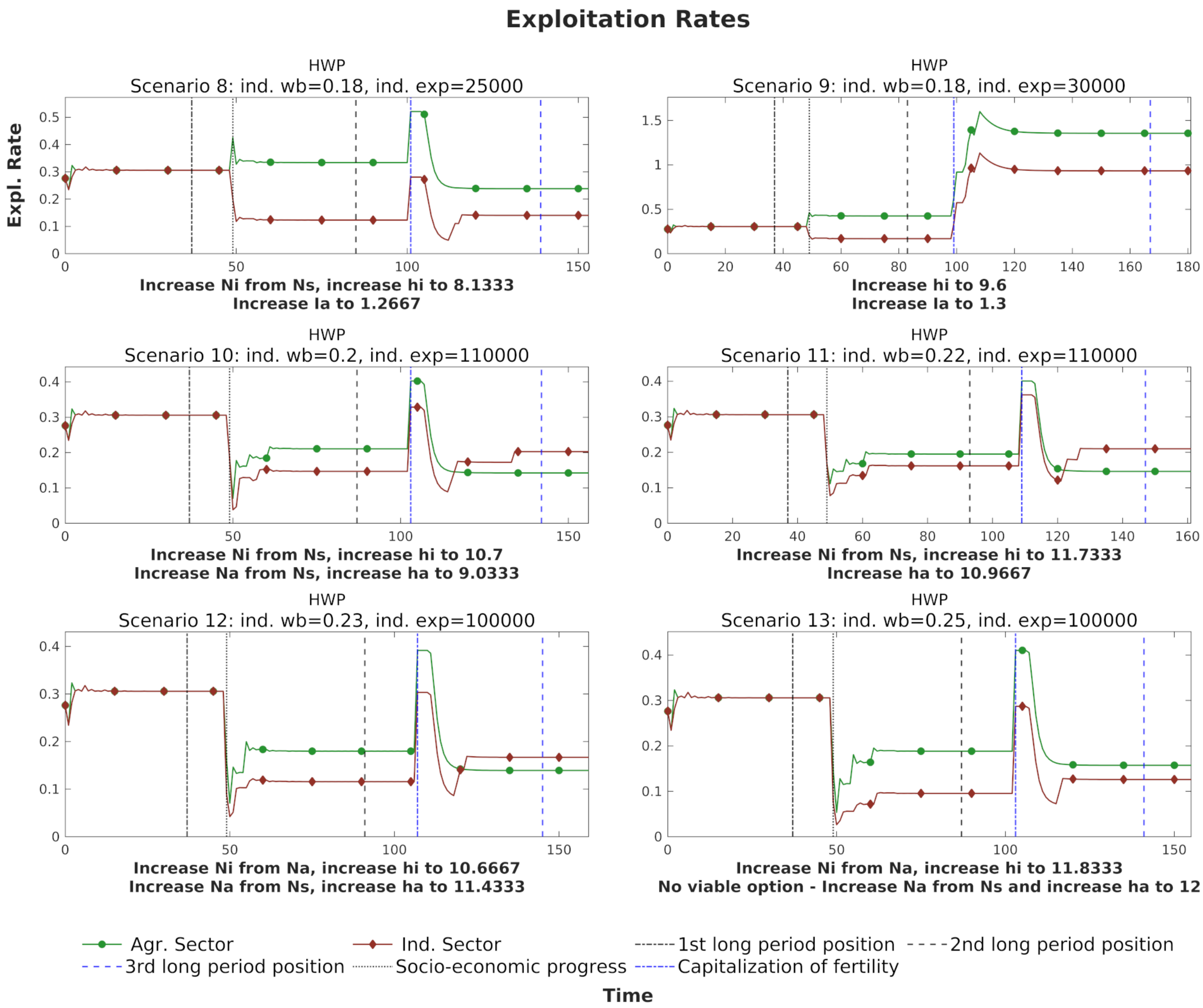

Soil Fertility Agr. Sector
LWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
HWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase li to 1.1667
No labour hour increase required
HWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase li to 1.2
No labour hour increase required
HWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase li to 1.2667
Increase la to 1.1
HWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase li to 1.2667
HWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
HWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
HWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
HWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase la to 1.2667
HWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
HWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
HWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
F^A
Agr. Fertility
1st long period position
2nd long period position
Socio-economic progress
Time




## D.5. Exploitation




Exploitation Rates
Expl. Rate
LWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
LWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
LWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
LWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
LWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
HWP
Scenario 1: ind. wb=0.12, ind. exp=5000
Increase li to 1.1667
No labour hour increase required
Expl. Rate
HWP
Scenario 2: ind. wb=0.12, ind. exp=10000
Increase li to 1.2
No labour hour increase required
HWP
Scenario 3: ind. wb=0.14, ind. exp=0
Increase li to 1.2667
Increase la to 1.1
HWP
Scenario 4: ind. wb=0.14, ind. exp=5000
Increase li to 1.2667
Increase la to 1.1333
HWP
Scenario 5: ind. wb=0.18, ind. exp=5000
Increase li to 1.5
Increase la to 1.2333
HWP
Scenario 6: ind. wb=0.18, ind. exp=15000
Increase Ni from Ns, increase hi to 7.9333
Increase la to 1.2667
HWP
Scenario 7: ind. wb=0.18, ind. exp=20000
Increase hi to 9.3667
Increase la to 1.2667
Agr. Sector
Ind. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic progress
Capitalization of fertility
Time


Exploitation Rates
Expl. Rate
HWP
Scenario 8: ind. wb=0.18, ind. exp=25000
Increase Ni from Ns, increase hi to 8.1333
Increase la to 1.2667
HWP
Scenario 9: ind. wb=0.18, ind. exp=30000
Increase hi to 9.6
Increase la to 1.3
HWP
Scenario 10: ind. wb=0.2, ind. exp=110000
Increase Ni from Ns, increase hi to 10.7
Increase Na from Ns, increase ha to 9.0333
HWP
Scenario 11: ind. wb=0.22, ind. exp=110000
Increase Ni from Ns, increase hi to 11.7333
Increase ha to 10.9667
HWP
Scenario 12: ind. wb=0.23, ind. exp=100000
Increase Ni from Na, increase hi to 10.6667
Increase Na from Ns, increase ha to 11.4333
HWP
Scenario 13: ind. wb=0.25, ind. exp=100000
Increase Ni from Na, increase hi to 11.8333
No viable option - Increase Na from Ns and increase ha to 12
Agr. Sector
Ind. Sector
1st long period position
2nd long period position
3rd long period position
Socio-economic progress
Capitalization of fertility
Time

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