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Short Communication

Stocks and flows of natural capital: Implications for Ecological Footprint

Maria Serena Mancini[a,b], Alessandro Galli[b,*], Valentina Niccolucci[a,*], David Lin[c], Laurel Hanscom[c], Mathis Wackernagel[c], Simone Bastianoni[a], Nadia Marchettini[a]

[a] Department of Physical Science, Earth and Environment, University of Siena, Pian dei Mantellini, 44, 53100, Siena, Italy
[b] Global Footprint Network, 18 Avenue Louis-Casai, 1219 Geneva, Switzerland
[c] Global Footprint Network, 312 Clay Street, Suite 300, Oakland, CA 94607-3510, USA

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ABSTRACT

Over the past decade, Ecological Footprint has become one of the most popular and widespread indicators for sustainability assessment and resource management. However, its popularity has been coupled, especially in recent years, by the emergence of critical views on the indicator's rationale, methodology and policy usefulness. Most of these criticisms commonly point to the inability of the Ecological Footprint to track the human-induced depletion of natural capital stocks as one of the main shortcomings of the methodology. Fully addressing this issue will require research efforts and, most likely, further methodological refinements. The aim of this paper is therefore to outline the basis of a new area of investigation in Ecological Footprint research, primarily aimed at implementing the distinction between the use of stocks and the use of flows in Ecological Footprint Accounting and debating its implications.

1. Natural capital and the Ecological Footprint: an introduction

There are many meanings to the term 'capital' depending on the subject being discussed and the pertinent adjective matched with it. Capital, in whatever form it is conceived, is generally referred to as a stock able to generate a flow, which in turn serves as an input for the production of something else (Ekins et al., 2003). In particular, the term *natural* capital concerns natural resources and the environment surrounding and supporting human life (De Groot, 1992; Hinterberger et al., 1997). It is usually defined as '*a stock that yields a flow of natural resources and/or ecological services*' (Costanza and Daly, 1992. See also: Hinterberger et al., 1997; Ekins et al., 2003; Farley and Daly, 2006).

Georgescu-Roegen was one of the first authors to introduce the stock-flow model into the bio-economic paradigm (Georgescu-Roegen, 1971), which was then used as the basis for the ecological economics' principles (Daly and Farley, 2004). Since then, the concept of natural capital has increasingly gained importance from an anthropocentric perspective in the field of ecological economics and sustainability (Jansson et al., 1994; Hinterberger et al., 1997; Ekins et al., 2003). It has also been used in assessing the vital role ecosystem services play in supporting societies and human well-being (MEA, 2005; TEEB, 2013; Costanza et al., 1997, 2014).

The paradigm of strong sustainability requires all kinds of capital (natural, human, labor, etc.) to be complementary among each other, and always to remain intact at the optimum level, as each capital's productivity depends on the availability of the others (Daly, 1990; Jansson et al., 1994). Although a certain degree of substitutability might exist at the local level among different kinds of capital – due to new technologies and financial investments (Markandya and Pedroso-Galinato, 2007) – natural resources are globally limited and biophysically constrained. As natural capital degradation takes place, loss of such capital becomes irreversible and resources turn out to be highly non-substitutable (Cleveland et al., 1996). This rationale is supported by the two sustainable development principles (necessary conditions), which according to Daly (1990) are stated as follows:

1. *harvest rates of [renewable resources] should equal [their] regeneration rates*
2. *waste emission rates should equal the natural assimilative capacities of the ecosystem into which the wastes are emitted*

* Corresponding authors.
E-mail addresses: alessandro.galli@footprintnetwork.org (A. Galli), vniccolucci@unisi.it (V. Niccolucci).

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Natural capital is at the core of the Ecological Footprint accounting (Wackernagel and Rees, 1997; Wackernagel et al., 1999; Wackernagel et al., 2002; Monfreda et al., 2004). Consistent with Daly's two principles of sustainability, the Ecological Footprint methodology accounts for the supply and demand of the basic resource provisioning and regulatory ecosystem services humans require to support their lifestyles (Galli et al., 2016; Goldfinger et al., 2014; Bastianoni et al., 2013). According to Galli et al. (2014), it can be applied at scales from global to local and gives insight on the above by means of two indicators:

- Representing regeneration/assimilation, **biocapacity** tracks the ecological assets[1] actually available in countries, regions or at the global level and their capacity to produce renewable resources and ecological services.
- Representing harvest/emission, the **Ecological Footprint** measures the equivalent biologically productive land and sea area – the ecological assets – that might actually exist or not on the Earth surface and that a population requires to produce the renewable resources and ecological services it uses.

More precisely, the Ecological Footprint deals with ecosystem services to the extent that these services occupy mutually exclusive, biologically productive areas. Accordingly, resource availability, as well as level of consumption, are both converted into the corresponding required area of biological productive ecosystems. Biocapacity and Ecological Footprint are expressed in terms of hectares normalized to represent the world average productivity: global hectares (gha) (Galli et al., 2007; Borucke et al., 2013; Wackernagel, 2014). These ecological services – generated by the photosynthetic activity of plants – include provision of biomass-based resources such as food, fibers and raw materials (e.g., wood-fuels and plant oils), and regulation and maintenance of ecosystems through waste absorption, using prevailing technology and management practices. The current national and global application of Ecological Footprint accounting, the National Footprint Accounts (Global Footprint Network, 2016) limits the direct tracking of waste to CO_2. Thus climate regulation via sequestration and long term storage of carbon is the only regulating service tracked (Galli et al., 2014; Mancini et al., 2016).

According to the 2016 Edition of the National Footprint Accounts, humanity's Ecological Footprint initially surpassed the Earth's biocapacity in the early 70s, and recent results indicate 64% overconsumption in 2012 (Global Footprint Network, 2016). When global demand on natural resources and ecosystem services exceeds the capacity of ecological systems to regenerate, ecological overshoot occurs (Borucke et al., 2013; Galli, 2015; Lin et al., 2015a). In a world with physical boundaries and limited resources, overshoot cannot last indefinitely as it might lead to the break down of natural cycles, liquidation of stocks like forest and fish biomass and depletion of the bioproductive capacity of fertile lands (Niccolucci et al., 2009). In other words, a prolonged use of flows of resources at a rate faster than their regeneration rates is likely to cause the depletion of the stocks of natural capital yielding such resources. This topic represents one of the most challenging research frontiers in Footprint accounting, also referred to as 'fragility of biocapacity' (Wackernagel et al., 2014). Unfortunately, the Ecological Footprint methodology applied to national assessments is not currently able to quantify such depletion and cannot forecast the consequences of overconsumption on the sustainable biological productivity of ecological assets (Galli et al., 2016).

Initial attempts to combine a "stock vs. flow" perspective into the Ecological Footprint have been made by Niccolucci et al. (2009, 2011). Along with the annual appropriation of natural flows, representing the classical spatial component, the authors introduced a component of the Footprint, called Footprint depth, related to the depletion of natural stocks (Niccolucci et al., 2009, 2011). While such three-dimensional Footprint approach can provide a more actionable conceptualization of the global overshoot situation, it is still difficult to calculate. Developing the distinction between depletion of stocks and use of flows within the Ecological Footprint is of key importance to clarify the ecological system dynamics and better depict the current overuse of ecosystem services by human societies and the resulting overshoot. Furthermore, it would allow users to track a certain biophysical (rather than monetary) threshold beyond which our societies' use of the planet's ecosystem services is unsustainable. This threshold is represented by the specific point in which humans shift from using flows (as they are completely used up) to using stocks, thus undermining the long term capacity of these stocks to yield a continual flow of ecosystem services. The stock and flow model could thus provide an understanding of what overexploitation of a certain subset of ecosystem services could entail for the future of humanity and how long we can maintain current levels of consumption before bioproductivity will collapse.

As such, the aim of this paper is to first provide a comprehensive definition of natural capital's stocks and flows as well as a framework for understanding the dynamics between these two concepts. Consequently, the Ecological Footprint methodology is then described in light of the "stock vs. flow" perspective to clarify how these two concepts are currently implemented within the methodology and what it would take for their full implementation within the Footprint methodology. Accordingly, new and revised Ecological Footprint and Biocapacity definitions – consistent with the proposed stock vs. flow perspective – are here suggested and a research agenda set up to guide Footprint practitioners' future research efforts in quantifying the human resources consumption within a more tangible ecosystem services framework.

2. The natural capital and the stock vs. flow perspective

Natural capital is directly related to the concepts of stocks and flows of ecosystem services they produce (Costanza et al., 1997). Stocks refer to the elements of an ecosystem describing the state of the ecosystem itself at any particular time; conversely, flows are variables of the ecosystem measured over a period of time (Meadows, 1998). In analogy with the economic assets and balance sheet in financial accounting, as stocks are identified as natural capital, flows can be considered as the income of natural capital (Costanza and Daly, 1992; Wackernagel and Rees, 1997; Meadows, 1998; Wackernagel et al., 2014).

The stock and flow concepts are also at the core of the SEEA (UN et al., 2014), in which stocks are identified as ecosystem assets – the spatial areas with biotic and abiotic components functioning together – on which economic and other human activities take place using the processes and resources generated by those assets. These processes and resources are collectively referred to as flows of ecosystem services, which can be both inputs from the environment to the economy (i.e. forest timber, fishes or crops) and outputs of residues from human activity to the environment (i.e. wastes and emissions) (UN et al., 2014). In this view, stocks and flows have a strong spatial dynamic and a strong connection with the economic sphere. Therefore, the capacity of an ecosystem asset to generate ecosystem services is also function of its extent and condition (Lars et al., 2015).

[1] The spatial areas with biotic and abiotic components functioning together, and whose processes and resources are essential for economic and other human activities. See section 2.

Stocks and flows are primarily described in the current literature by a prevalent dynamics: stocks generate outgoing flows of goods and services (see e.g. Costanza and Daly, 1992; Hinterberger et al., 1997; Ekins et al., 2003). Although this is certainly the main dynamic between stocks and flows within natural ecosystems, Meadows (1998) and Wall (2002) pointed out the possible existence of other complementary dynamics: stocks may be both sources and sinks of natural resources, while flows may be both inputs and outputs that increase or decrease stocks (Meadows, 1998). Moreover, stocks and flows of resources are also characterized by different regeneration rates (Wall, 2002), which determine whether resources are referred to as renewable or non-renewable (Costanza and Daly, 1992). According to Tiezzi (2003), all these characteristics should be taken into account in determining the way in which humans use and extract resources.

To meaningfully understand the model of stocks and flows, we need to first outline the reference system under study and its boundaries, on which their interactions and origins depend, as well as the timeframe considered. From a global viewpoint, the solar system – specifically the sun and Earth – represents the all-encompassing reference system: the sun is the very first stock, which yields a main flow, solar radiation, which in turn comes into our planet and triggers photosynthesis, which is the foundation of almost all ecosystems on the planet Earth. Therefore, in the context of natural capital, a stock yielding a flow is usually considered the prevalent, and perhaps sole, fundamental interaction between stocks and flows.

However, when the Biosphere is considered as the reference system,[2] a multitude of resulting secondary dynamics between stocks and flows has to be considered, which are put in motion by the primary flow of solar radiation. This includes the possibility of flows produced by other flows: photosynthesis, electric power generated by sunlight, wind or water streams are examples of flows generated by flows, or with H.T. Odum's words "flow-limited resources" (Odum, 1988).

These dynamics are all part of nature in its wider sense, including both life forms and non-living elements. Although these dynamics exist regardless of human life, most of them are essential for the human survival and humans' appropriation of natural resources – both in stock and flow forms – as they constitute the basis for all societies and economies.

Table 1 provides all the possible combinations between stock and flow that may take place within the Biosphere, considering 1 year as the reference period. This comprehensive overview on the possible dynamics, which we provide here for the first time, will then serve as the starting point for discussing the implementation of the stock vs. flow dynamics within Ecological Footprint Accounting.

Each case given in Table 1 is briefly described below:

- Case 1: as mentioned, this is the most commonly reported interaction between stocks and flows. Within the Biosphere, it could refer to a forest ecosystem generating each year a number of trees and new branches or a stock of fish in the sea yielding each year a certain amount of new fishes. Forests and fishes in their entirety constitute the stock. This stock is made of single elements, some of which are "produced" each year as annual flow of new entities. In this case, the flow – as a second element – is not only a product of the first element (the stock), but it also functions as a feedback that sustains and maintains the stock itself in a steady (or even prosperous) state. These stocks can be used in a sustainable way (if flows are such that allow for reformation of stocks through feedbacks) or in a non-renewable way (if time of uptake is faster than time of re-generation.
- Case 2: in this case, a physical transformation is involved, in which resources undergo a phase transition shifting their physical form from one state to another. For instance, the ice caps melting and dissolving into water ponds.
- Case 3: here we consider those resources that do not naturally yield any flows, unless humans extract them (e.g., oil or coal extracted from underground deposits). These resources are regenerated over geological eras due to the process of sedimentation of biological biomass into the crust. This case can be seen as an extreme situation of case 1 in which, due to their long regeneration rate, resources are considered non-renewable. Humans need to invest energy to extract them. Since they are used at a rate faster than their generation rate, they are bound to be depleted.
- Case 4: in this case, flows originate other types of flows, of higher or lower quality. This phenomenon is of paramount importance for the development of ecosystems and other Biosphere processes, since photosynthesis is the mechanism through which Biosphere has been able to reduce its entropy over time. Very often, the originating flows do not accumulate in a stock and they need to be "intercepted" to become "useful" flows (e.g., solar and wind power, annual crops, fruits spontaneously produced plants, etc) otherwise they are lost as degraded energy (thus turning into case 6).
- Case 5: this is the case in which, within the Biosphere, a flow creates a stock of resources. It could be either the decaying vegetation (i.e. debris falling from a tree) forming the peat or the carbon emission accumulating into the atmosphere due to the saturation of terrestrial sinks.
- Case 6: in this case, a flow exists by itself within the reference system (i.e., the biosphere), but it does not generate any other stock or flow. As example of this might be any flow that humans do not use up or they might even be unaware of (i.e. the "non-intercepted" wind blowing). Thermodynamically, an example could be the low-temperature heat that is not able to perform further work.

3. Introducing the "stock vs. flow" perspective within Ecological Footprint Accounting

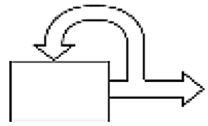
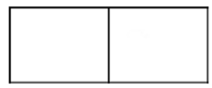
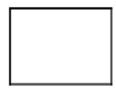
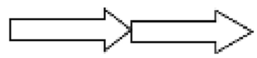
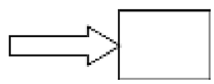
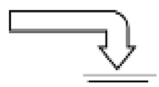
The Ecological Footprint methodology uses a biophysical approach to evaluate the natural capital and its relevant stocks and flows of resources and services, as well as the extent to which human societies place a demand on them (Wackernagel and Rees, 1997). As mentioned in Section 1, the stocks considered by the methodology are spatial areas – with biotic and abiotic components – such as crops, grazing lands, forests, and fishing grounds. The flows considered – primarily generated by the photosynthetic activity of those biotic components – are food, fibers, and raw materials such as wood-fuels and plant oils (or their perpetual degradation through pavement) flowing into the economy as well as CO_2 residues flowing out from the economy, in need to be disposed.

The biocapacity concept is at the core of the methodology, as it accounts for the above resource provisioning and regulatory ecosystem services made available by the Biosphere, against which to compare human consumption (Galli et al., 2016, 2012; Wackernagel et al., 2014; Lin et al., 2015a,b; Goldfinger et al., 2014). The rationale behind the biocapacity concept is that autotrophic organisms are able to capture solar energy and transform it into biological structures and resources/services useful to humans (Galli,

[2] From a thermodynamic point of view, the planet Earth is here considered as a closed system, which is passed through by solely a flow of energy, which generates a succession of stocks and flows of resources within the Biosphere.

[4] This reflects the usual way of saying in Ecological Footprint communication that "humans use one and half Earth": we do not have the extra half.

Table 1
Proposed classification of possible theoretical interactions between stocks and flows of energy and materials within the Biosphere. The Biosphere is thus the reference system and the time frame is 1 year. Note that the solar radiation is the key underlying factor that triggers all the dynamics reported in the table. As such, it is not itself included in the modeled diagrams.

Case	Type of dynamic triggered by the solar radiation	Modeling diagram	Example
1	Stock yielding a flow		The biomass accumulated in a forest contributing, through photosynthesis, to the annual growth of new biomass in trees
2	Stock generating other stocks		Ice caps melting into water pounds due to solar radiation (phase transition)
3	Stock not naturally generating a sustainable flow		Oil deposits unreached by solar radiation in the year, which remain unvaried unless extracted by humans.
4	Flow generating other flow		Nutrients flowing into water and yielding a rate of new algae
5	Flow generating a stock		Organic debris decaying from trees that generates peat
6	Flow degraded in quality[4]		Solar radiation dispersed and unavailable to do further work

2015; Rees, 2013; Monfreda et al., 2004). Biocapacity is thus the core parameter from which to depart in analyzing the stock and flow distinction and evaluate consumption and potential depletion from the Ecological Footprint side. Footprint and biocapacity values are annually compared according to their flow dimension (Galli et al., 2014; Lin et al., 2015a; Goldfinger et al., 2014).

In this context, the unit of measure used by the methodology – the global hectare – requires a further clarification. Global hectares refer to area-*equivalent* units, able to provide a certain amount of productivity (Galli et al., 2007; Galli, 2015; Goldfinger et al., 2014). They are not a measure of an actual physical area, as in this case they would point to a measure of stocks. Rather, they primarily reflect productivity – that is the amount of resources yielded per year – and thus represent a measure of flow of resources. The productivity amount is determined by accounting the area requirement for resource production, which is a very effective way to clarify the issue of resource use. Actual hectares are thus directly related to their biomass productivity through yield and equivalence factors (Galli et al., 2007). To avoid confusion, we clarify that a global hectare represents a given flow of resources, which is however defined in terms of the stock producing it.

To date, time series records show that annual Ecological Footprint have been greater than biocapacity for nearly the past 40 years, causing a global overshoot situation and potentially leading to a depletion of the underlying stocks of natural resources (Lin et al., 2015a; Kitzes et al., 2008; Rees, 2013). Introducing the stock and flow distinction into the Ecological Footprint methodology for the resources used by humans expands Footprint accounting to clearly include a physical measure of the depletion of our Biosphere's ecological stocks, without necessarily changing the current results of Ecological Footprint (Niccolucci et al., 2011). This allows identifying the threshold of human use of resources beyond which such use starts to be unsustainable and to put at risk the long-term capacity of ecological assets (i.e., stocks) to produce such resources.

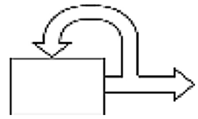
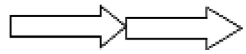
As a first step towards a new line of research focusing on the implementation of a stock vs. flow perspective in Ecological Footprint Accounting, we propose here revised biocapacity and Ecological Footprint definitions, which are based on the dynamics described in Table 1.

Biocapacity represents all existing natural ecological assets with the capacity to produce a given amount of ecosystem services that are useful to society every year. In this sense, it includes both the stock and flow dimensions of the natural capital humans are using. Particularly, it reflects the Case 4 described in Table 1 where the natural flow of solar radiation reaches the Earth, triggers the photosynthesis process, which in turn yields resources and ecosystem services each year – flow yielding other flow over a period of time. Also, the same process reflects Case 1 in the long run: over past centuries, photosynthesis-derived biomass has accumulated in stockpiles thus creating those ecological assets – forests, fertile soils, marine and freshwater life beings – which constitute our steady natural capital and which provide us with new natural resources each year – stocks yielding flows (see Table 2).

On the other side, Ecological Footprint is the yearly human consumption of those ecological services. By comparing consumption with what it is actually available every year (Galli et al., 2016), we are able to know whether human demand is placed on actual flows produced each year or are rather using "virtual" flows, i.e. flows whose production means digging into the assets beneath those flows. In the first case, we remain in an ecological balance, as Ecological Footprint would not exceed biocapacity in its annual flows. Also it could be the case where we can improve the technology and improve the efficiency in transforming natural services into real flows of resources, yet keeping the biocapacity in its natural state. In the second case the demand can exceed the natural biocapacity, as observed in global ecological overshoot, by forcing flows out of their natural annual yield. This can only happen when there is a stock of resources yielding a flow (see case 1 in Table 2). We can increase the annual flow by overexploiting and depleting the stock of resources, compromising the steady capacity to produce resources and eventually affecting future flows. This reflects the unsustainable use of resources.

Given the above, the new definitions we are proposing within the "stock vs. flow" perspective are as follows:

Table 2
Identified stock-flow dynamics tracked by Ecological Footprint Accounting.

Case	Type of dynamic triggered by the solar radiation	Modeling diagram	Example in Ecological Footprint methodology
1	Stock yielding a flow		Forests yielding each year new trees; Fish stock in sea yielding each year new fishes
4	Flow generating other flow		Photosynthesis process producing yearly products (i.e. annual crops) that humans harvest.

- **biocapacity** represents the "world-average hectare-equivalents (i.e., a stock-equivalent measure) that are available to provide the amount of ecosystem service flows actually regenerated by the Biosphere every year";
- **Ecological Footprint** represents the "hectare-equivalent units that are or would be[3] needed to produce, in a year, the amount of ecosystem service flows humans actually use in that year".

Within the new definitions, global hectares acquire a different meaning as well. They are still not a measure of land use, but rather they become a measure of the inherent capacity of the Biosphere assets to produce useful biomass and services for appropriation by humans. As technology, climate, environmental conditions and management practices change every year, the value of a global hectare also varies year by year. Dividing the total biocapacity of Earth by the total number of bioproductive hectares yields the value of an average productive hectare – a "global hectare". Each global hectare represents the same biological productivity, a flow, yielded by a particular fraction of the earth's total biocapacity, a stock. For instance, when a world-average resident is said to have an Ecological Footprint of 2.8 gha, it does not mean that 2.8 ha of physical land in the world are used. It means that the equivalent capacity of 2.8 ha of productive land with world average productivity is needed to produce (via photosynthesis) the resources and services that such world resident demands – this biocapacity could be anywhere in the world and could be originating from an actual land area smaller or larger than 2.8 ha.

We acknowledge that analyzing the local ecological scale and applying these variations on calculations for all the land categories involved in the Footprint accounts might be challenging. Currently, cropland, grazing land, forest, and fishing area represent ecological assets supplying most of the regenerative capacity of human consumption, which is measured in gha. It would be extremely illuminating for each of them to set a threshold to highlight the cases in which the annual rate of resources (flows) is exceeded and the human consumption starts undermining stocks.

For instance, current calculations for national Footprint assessments do not show any overexploitation of resources in the cropland category as the Footprint accounts for the harvest of annual productivity, given the prevailing technologies, and it equals cropland biocapacity, which is the productivity of all lands devoted to growing crops (Borucke et al., 2013). Understanding the difference between flows and stock in cropland, what is the natural capital in stock form that allows growing crops and how to account for it, may address the problem of quality loss of the soil and the sustainability of the management practices (Bastianoni et al., 2012).

A similar rationale is likely to be applicable to all other land types: we are experiencing phenomena of deforestation, collapse of fisheries and accumulation of CO_2 in the atmosphere and the stock and flow model might be a way to physically account for these deficits.

[3] According to the second law of thermodynamics, this may be the energy that is either dissipated – as it is not able to perform further work – or dispersed due to its non-use.

4. Conclusions and research agenda

This paper analyzes the existing literature around the concept of stocks and flows of natural capital and ecosystem services and provides a more comprehensive framework of their mutual dynamics. This model provides an insightful perspective from which to look differently at the Ecological Footprint methodology.

Coupling the perspective of ecosystem services in stock and flow forms with Ecological Footprint helps characterize the available resources – biocapacity – and distinguish between the use of flows and the consumption of stocks of resources – the pressure of human Footprint. This is of key importance to clarify and better depict the overshoot situation and understand to what extent the levels of stock change and how much biological capacity is being compromised to sustain long-term productivity.

According to the proposed framework on stock and flow, we have here suggested tentative new conceptual definitions of Ecological Footprint and biocapacity, involving the distinction in stock and flow of resources. However, this paper is a first, non-exhaustive, step towards opening up a future research line aimed at better accounting for natural capital, in both its stock and flow dimensions, within Ecological Footprint Accounting.

A research agenda is proposed to properly implement the stock/flow distinction in Ecological Footprint and separately quantifying the use of flows from the consumption of stock of resources and thus better address the consequences of the ecological overshoot.

The main elements of such an agenda, are as follow:

- To carefully examine the proposed conceptual definitions of both biocapacity and Ecological Footprint in order to understand how they could be translated into practical assessments of both the stock and flow dimensions. This would help clarify how the overshoot situation makes it possible that Ecological Footprint is greater than biocapacity and to what extent the overuse of ecosystem services may deplete the ecological assets.
- To analyze the precise meaning of the stocks and flows concepts when applied to each land type, and investigate how they might be distinguished and accounted for. An outcome of this step would be to identify a threshold for each land type, to differentiate the use of flows from the consumption of stocks. Applying the stock vs. flow conceptual framework to the Ecological Footprint and biocapacity calculation might be challenging and will likely require to be initially investigated for a single specific land type for which most of the structural and characteristic dynamics are known (i.e., cropland). While doing so, a logical pattern to follow in order to address consistently all the land types involved in the methodology shall be set-up as well.

- Eventually, outcomes from the above two steps will contribute to researching the 'fragility of biocapacity' (Wackernagel et al., 2014; Lin et al., 2015a) issue.

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