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Agroforestry enhances biological activity, diversity and soil-based ecosystem functions in mountain agroecosystems of Latin America: A meta-analysis

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Abstract

Mountain agroecosystems in Latin America provide multiple ecosystem functions (EFs) and products from global to local scales, particularly for the rural communities who depend on them. Agroforestry has been proposed as a climate-smart farming strategy throughout much of the region to help conserve biodiversity and enhance multiple EFs, especially in mountainous regions. However, large-scale synthesis on the potential of agroforestry across Latin America is lacking. To understand the potential impacts of agroforestry at the continental level, we conducted a meta-analysis examining the effects of agroforestry on biological activity and diversity (BIAD) and multiple EFs across mountain agroecosystems of Latin America. A total of 78 studies were selected based on a formalized literature search in the Web of Science. We analysed differences between (i) silvoarable systems versus cropland, (ii) silvopastoral systems versus pastureland, and (iii) agroforestry versus forest systems, based on response ratios. Response ratios were further used to understand how climate type, precipitation and soil properties (texture) influence key EFs (carbon sequestration, nutrient provision, erosion control, yield production) and BIAD in agroforestry systems. Results revealed that BIAD and EFs related to carbon sequestration and nutrient provisioning were generally higher in agroforestry systems (silvopastoral and silvoarable) compared to croplands and pasturelands without trees. However, the impacts of agroforestry systems on crop yields varied depending on the system considered (i.e., coffee vs. cereals), while forest systems generally provided greater levels of BIAD and EFs than agroforestry systems. Further analysis demonstrated that the impacts of agroforestry systems on BIAD and EFs depend greatly on climate type, soil, and precipitation. For example, silvoarable systems appear to generate the greatest benefits in arid or tropical climates, on sandier soils, and under lower precipitation regimes. Overall, our findings highlight the widespread potential of agroforestry systems to BIAD and multiple EFs across montane regions of Latin America.

KEYWORDS
climate-smart agriculture, forest, grassland, land-use management, pasture, silvoarable, silvopastoral, soil health, systematic review

1 | INTRODUCTION

Montane regions around the globe are critical for supporting the provision of fresh water, energy, and agricultural production, and often represent biodiversity hotspots, especially in the tropics (Malcolm et al., 2006; Myers et al., 2000). In Latin America, mountain ecosystems are home to many rural communities and essential to maintaining their livelihoods (Eckholm, 1997; Koohafkan & Altieri, 2011). The isolation, inaccessibility, and relative poverty of many smallholder mountain communities, and the increasing reliance on agrochemical inputs to meet crop nutrient demands and control pests threatens the resilience of montane landscapes (Cuni-Sanchez et al., 2019; Elsen & Tingley, 2015; Garavito et al., 2015). Climate change threats agricultural sustainability in many montane regions, and is particularly visible in the tropical Andes, where warming conditions are melting glaciers and associated with more erratic precipitation, thus threatening water supplies (Chevallier et al., 2011; Hijmans et al., 2005; Ruiz et al., 2008; Urrutia & Vuille, 2009; Valdivia et al., 2013; Vuille et al., 2008). These effects not only have implications for agricultural and landscape functioning in mountain ecosystems but will also affect smallholder communities vulnerable to food insecurity (Valdivia et al., 2010). Furthermore, it is often not feasible to use mechanized agriculture in steep terrain, which has contributed land abandonment in montane regions around the world (Aide et al., 2019). Hence, there is an urgent need to develop and better understand climate-smart farming systems in the region that help to both, mitigate climate change, and enhance the resilience of these montane agricultural landscapes.

Agroforestry systems (AFS) represent a promising strategy to address global change, especially in mountain ecosystems (Lasco et al., 2014). Agroforestry, in which different strata of tree vegetation are spatially or temporally integrated with crops, represents an option for agroecological intensification (Nair, 1993, 2011) that can strengthen natural ecosystem functions (EFs) and reduce dependency on external inputs. Agroforestry practices, including slash and mulch strategies or managed perennial field margins, can help control erosion and support nutrient provisioning in production systems, while also sequestering atmospheric carbon (C; Jose, 2009; Kearney et al., 2019). By enhancing the resilience of smallholder farms and mitigating greenhouse gas emissions, agroforestry can thus represent a climate-smart agricultural strategy (Vaast et al., 2016). Despite the tremendous promise of agroforestry, management of these systems is often much more complex than for simplified agroecosystems based on one or a few crops/forages, and resource competition with trees can reduce crop productivity (Steffan-Dewenter et al., 2007).

In Latin America, AFS cover 200 million hectares (Somarriba et al., 2012), with shaded tree-crop and commercial silvopastoral systems being the most common and well-studied (Krishnamurthy et al., 2019; Somarriba et al., 2001). Many field studies in Latin America have demonstrate positive effects of AFS on biodiversity and multiple EFs such as nutrient provision, erosion control, biocontrol or pests, and food production (Jose, 2009; Udawatta et al., 2019). However, a comprehensive analysis is needed to better understand the dominant benefits of AFS on biological activity and diversity (BIAD) and EFs, specifically in montane regions of Latin America, where the effects may be most pronounced (Bilotta et al., 2014; Pullin & Knight, 2009; Pullin & Stewart, 2006). While meta-analyses with similar goals have been conducted for other geographical regions (Kuyah et al., 2019; Muchane et al., 2020; Santos et al., 2019; Torralba et al., 2016; Veldkamp et al., 2020), the potential of AFS (with differing shade species) to enhance social and biological outcomes in mountain environments in Latin America remains poorly understood (Krishnamurthy, 2019). Hillslope agroecosystems often differ from flatter terrain due to a range of factors. These include susceptibility to erosion, degree of mechanization, and the existence of environmental gradients across elevations that influence BIAD and may interact with anthropogenic forces that shape EFs (Caulfield et al., 2020; Poveda et al., 2012). Our objective was to quantify the benefits of agroforestry systems (AFS) on BIAD and multiple EFs in montane landscapes of Latin America. To achieve this, we conducted a meta-analysis of existing field studies, which compare AFS to conventional agricultural or grazing systems without trees. Results of this study are crucial to developing and implementing effective climate adaptation strategies and policy in Latin America.

2 | METHODS

2.1 | Literature searching and data collection

In this meta-analysis, we followed the PRISMA guidelines (Page et al., 2021) for study selection and screening, with some modifications to account for our specific research questions and available data sources. The PRISMA method ensured a systematic and transparent approach to identifying and evaluating relevant studies. We conducted our literature search using the Web of Science and Scientific Electronic Library Online to identify published studies in English, Spanish, and Portuguese, covering all years from 1990 until March 2021. Our search included three strings: (1) geographic areas of AFS in Latin America's montane regions (including the Caribbean), (2) definitions and terms to describe AFS and (3) terms relating to BIAD and EFs as well as proxies or indicators thereof (Table S1). For the selection of studies, we adopted the elevation criterion (>300 m) from the National Geographic Society. Our search resulted in 1794 titles (Figure 1). After removing duplicates and screening for studies conducted in Latin America this number was reduced to 845 studies. We considered further criteria related to the geographical scope (i.e., mountain ecosystems), the study type (i.e., only field studies), and methodological procedure (i.e., providing relevant comparisons of BIAD or EFs in AFS relative to similar land-uses without trees; Figure 1), resulting in a total of 63 studies to be included in our analyses. We also consulted regional experts to identify relevant publications that might not have shown-up in our literature search. This process resulted in a total of 78 studies (1451 observations) that met all our criteria and could be used for subsequent analysis (Figure 1).

2.2 | Database building and effect size estimation

We constructed a database to compare BIAD and EFs between AFS and the other land-uses evaluated in each study. For each data record, we applied a similar strategy for grouping response variables or indicators into EFs groups as Kuyah et al. (2019) and Torralba et al. (2016), see Section 2.3 below. We also identified 22 explanatory variables that help characterize locations and management systems, which were used as independent variables for grouping similar studies in the analyses (Table S2). These variables were: (i) latitude and longitude; (ii) country; (iii) climate (Köppen-Geiger climate classification); (iv) biogeographic realms (according to Olson et al., 2001); (v) topography (categories of slope based on USDA Natural Resources Conservation); (vi) soil type (WRB taxonomy); (vii) soil texture (descriptive); (viii) AFS type (silvoarable and silvopastoral); (ix) tree species composition; (x) elevation (m above the sea level); (xi) annual precipitation (mm); (xii) mean annual temperature (°C); (xiii) clay content in soil (%); and the land-use type for compared with AFS (i.e., pasturelands, croplands, forest; see Table S2 for all variables and associated details). In this study, croplands generally refer to crop monocultures and more simplified production land-uses. Three values were needed for each observation: a mean, sample size and an indication of variance from which the standard deviation could be calculated. Values of each group were extracted directly from the text and tables or indirectly from graphs using WebPlotDigitizer software version 4.4 (Drevon et al., 2017). In the case of missing summary statistics, values were calculated from original data, if available, or authors were contacted to obtain the necessary data. When the primary study did not report the elevation, slope, ecoregion, biome, soil type or texture, we relied on the location to extract this information from Google Earth Pro. Additionally, we used the measuring tools of Google Earth pro to determine the slope and elevation of each site when data was absent, while Worldclim (www.worldclim.org) to identify missing data on temperature and precipitation at a resolution of 1 km^2 (Beck et al., 2018).

Since our meta-analysis includes studies differing in response variables, units, and experimental designs, we used response ratios (RR) to estimate the effect size as an indicator of potential differences in BIAD and EFs (Borestein, 2009; Hedges et al., 1999). We calculated RRs comparing other land-use types (oth, i.e., pasturelands, croplands, and forest) with the AFS at each site as the reference (ref) as RR = [ln(oth/ref)]. This approach allows multiple comparisons and unit measures, and it does not depend on the expectation of the result (e.g., positive or negative). Moreover, since RRs compares BIAD or EFs in other land-uses relative to the AFS, all

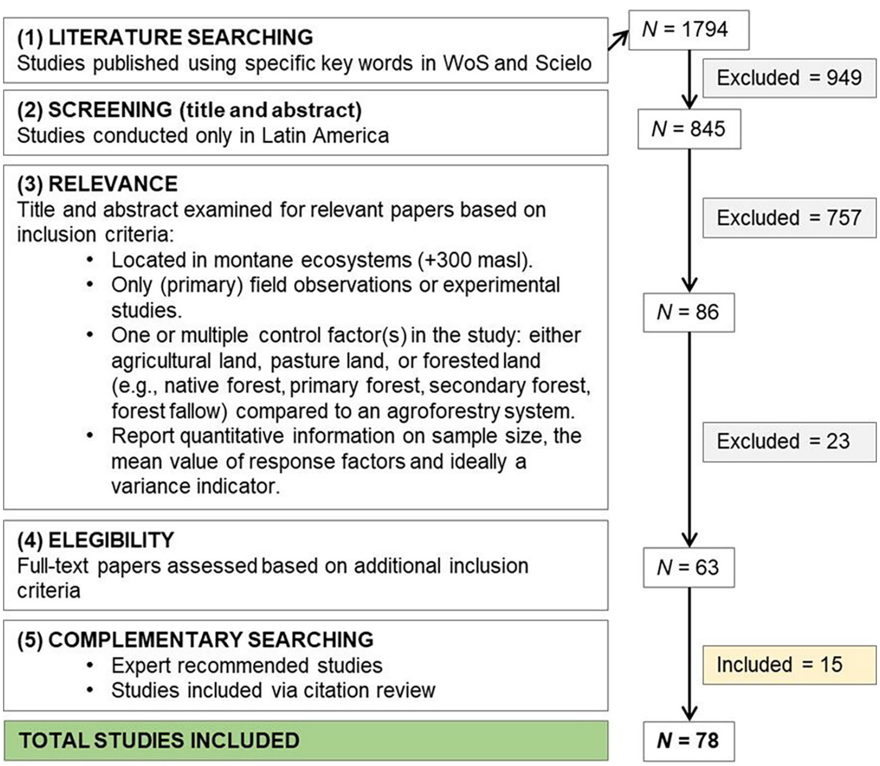

FIGURE 1 Flow chart of methodological procedures to obtain relevant literature.

data points have a common denominator that makes them broadly comparable. Response ratios close to zero indicate BIAD or EFs with similar values in the AFS or other land-uses; whereas, negative (and positive) response ratio values indicate lower (or higher) levels of function under the AFS relative to other land-uses (depending on the type of indicator involved). Since RRs represent ln-transformed proportional differences between two conditions, we report these throughout as percentage values to improve clarity.

2.3 | Biological activity, diversity, ecosystem functions and their indicators

Numerous methods have been proposed to evaluate the multiple EFs associated with different land-uses or management systems, yet no universally preferred approach has emerged. In our work, we adopted the definition of EFs as 'bundles of (soil) processes that underpin the delivery of ecosystem services (Bünemann et al., 2018). Soil processes such as habitat provision, element cycling, decomposition, structure maintenance, biological population regulation, water and organic matter cycling. We aimed to quantify the typical pros and cons for agroforestry within the context of an EFs framework applied to our assessed management systems (Figure S1). We initiated our process with a selection of essential EFs deemed crucial in assessing the benefits of AFS. We distinguished four key (mainly soil-based) EFs: (a) biological activity and diversity; (b) above- and belowground C sequestration; (c) nutrient provisioning; (d) erosion control; and (e) yield production, based on previous classifications for agricultural systems (Dainese et al., 2019; MEA, 2005; TEEB, 2010). It was not possible to include further EFs such as non-CO_2 greenhouse gas emissions, pollination, or pest control, because there were not enough studies available that met the criteria to be considered for analysis.

The indicators used in the metric of nutrient provisioning encompass a range of soil parameters that are likely to influence soil nutrient turnover and availability. These include soil and litter chemical properties and biological diversity measures. In this study, BIAD refers to the variety of living organisms, including plants, animals, fungi, and microorganisms that inhabit the ecological systems considered. Metrics in this category include measures of species diversity, richness (alpha-diversity) and abundance from the relevant studies (Table S3a). This research emphasizes the importance of soil biota in facilitating critical EFs related to soil structure and nutrient provisioning (Creamer et al., 2022; Pulleman et al., 2022). While we recognize the potential hazards posed by alien species in agroforestry systems, we did not differentiate native versus non-native species for the BIAD metrics, since this information was not always available, and the main objective of the study was to make a more generic comparison between agroforestry systems and land-uses without trees. Metrics of water regulation (such as infiltration and run-off) were added as indicators of the erosion control EFs, as they indicators are often measured to quantify erosion (Lal, 2001). The indicators used for yield production primarily pertain to specific crop and plant yields, including fruits, grains, beans, coffee, oats, rice, forage, sugarcane, maize, potatoes, and cocoa.

The examined EFs within this study are inherently interconnected within the framework of soil health (Giller et al., 2023). A single indicator can therefore simultaneously correspond to multiple EFs. See Table S3b–e for an overview of the study, country, elevation, comparator, soil type and indicator extracted for the five EFs. It is important to note that grouping the same variable into different EFs was further necessary in specific cases due to the lack of studies and source data on direct indicators of each EFs, such as nutrient provisioning or soil erosion. Careful grouping of available data was required to ensure comprehensive analysis and interpretation of the available information. We acknowledge the need to explicitly state the lack of measurements in certain areas and encourage further studies to address these gaps in understanding.

2.4 | Statistical approach and data analysis

We performed three meta-analyses where we compared silvoarable system with croplands, silvopastoral system with pasturelands, and any type of agroforestry system with forest land. Separate models were fitted to obtain the effect size estimates and confidence intervals for each comparison (i.e., other land-uses vs. AFS), where BIAD and the five EFs constituted categories. Meta-analyses are often weighted by the inverse variance of the response ratio in each study (Gurevitch et al., 2001), while unweighted models may yield confidence intervals that are too narrow as they do not account for the within- and among-study variation components that are accounted for in random-effects models. In our meta-analysis, we could not obtain or estimate variance information for 37.8% of the data. Thus, we followed the approach of Moreno-Mateos et al. (2017) to run a weighted meta-analysis. We used the subset of studies reporting variances and computed the I^2 index (Higgins & Thompson, 2002) separately for each outcome variable. All I^2 values were >90% (range 95.3%–99.8%), suggesting that among-study heterogeneity accounted for most variation and that random-effect weights across effect sizes would be expected to be very similar (the overall I^2 was 99.98%). We used this database subset to estimate the average within-study variances as an arithmetic mean of the available within-study variances for each outcome variable and used this obtained value as approximate within-study variances for the remaining effect sizes, which had that information missing.

The normal quantile plot indicated that the data was not normally distributed (Figure S2), and thus, we estimated effect sizes and corresponding 95% conference intervals using a bootstrapping procedure. The overall trends and patterns did not differ between the forest plots (Figure S3); thus, we report data based on the normal distribution. We checked for publication bias by the Kendall Regression Test for Funnel Plot Asymmetry (Begg & Mazumdar, 1994) and the TrimFill method (Duval & Tweedie, 2000). The funnel plot (Figure S4), the Kendall test ($t = -1.5886$, $df = 930$, $p = .1125$) and the TrimFill method showed no publication bias in our data.

We performed an additional meta-analysis using distinct environmental factors (i.e., climate type, precipitation, and soil clay content) as explanatory variables to see if the RRs vary under different environmental factors. These categories were chosen as most influential after model selection using ANOVA and Pearson correlation tests for categorical and continuous variables, respectively. These meta-analyses were conducted separately for silvoarable and silvopastoral systems. The heterogeneity statistics (I^2) can be biased in smaller meta-analyses, hence we relied on 95% intervals for the interpretation of the data in these additional analyses as suggested by von Hippel (2015). All analyses regarding the traditional meta-analysis were performed in R using the 'metafor' package (Viechtbauer, 2010).

3 | RESULTS

Studies included in this meta-analysis originated from twelve different countries across Latin America, with most studies conducted in Brazil, Mexico, and Peru (Figure 2). Elevation of the research areas ranged from 300 to 3500 m a.s.l., with a median of 950 m a.s.l. The upper and lower quartile were 1475 and 650 m a.s.l., respectively. All studies were conducted in either tropical, temperate, or desert biomes, with the majority being from a tropical biome. Impacts of AFS on BIAD and a variety of EFs were compared with croplands, pasturelands, and forest-based land-uses across montane regions of Latin America (Figure S5). BIAD metrics mainly included flora (20%) and soil macrofauna indicators (17%) such as abundance, richness, and diversity. Some studies considered the specific taxa including fungi (17%), Hymenoptera (ants, bees, and wasps; 11.3%), Coleoptera (beetles; 8.6%), Anellida (earthworms; 8.0%), and bacteria (2.1%). A total of 133 tree species were recorded across all AFS with the majority belonging to the plant families Fabaceae (40.6%), Myrtaceae (6.7%), Musaceae (6.3%), and Anacardiaceae (4.0%).

3.1 | Silvoarable systems compared with croplands

Metrics of BIAD were reported in 16 studies ($n = 124$ observations) that compared AFS with croplands. Overall, BIAD was 18% higher within AFS compared to the corresponding croplands (Figure 3). Additional analyses to understand the impact of broad environmental factors showed that climate zone significantly influenced AFS impacts on BIAD ($p = .045$), with AFS enhancing BIAD metrics the most in tropical climates (RR = 0.43, $p < .015$, Figure 4). There were no significant differences observed in RRs between precipitation regimes or in different soil textures (i.e., ranges of clay content) when examining the impact of AFS (vs. croplands) on BIAD. Carbon sequestration was reported in 17 studies ($n = 44$) and was on average 33% higher ($p < .001$) within AFS compared to croplands. The positive effect of AFS (vs. croplands) on C sequestration was significantly higher ($p = .013$) for low precipitation regimes (RR = 0.68, $p = .011$) compared to high precipitation regimes (RR = 0.22, $p < .001$), while RRs of C sequestration were not significantly different between classes of climate or soil texture (Figure 4). Nutrient provisioning was reported in 29 studies ($n = 269$) and was significantly higher ($p < .001$) in AFS compared to croplands without trees (17%; Figure 3). The positive effect of AFS (vs. croplands) on nutrient provisioning did not differ with climate zone but did with precipitation regime ($p = .006$) and clay content ($p = .020$), such that RRs were highest in areas with a low precipitation regime (RR = 0.24, $p < .001$) and low to medium soil clay content (RR = 0.12 and

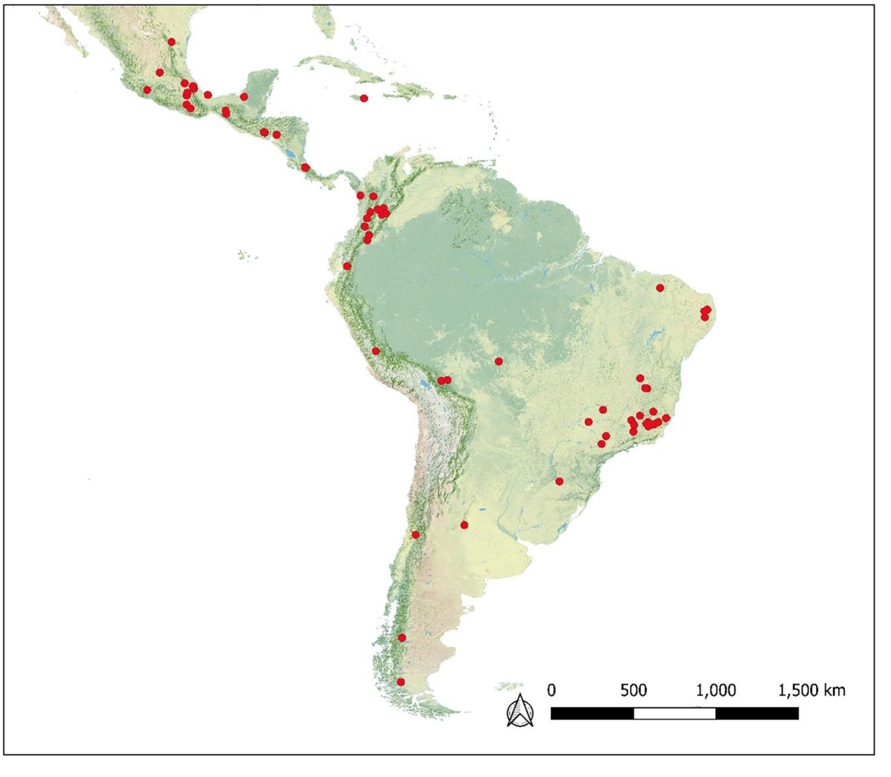

FIGURE 2 Overview of study locations in Latin America included in our meta-analysis.

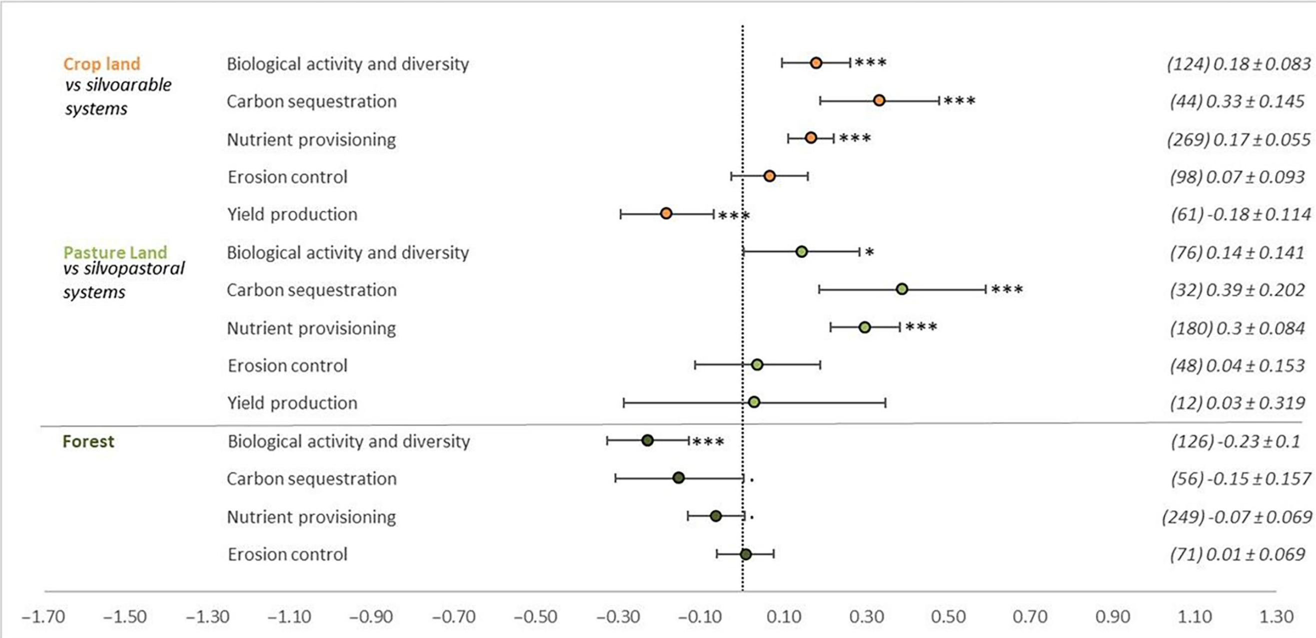

FIGURE 3 Forest plot showing the variation in biological activity, diversity, and ecosystem functions related indicators as affected by agroforestry and separated by comparator. The dotted line indicates the response ratio (RR) = 0, that is, where responses in agroforestry and control (croplands, pasturelands and forest lands) are equivalent. Significant reductions or increases are indicated when 95% confidence intervals lie below or above the dotted line, respectively. The error bars represent the 95% confidence interval. The number in parentheses represent the number of studies used in the analyses and is followed by the effect size and length of the 95% confidence interval. A *p*-value less than .05 is denoted by one star (*), while a *p*-value less than .01 is denoted by two stars (**). A *p*-value less than .001 is denoted by three stars (***). A *p*-value less than .10 is denoted by a dot.

0.26, respectively; $p < .001$). Erosion control was reported in 16 studies ($n = 98$) and did not significantly differ between AFS and croplands without trees ($p = .164$). However, when considering the impact of AFS across different soil textures ($p = .020$), soils with lower clay content tended to have lower erosion control under AFS than soil with fine texture. Agroecosystem productivity (i.e., crop yield) was reported in 15 studies ($n = 61$). The overall RR was negative, indicating that yield was 18% ($p = .001$) lower in AFS compared to monoculture croplands. While yields under silvoarable systems were on average 18% ($p = .002$) lower than that observed for croplands; this was not the case for coffee plantations, where no clear trend was observed (Figure 4).

3.2 | Silvopastoral systems compared with pasturelands

Metrics of BIAD were reported in 12 studies that compared AFS with pasturelands ($n = 76$), and overall were 14% higher ($p < .045$) under silvopastoral systems compared to the corresponding pasturelands (Figure 3). Further analysis of environmental factors did not reveal any significant effects for climate type, precipitation regime, or soil (Figure 5). Carbon sequestration was reported in 12 studies ($n = 76$), and indicated that C sequestration was 39% higher in silvopastoral versus pasturelands without trees ($p < .001$; Figure 3). The positive effect of AFS (vs. pasturelands) on C sequestration varied significantly ($p = .022$) with precipitation regimes, such that low precipitation regimes (RR = 0.52, $p = .001$) showed a higher RR than high precipitation regimes (RR = 0.30, $p = .022$). RRs of C sequestration did not differ between climates or with soil texture. Nutrient provisioning was reported in 27 studies ($n = 180$) and metrics were 30% higher ($p < .001$) in silvopastoral systems compared to pasturelands. Further analysis indicated that the effect of AFS (vs. pasturelands) on nutrient provisioning differs with precipitation regime ($p = .011$) and soil texture ($p = .005$), such that RRs were highest under low precipitation regimes (RR = 0.38, $p < .001$) and soils with a high clay content (RR = 0.46, $p < .001$). RRs of nutrient provisioning did not differ between climate types. Erosion control was reported in 15 studies ($n = 58$) and was not significantly different between the pasture systems with and without trees. Further analysis indicates that the impact of AFS (vs. pasturelands) on erosion control was most pronounced in coarse textured (low clay) soils ($p = .013$), but did not differ among climate or precipitation regimes. Forage production was reported in just 8 studies ($n = 12$, RR = 0.03) and showed no significant impacts of AFS, while the low number of observations for forage production did not allow for analysis of environmental factors.

3.3 | Agroforestry compared with forest stands

BIAD was reported in 20 studies ($n = 126$) comparing either silvopastoral or croplands based AFS with forest stands. Overall, RR was lower than 0, indicating that proxies for BIAD were 23% lower under

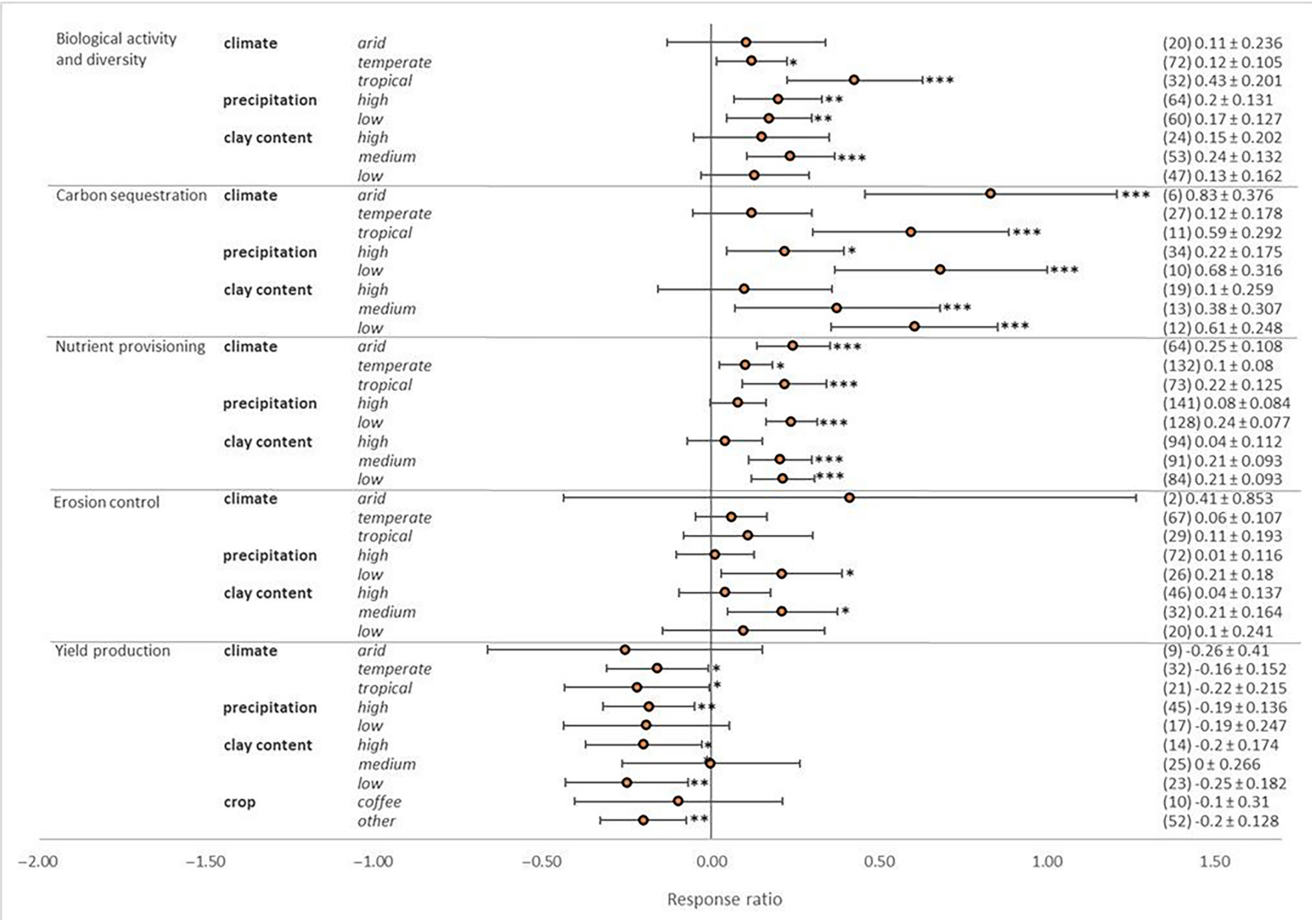

FIGURE 4 Forest plot showing the impact of agroforestry on biological activity, diversity, and ecosystem functions as affected by key environmental factors (i.e. climate, precipitation, soil texture). The dotted line indicates the response ratio (RR) = 0, that is, where responses between silvoarable systems and croplands (comparator) are equivalent. Significant reductions or increases are indicated when 95% confidence intervals lie below or above the dotted line, respectively. The error bars represent the 95% confidence interval. The number in parentheses represent the number of observations used in the analyses and is followed by the effect size and length of the 95% confidence interval. A *p*-value less than .05 is denoted by one star (*), while a *p*-value less than .01 is denoted by two stars (**). A *p*-value less than .001 is denoted by three stars (***).

AFS than in forests ($p < .001$; Figure 3). Likewise, C sequestration was reported in 17 studies ($n = 56$) and demonstrated marginally significant differences between forest and AFS ($p = .056$), such that long standing forests demonstrated 15% higher C stocks compared to AFS. Nutrient provisioning was reported in 22 studies ($n = 249$) and was marginally significant between the two land-uses considered, being 7% lower under AFS ($p = .083$). No differences were observed for erosion control (RR = 0.01) between AFS and forest systems.

4 | DISCUSSION

4.1 | Impact of agroforestry on biological activity, diversity, and ecosystem functions

Our findings demonstrate a strong positive effect of both silvoarable and silvopastoral systems on BIAD relative to comparable land-uses without trees, and this is in line with findings reported in recent studies around the globe (de Beenhouwer et al., 2013; Felton et al., 2010; Torralba et al., 2016). Past research indicates that AFS provide diverse types of shelter, habitat, food, and other resources for multiple species (Jose, 2009; McAdam & McEvoy, 2009); however, the benefits of AFS differ for different taxa and can strongly depend on the tree species present within AFS (Ma et al., 2020; Visscher et al., 2020). Different tree species support BIAD by offering a variety of resources such as shade, food, nesting sites, and unique life cycles that provide changing supplies of resources and habitats over time (Schellhorn et al., 2005). Structural complexity in AFS can also improve resilience in response to ecosystem disturbances, such as drought, fire, or pests by providing refugia and alternative habitat resources (Jose, 2012). In contrast, more homogeneous landscapes, such as those dominated by monoculture crops, are often more susceptible to disturbances, which can result in the loss of BIAD (Tscharntke et al., 2005). Past literature shows that in some cases, agroforestry may also negatively impact BIAD if not managed properly, for example, in cases of excessive

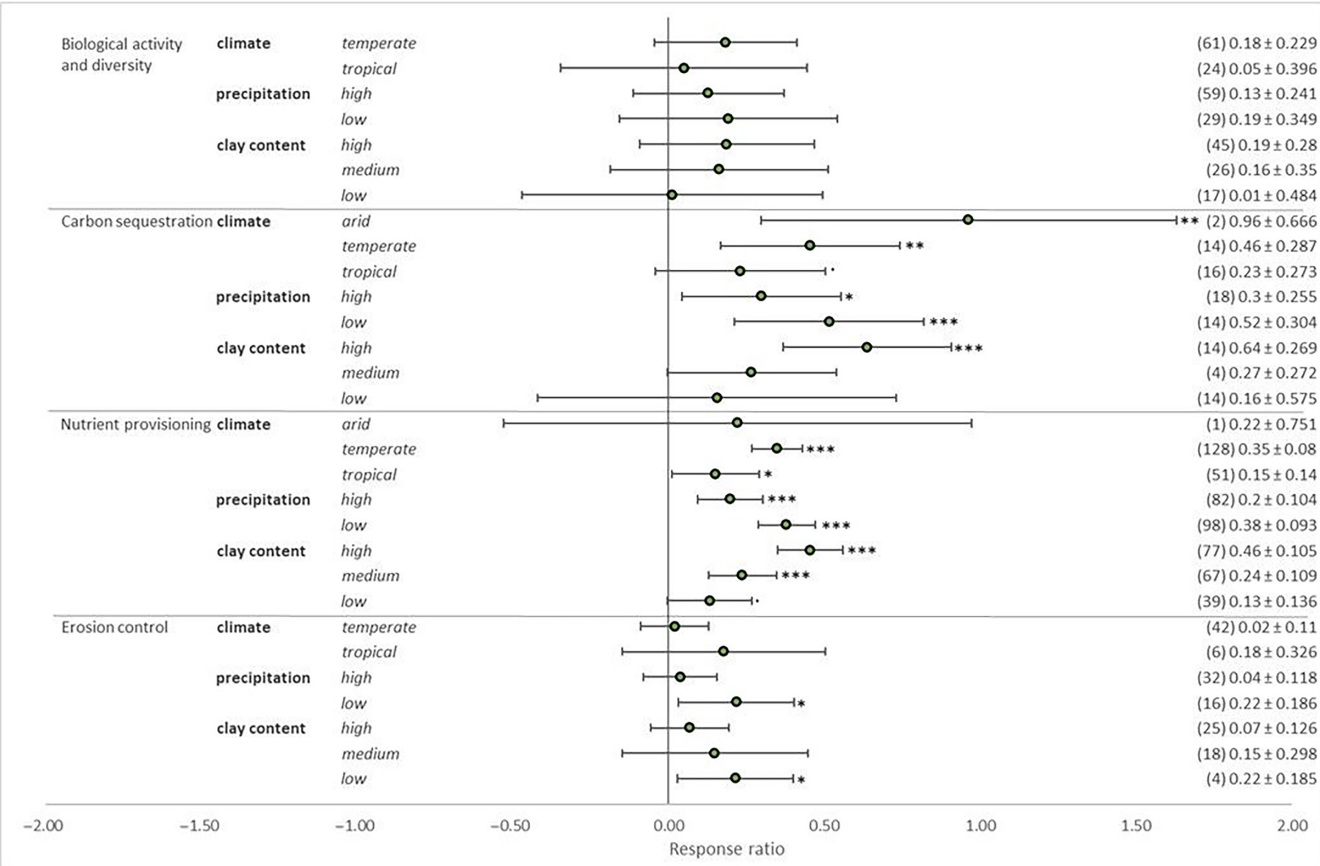

FIGURE 5 Forest plot showing the impact of agroforestry on biological activity, diversity and ecosystem functions as affected by key environmental factors (i.e. climate, precipitation, soil texture). The dotted line indicates RR = 0, that is where responses between silvopastoral systems and pasturelands (comparator) are equivalent. Significant reductions or increases are indicated when 95% confidence intervals lie below or above the dotted line, respectively. The error bars represent the 95% confidence interval. The number in parentheses represent the number of observations used in the analyses and is followed by the effect size and length of the 95% confidence interval. A *p*-value less than .05 is denoted by one star (*), while a *p*-value less than .01 is denoted by two stars (**). A *p*-value less than .001 is denoted by three stars (***). A *p*-value less than .10 is denoted by a dot.

chemical use, invasive species, overgrazing, and habitat destruction (McNeely, 2004). It is important to be mindful of these potential impacts when planning and implementing agroforestry practices to ensure they are managed sustainably and have a positive impact on BIAD.

Compared to treeless systems, the capacity of AFS to improve soil fertility has been documented in various parts of the tropics (Pinho et al., 2012; Zake et al., 2015), and our findings further corroborate this by showing clear benefits of AFS on proxies of nutrient provisioning (i.e., soil organic matter and nutrient availability) in montane landscapes across Latin America. Furthermore, in line with other studies (Andrade & Zapata, 2019; López-Santiago et al., 2019; Rocha et al., 2014; Visscher et al., 2023), we showed that AFS may play a key role as a C sink in these regions due to their ability to conserve soil, prevent degradation, provide alternative food production, and mitigate impacts of climate change in a region vulnerable to environmental degradation (Jat et al., 2016; Lal, 2015). The effects of AFS on erosion control resulted highly variable, thus not allowing for generalizable impacts. Despite the widely recognized ability of AFS to enhance soil protection and productivity, the extent to which these benefits can be realized appears to be strongly dependent on site-specific conditions and management practices (Nair et al., 1995). We suspect that the lack of an overall effect of AFS on erosion control in our study could therefore be attributed to variations in AFS practices, complex interactions with soil type, slope, and precipitation, as well as the presence of confounding variables such as prior land-use history. It is worth noting that few studies in mountainous areas of Latin America have directly evaluated erosion, and thus we also considered soil properties (e.g., aggregation, bulk density, soil cover) that likely have strong influences on erosion. While inclusion of these indirect variables may suggest the need for caution in interpretation of our erosion metrics, it allows for valuable insights into potential erosion dynamics and severity that would otherwise not be possible in our meta-analysis.

The adoption of AFS by farmers is in part influenced by the effects on crop yields, and this may vary with the system in question. We found that AFS generally decrease yields of cereals, potatoes, and cocoa, while impacts on coffee showed no clear trends. In some cases, we might expect productivity to be higher under AFS due to the complementary use of resources available within the system (Cannell et al., 1996). Nevertheless, competitive interactions for water, light, and other key nutrients appear to dominate in the studies considered here (Dodd et al., 2005). It should be noted that demonstrating complementary resource use would require assessing the productivity of the tree component, which was almost entirely lacking in the literature. Our results suggest that the competition for resources reduces biomass production and yields of the associated crops, and may thus act as a barrier to the adoption of AFS (Smith et al., 2013). Besides the potential for negative impacts on yields, AFS may be associated with other factors that limit their adoption, including lack of capital or financing to implement new AFS, relatively high labor demands, decreased potential for mechanization, lack of market incentives and technical support, and issues related to land tenure (Mercer, 2004; Pattanayak et al., 2003). The negative impact of AFS on production in silvoarable systems certainly raises some concerns, especially if this drives agricultural expansion into natural habitats, thus affecting BIAD and EFs in these areas. To address issue, we suggest that strategies such as precision farming, cropping system diversification and targeted crop breeding for AFS should be further explored.

4.2 | The positive benefits from agroforestry depends on the systems compared

Our study revealed a substantial positive impact of both, silvoarable and silvopastoral systems on the promotion of BIAD and provision of EFs, compared to treeless systems in mountain agroecosystems in Latin America, with the benefits appearing to be more pronounced for silvopastoral systems. In contrast to our findings, a meta-analysis conducted by Torralba et al. (2016) indicated that the overall effect size across various types of landscapes and elevations in Europe was higher for silvoarable systems. This discrepancy may be attributed to several factors, such as differing socio-ecological conditions, species composition, and management practices in Latin America and Europe, which may result in varied outcomes for the two systems in terms of delivering BIAD and EFs. For example, in many countries in Latin America, traditional land-use practices, such as those incorporating trees and livestock, are still accepted and valued, providing a strong cultural and social foundation for the adaptation and expansion of silvopastoral systems (Somarriba et al., 2012). In contrast, in many European countries, traditional land-use practices may have been largely abandoned or replaced by more intensive agricultural systems, making it more challenging to revive or expand silvopastoral systems (Zerbe, 2022). Still, our study shows that, compared to treeless systems, BIAD metrics were generally higher for silvoarable systems than for silvopastoral systems. The relatively large difference between monoculture cropping and agroforestry in terms of preserving BIAD is understandable given that many treeless grasslands already have a high nature value (i.e., higher diversity, more perennials, less disturbance) compared to croplands, resulting in a smaller potential for impact when incorporating trees (Veen et al., 2009).

Agroforestry studies focusing on BIAD and EFs often rely on primary or secondary forest as a reference to understand how well AFS can support key functions relative to the potential for a particular site. From the literature considered here, 34 studies considered nearby forests within their experimental designs. Most studies reported that AFS cannot achieve the same functioning as forests when considering BIAD and effects on nutrient provisioning, C sequestration. Forest ecosystems are likely to be more complex and thus better able to support and stabilize multiple EFs (Gamfeldt et al., 2013). Forests typically experience much lower levels of disturbance, and also have multiple canopy layers and complex litter/soil layers that can contribute to supporting BIAD and associated EFs (Liang et al., 2016; Tilman et al., 2014). Our results show that metrics of BIAD were overall 23% higher in forests compared to AFS across montane regions in Latin America. Many of the studies considered focused on soil-based EFs and demonstrated that forests tend to have a higher nutrient provisioning than the agricultural land-uses that replace them. Forests likely maintain higher fertility due to low nutrient losses, tighter nutrient cycling and high inputs of organic matter that help to build soil C (Foster & Bhatti, 2006; Loranger-Merciris et al., 2007).

4.3 | The role of environmental factors

Upon examining the impact of various environmental drivers, we observed pronounced impacts of both climate zone and precipitation on the functionality of AFS. For example, the impact of silvoarable systems on C sequestration, nutrient provisioning and erosion were strongest within low precipitation areas and those with an arid climate. We speculate that water scarcity in arid regions increases the sensitivity of the ecosystem to changes brought about by agroforestry practices, making any modifications to the functioning of the ecosystem have significant impacts on crops, livestock, and the surrounding environment (Tewari et al., 2014). For example, the introduction of trees in an arid area with scarce water resources could alter microclimates, leading to decreases in temperature meanwhile increases of humidity in the vicinity of shade trees. Trees that have an extensive root system could, for example, move water from the deeper soil strata to the shallower layers, thereby aiding in the growth and survival of crops and grasses. Yet, in arid regions, particularly those with sandy soils, we note that establishing AFS might require supplemental watering before they start providing advantages. As such, any promotion of AFS within mountainous arid regions should be considered with caution and account for available water and related trade-offs. Conversely, tropical, and temperate AFS, with higher water availability and well-distributed precipitation regime, may be less influenced by changes associated with including trees and therefore exhibit a lower contrast between AFS and croplands in these climates (van Noordwijk et al., 2021). We suspect that reduced rainfall (or drought) may be balanced by increased water capture and retention capacity under AFS (Wang et al., 2017), which can promote better C storage and nutrient provisioning by providing a more stable soil moisture environment for plant growth, thereby reducing evapotranspiration or heat stress, and promoting the mineralization and uptake of nutrients. Greater water availability and nutrient cycling would likely increase overall ecosystem productivity and SOM, which could enhance EFs related to C storage and nutrient provisioning for ecosystems characterized with lower rainfall. On the other hand, silvopastoral systems appear to better support EFs in temperate areas with lower precipitation, as compared to tropical or arid climates. In temperate areas with moderate temperatures and stable rainfall, silvopastoral systems might contribute better to promote a productive and stable ecosystem, compared to arid or tropical climates with frequent environmental challenges such as high temperatures, intense storms, droughts, and frequent fires. We note however, that the severity of climate challenges and hazards may differ based on the location and environmental factors and may also appear in temperate climates.

The extent to which soil characteristics influence the benefits derived from AFS is dependent on the specific type of system being employed. For instance, our findings indicate that silvoarable systems greatly benefit the provision of EFs, particularly in soils with low to medium clay content. On the other hand, silvopastoral systems appear to benefit EF more under fine soil textures. The apparent disparities in how silvopastoral and silvoarable systems influence multiple EFs may be attributed to soil properties that impact plant growth, nutrient uptake, and water retention. For example, in their review on C sequestration within AFS, Nair et al. (2010) likewise report that C sequestration depends greatly on environmental features, such as the soil properties. Clayey soil, with a high surface area, influence nutrient availability through various processes, that is (a) stabilization of soil organic matter; (b) an increased CEC capacity; (c) microaggregate formation; (d) controlling soil acidity and the microbial communities and its activity (Blanco & Lal, 2008; Wilson, 1999). We suspect that in areas with fine textured soils, organic C and associated soil functioning will generally be higher due to a greater capacity to store SOM in the long-term, but coarse textured soils we need high OM input practices, like AFS to maintain soil organic C (Binkley & Giardina, 1998). Conversely, our results show that silvopastoral systems have the potential to yield the highest degree of EFs support in soils with fine texture, perhaps as a result of the combined ability of trees' and perennial pastures' ability to increase soil permeability. This means that the effect of improved permeability on soil-based EFs is likely to be higher when comparing silvopastoral systems to pasturelands, compared to assessing silvoarable systems to croplands. The enhancement of soil permeability may facilitate the growth of both trees and pasture vegetation, thereby leading to elevated C sequestration and improved nutrient provisioning (Smith et al., 2016). It is important to note that pasturelands generally exhibit a greater provision of EFs compared to other land-uses (Veen et al., 2009), which can make it difficult to differentiate effect sizes between silvopastoral systems and pasturelands in soils with low or medium clay content. Nonetheless, it should be noted that the relationships between soil properties and EFs can vary based on regional climate conditions, land-use practices, and other relevant factors, and therefore, generalizations may not always be applicable.

These findings suggest that the climate and soil conditions play a crucial role in determining the benefits that can be achieved from agroforestry practices. This has important implications for the management of AFS and the development of policies aimed at promoting sustainable agriculture in mountain agroecosystems in Latin America. We acknowledge that the landscape context and the age of AFS are additional factors that likely influence the AFS impacts on BIAD and EF. However, the existing literature often lacks comprehensive data on these aspects, which poses a challenge for their inclusion in meta-analyses. We recommend future research to better consider these factors during field evaluations to provide additional insight and enable a more comprehensive analysis. Our findings indicate that BIAD, but also the provision of EFs such as C sequestration, nutrient provisioning can vary depending on the type of AFS utilized and the regional climate and soil properties. For example, policy makers would get greater return on investment promoting silvoarable systems in arid regions, where their impact on multiple EFs is greatest, and silvopastoral systems in areas with low precipitation and temperate climates, where they have been shown to be most effective in supporting BIAD and EFs. Similarly, they could incentivize the use of silvoarable systems in soils with low to medium clay content, where they have demonstrated a high level of EFs provisioning, and silvopastoral systems in soils with fine textures, where they exhibit the greatest enhancement in ecosystem functions.

5 | CONCLUSIONS

Agroforestry practices in mountain agroecosystems of Latin America generally enhance BIAD and EFs compared to simpler crop and pasture systems without trees, but do not achieve the same levels of BIAD and associated EFs occurring in less-managed forest ecosystems. While the relative impact of AFS on multiple EFs varies with environmental factors and the type of system in place, our findings suggest that AFS offer a promising option for montane regions across Latin America, and they may represent a valuable climate-smart alternative for supporting local livelihoods and mitigating the impacts of global warming. Moreover, land-uses that incorporate multifunctional AFS offer greater adaptability to environmental and socio-economic changes than those without trees. However, more research is needed to understand the specific mechanisms and the extent of these influences. Nonetheless, future landscape planning should also recognize potential barriers when aiming at the adoption of AFS, such as the lack of capital or financing to implement new AFS, relatively high labor demands, decreased potential for mechanization, lack of market incentives and technical support, and issues related to land tenure.

AUTHOR CONTRIBUTIONS

Anna M. Visscher: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft;

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CONFLICT OF INTEREST STATEMENT

The authors confirm that there are no competing interest.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available within the Zenodo repository at https://doi.org/10.5281/zenodo.10078894

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DATA SOURCES

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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