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Scaling agroforestry through payments for ecosystem services: a scoping review

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ABSTRACT

Agroforestry land use systems manage trees, crops and/or livestock on the same unit of land. As a technologically mature method of Carbon Dioxide Removal (CDR), it also offers significant removal potential. Payments for Ecosystem Services (PES) can help overcome barriers to agroforestry adoption. To better understand this potential, the existing research landscape and practice, this review has three objectives. First, to situate agroforestry within the broader PES literature. Second, to elaborate on the thematic scope of the literature related to PES *and* agroforestry. And third, to identify empirical evidence on the characteristics and effectiveness of PES promoting agroforestry, as well as the conditions and causes for its application. The results suggest that the subfield is rather small compared to the literature on PES *and* forests and PES *and* agriculture, and is focused on the Global South, especially Central America and Asia. The literature focuses on the issue of carbon removal as an ecosystem service, but the issues surrounding the PES mechanism seem somewhat neglected. The empirical evidence confirms the positive role of PES in the adoption of agroforestry as a CDR method. Small farm size, high transaction costs and insufficient incentives are the main barriers for farmers to participate in PES. However, an enabling policy and regulatory framework such as the resolution of land tenure issues can increase the effectiveness of PES schemes promoting agroforestry.

Key policy insights

- PES can be effective in stimulating the adoption of agroforestry and related ecological, economic and social benefits.
- Small farm size, high transaction costs, and insufficient incentives are key barriers to enrollment into PES schemes.
- Supportive political-legal frameworks for PES and agroforestry such as the resolution of land tenure issues can have significant scaling effects.

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Payments for environmental services; policy; literature review; incentives; conceptual framework; drivers and barriers

1. Introduction

In Paris, world leaders agreed to combat climate change by limiting global warming to well below 2°C compared to pre-industrial levels. In Art. 5, the Paris Agreement recognizes biomass, forests and oceans, as well

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as other terrestrial, coastal and marine ecosystems as sinks and reservoirs of greenhouse gases for achieving the climate neutrality goal set out in Art. 4 (UNFCCC, 2016).

Agroforestry, which combines perennial woody vegetation with crops (silvoarable) or livestock grazing (silvopastoral), or both (agrosilvopastoral) (Nair et al., 2021; World Agroforestry, 2024), is a land-based method of Carbon Dioxide Removal (CDR) with 'high technology readiness' (IPCC, 2022). The average annual mitigation potential of 4.1 (0.3–9.4) GtCO2-eq for the period 2020–2050 represents 6.7% of global emissions in 2019 (IPCC, 2022). In addition, agroforestry offers numerous environmental or socio-economic co-benefits, such as improved local livelihoods, improved soil fertility or more resilient ecosystems (Grima et al., 2016; Reed et al., 2017; Torralba et al., 2016). The expectation that agroforestry can reduce pressure on (primary) forests is widely supported in policy (Rosenstock et al., 2019).

Despite its technological readiness, mitigation potential, co-benefits, and political support, agroforestry has been slow to expand spatially (Den Herder et al., 2017; Liu & Chuang, 2023; Zomer et al., 2016). Although farmers may prefer systems with trees, there are a number of barriers to agroforestry adoption, including resource endowments, market incentives, biophysical factors, and higher risk and uncertainty (Mercer & Pattanayak, 2003; Montoya-Zumaeta et al., 2019; Sollen-Norrlin et al., 2020). From an economic perspective, agroforestry systems are financially challenging. While the costs of land preparation, planting, planting materials, management and maintenance are relatively higher, profitability is achieved only in the long term. In addition, more profitable land uses and off-farm activities imply significant and more immediate opportunity costs for agroforestry. The built-in diversity of agroforestry also requires considerable know-how, adequate infrastructure and markets to compete with intensive monoculture (Thiesmeier & Zander, 2023).

In this context, Payments for Ecosystem Services (PES), understood as a conditional and voluntary financing scheme between ecosystem service providers (farmers) and private or public beneficiaries (Derissen & Latacz-Lohmann, 2013; Kaiser et al., 2021; Muradian et al., 2010; Wunder, 2005, 2015), can help farmers overcome investment barriers to agroforestry by 'tipping the balance' (Engel et al., 2008) earlier and in favour of agroforestry. Salzman et al. (2018) estimate that there are about 550 PES schemes worldwide, with an annual transaction volume of US$40 billion.

PES range from cash to in-kind payments, which may include technical assistance (Wunder, 2005). PES are based on the 'beneficiary pays' principle and facilitate the internalization of negative environmental externalities caused by the beneficiary or the provision of (public) environmental goods. They reward the production of ecosystem services such as climate regulation, prevention of soil erosion or biodiversity loss. By definition, they are 'benefits that people derive from ecosystems' (Reid et al., 2005, p. v). Co-benefits, on the other hand, refer to non-remunerated positive effects of a PES intervention on the ecosystem or society (Ürge-Vorsatz et al., 2014). In principle, agroforestry PES schemes are either 'asset-building' or 'use-restricting'. An example of the first is to increase carbon removal stocks by transforming a degraded landscape into an agroforest or to improve an existing degraded agroforest. The second is to avoid carbon emissions from planned conversion or degradation of agroforests (Virgilio et al., 2010; Wunder, 2005).

In fact, Afforestation/Reforestation is the most common carbon removal PES project type (by volume) in the voluntary carbon market eligible under all standards (Michaelowa et al., 2023). However, only a fraction of the more than 200 Verified Carbon Standard project activities registered as Agriculture, Forestry and Other Land Use – projects by 2021 were agroforestry carbon removal projects (Verra, 2021). This raises the question of whether, and under what conditions, PES are suitable for promoting agroforestry adoption. However, we lack a comprehensive understanding of when and how PES applied to agroforestry have contributed, or could contribute, to the provision of climate-related ecosystem services, in particular carbon removals. Previous studies have evaluated PES outcomes either across all PES domains or in domains other than agroforestry (Boerner et al., 2017; Grieg-Gran et al., 2005; Grima et al., 2016; Liu & Kontoleon, 2018; Martin-Ortega et al., 2019; Piñeiro et al., 2020; Porras et al., 2008; Prager et al., 2016; Raes et al., 2016; Schomers & Matzdorf, 2013; Wunder et al., 2018), in specific regions (Castle et al., 2021; Grieg-Gran et al., 2005; Grima et al., 2016; Liu & Kontoleon, 2018; Martin-Ortega et al., 2019; Porras et al., 2008; Raes et al., 2016), or focused on specific PES design aspects or effects such as environmental additionality (Blundo-Canto et al., 2018; Boerner et al., 2017; Ezzine-de-Blas et al., 2016; Liu & Kontoleon, 2018; Prager et al., 2016).

Against this background, this study reviews the scientific literature linking PES with agroforestry and sheds light on a largely underexplored link. In doing so, the study adopts a scoping review approach (Elm et al., 2019) to the scientific literature on PES *and* agroforestry to achieve three specific objectives: (1) to situate the literature on PES *and* agroforestry within the general PES literature; (2) to elaborate the thematic foci of the literature on PES *and* agroforestry; and (3) to identify empirical evidence on the characteristics of PES, the effectiveness of PES promoting agroforestry, and the conditions and causes for its scaled application, including for achieving climate objectives.

2. Methods

Overall, the study combines quantitative and qualitative methods (Punch, 2014). The systematic and objective content analysis based on reading titles, abstracts, and full texts of articles (Krippendorff, 2019) was crucial. It involved the categorization of text material to identify relevant literature and thematic foci, and to assess the characteristics and effectiveness of PES, including its conditions and causes.

2.1. Search strategy, study selection and analysis

In accordance with the three specific objectives, the review process followed three sequential steps, each involving a specific approach to the identification and selection of relevant studies and the processing and analysis of data (Figure 1).

Step 1 'Identification' analyzed the place of agroforestry within the general PES literature; Step 2 'Screening' elaborated the thematic focus of the PES literature on agroforestry; and Step 3 'Inclusion' searched for empirical evidence on the effectiveness of PES promoting agroforestry, as well as possible barriers and drivers.

2.2.1. Selection of relevant publications

The selection of relevant peer-reviewed publications for the analysis of each of the three research steps was based on a detailed search strategy (see Supplementary Material).

The *identification* of relevant academic literature on PES *and* agroforestry in Step 1 involved 7 searches in the Web of Science Core Collection database: an initial search using the combination of the terms 'payments' and 'ecosystem services' (or 'environmental services'), and six additional searches using other key terms that potentially represent PES domains typically considered in the academic literature (Salzman et al., 2018), *viz*: 'agroforestry', 'forestry', 'agriculture', 'watershed', 'biodiversity', and 'land use'. The search yielded a total of 3,832 hits for PES.

For the *screening* in step 2, this literature was reduced to 196 publications by keeping only the 169 results for the combination of PES *and* agroforestry. These were supplemented by 27 studies resulting from a broader search

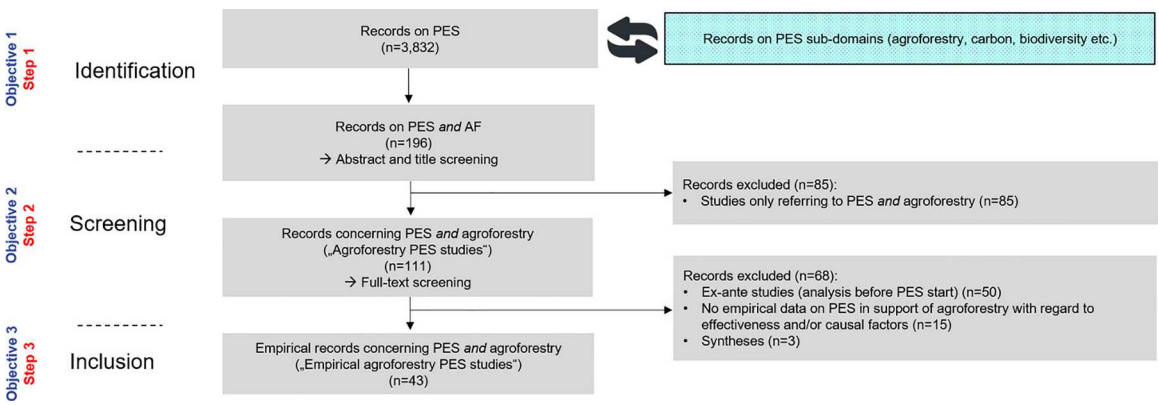

Figure 1. Flowchart of the publication selection process. Source: Web of Sciences Core Collection (date of access 22/10/2023), own development.

string that also included terms for the agroforestry types 'silvopastoral', 'silvoarable' and 'agrosilvopastoral'. For these publications, we screened the titles, abstracts and, where necessary, full texts to exclude those that only *referred* to PES *and* agroforestry rather than *concerning* them. This process resulted in the exclusion of a further 85 studies, leaving 111 articles (hereafter referred to as 'agroforestry PES studies') for the analysis under this step.

In step 3 (*inclusion*), we screened the full-texts of articles for empirical evidence on PES characteristics and PES effectiveness, and identified its main conditions and causes. We finally included 43 studies presenting relevant empirical information on 31 PES schemes (hereafter referred to as 'empirical agroforestry PES studies'). Five (5) of these studies relied exclusively on secondary data. The core evaluation of effects is based on a subsample of 20 PES schemes from only 34 studies, of which ten (10) used a difference-in-differences-like method, a combination of before-after and treatment-control group comparisons (Fredriksson & Oliveira, 2019) ('control designs' hereinafter). The remaining 11 PES schemes, based on nine (9) studies, are evaluated only in terms of enrollment and participation statistics and/or the conditions and causes of PES effectiveness based on the empirical data they provide. Only five (5) PES schemes based on six (6) studies are evaluated with respect to the permanence of the positive effects.

2.2.2. Data processing and analysis

All information collected was processed into a data file, which served as the basis for data analysis. The total of all 3,832 studies found with the first filter was used to compare the number of publications on PES *and* agroforestry with all PES-related publications over time, as well as with PES publications related to other domains beyond agroforestry (step 1).

In step 2, we categorized the 111 agroforestry PES studies remaining from the second filter in terms of country of study, agroforestry type(s), PES type(s), ecosystem service(s) rewarded, conservation and/or enhancement of carbon sinks, and stage of analysis (ex-ante or ex-post of intervention) by reading the titles and abstracts and performing a keyword search in the full texts. Studies could refer to more than one category (e.g. country of study) making the number of cases often larger than the number of studies. To gain insight into the most popular concepts, sub-themes and sentiments, an ATLAS.ti word cloud was created based on the articles' abstracts, ignoring the generic terms such as 'payment for ecosystem services', 'ecosystem services' or 'agroforestry', and excluding words that appeared less than 23 times and those that were obviously meaningless.

In step 3, PES characteristics were identified and PES effectiveness was assessed in terms of aggregated effect values (positive/neutral/negative), additionality and permanence, sorted by four effect types (carbon, ecosystem services, economic, social). To this end, information was extracted and processed from the 43 empirical agroforestry PES studies on PES characteristics (size, private vs. public funding, payment type, CDR enhancement vs. conservation, etc.), dimensions of PES effectiveness, effect types, effect indicators, effect outcomes (scores) and sizes (focusing on statistically significant effects), study designs, sample sizes, PES scheme performance targets, target indicators, and target achievement. For each effect type, we derived scores based on quantitative and qualitative information and indicators presented in the publications. For CDR-related, ecosystem services and economic effects, we distinguished between negative, no/low/neutral, positive and (im)permanent positive effects. For social effects, we distinguished between negative, positive and (im)permanent positive effects. In the case of multiple observations per PES scheme and effect type, averages were formed and conservatively rounded down where necessary, which sometimes led to neutral social effects. Finally, information on the conditions and causes of PES effectiveness was extracted from the abstracts and conclusions of the studies. For their analysis, we distinguished between the conditions and causes for participation, for PES effectiveness, and for the permanence of effects. For the participation dimension, we analyzed correlations between participation statistics and farm characteristics as well as socio-economic and PES-related factors. Additionally, we included studies that explicitly concluded on these participation factors.

3. Results

According to the three objectives of the study, first, we report on the role of agroforestry in the PES literature, second, we identify the foci of the PES literature on agroforestry, and finally, we elaborate on the insights gained on the effectiveness of PES promoting agroforestry and the conditions and causes of success.

3.1. The role of agroforestry in the PES literature

Since the first relevant scientific publications on PES in the year 2000 (Herrador & Dimas, 2000), research on both PES and the PES subfield of agroforestry has grown steadily (Figure 2). Agroforestry was mentioned in the PES literature somewhat later, in 2004 (Alavalapati et al., 2004). The annual number of publications in both fields has plateaued since 2018 at around 350 for PES and 15 for PES *and* agroforestry, albeit with significant year-to-year fluctuations. By October 22, 2023, a total of 3,832 PES studies were identified, of which 169 (4.4%) related to agroforestry.

A more detailed look shows that the most researched PES domains were PES related to forestry and biodiversity (Figure 3). Agriculture and land use followed with about 25% of the publications each.

3.2. Foci of the literature on PES and agroforestry

According to the Web of Science categorization, the supplemented sample of 196 publications that mention and PES and agroforestry, include 175 journal articles, 12 reviews, five book chapters and four papers in conference proceedings. However, only 111 (57%) of them *concern* PES and agroforestry in more detail, while the rest only *refer* to PES and agroforestry, mostly as part of policy recommendations and to a lesser extent of policy contexts. As Figure 4 reveals, in the abstracts of these 111 relevant articles (see Supplementary Material), the term 'land(s)' was central (234 times), but 'carbon' (183), 'forest(s)' (154), 'agriculture'/'agricultural' (101) were also mentioned prominently. 'Conservation' (89), 'biodiversity' (63) and 'REDD' (Reduced Emissions from Deforestation and forest Degradation) (41) were mentioned less frequently. The most frequently mentioned crops were 'coffee' (33) and 'cocoa'/'cacao' (24). Few PES-related and economic terms such as 'economic', 'financial', 'cost', 'income', 'risk' or 'market' were counted.

The majority of studies focus on developing countries, with Central America and Asia being the hot spots (Figure 5). The most frequently studied individual countries are Costa Rica ($n = 9$), Mexico (9), Colombia (8), Indonesia (8), Ecuador (7), Nicaragua (6), India (6), and Germany (4). Other countries were considered less frequently.

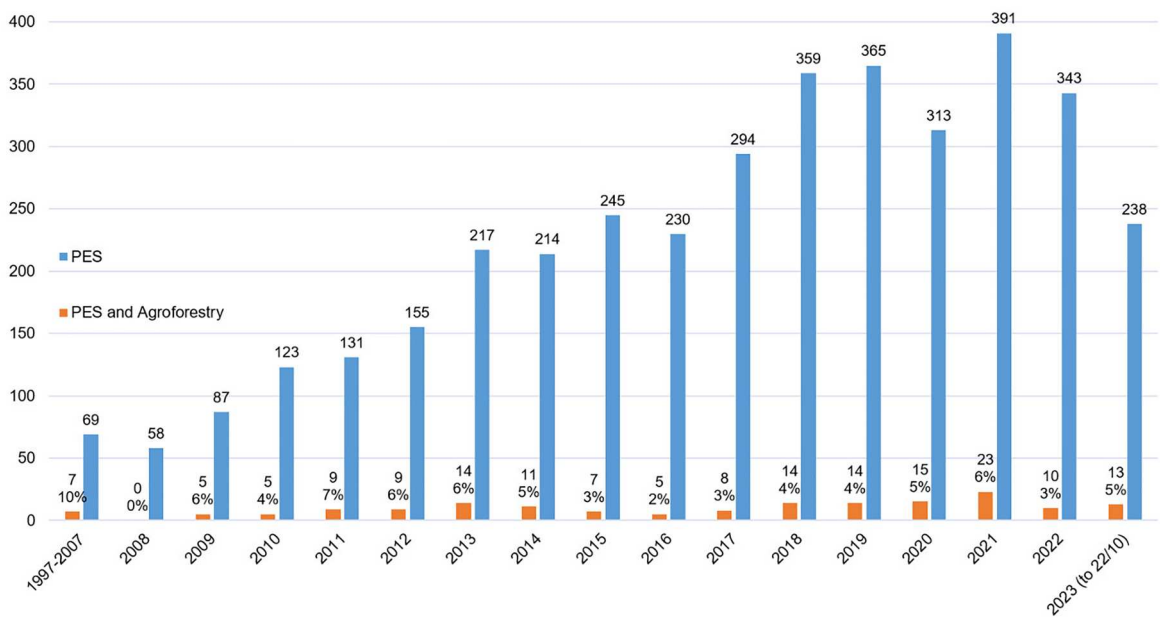

Figure 2. Number of annual publications on 'PES' and on 'PES and Agroforestry' since 1997. Source: Web of Sciences Core Collection (date of access 22/10/2023), own development.

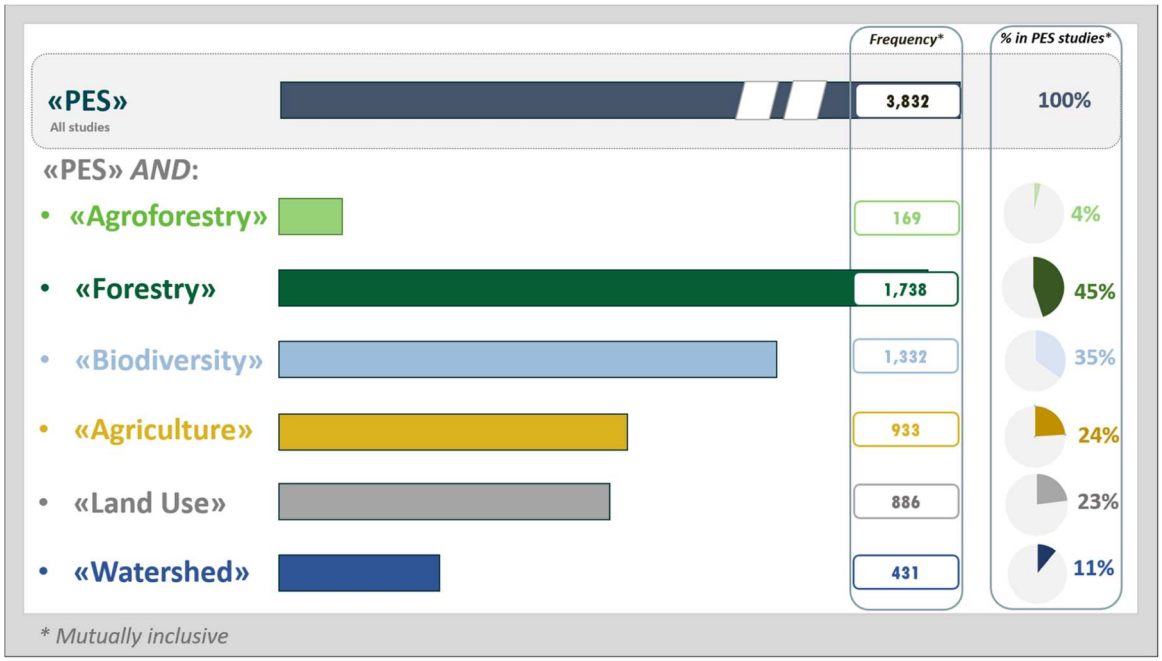

Figure 3. Most researched sub-domains of PES-literature since 1997. Source: Web of Science Core Collection (date of access 22/10/2023), own development.

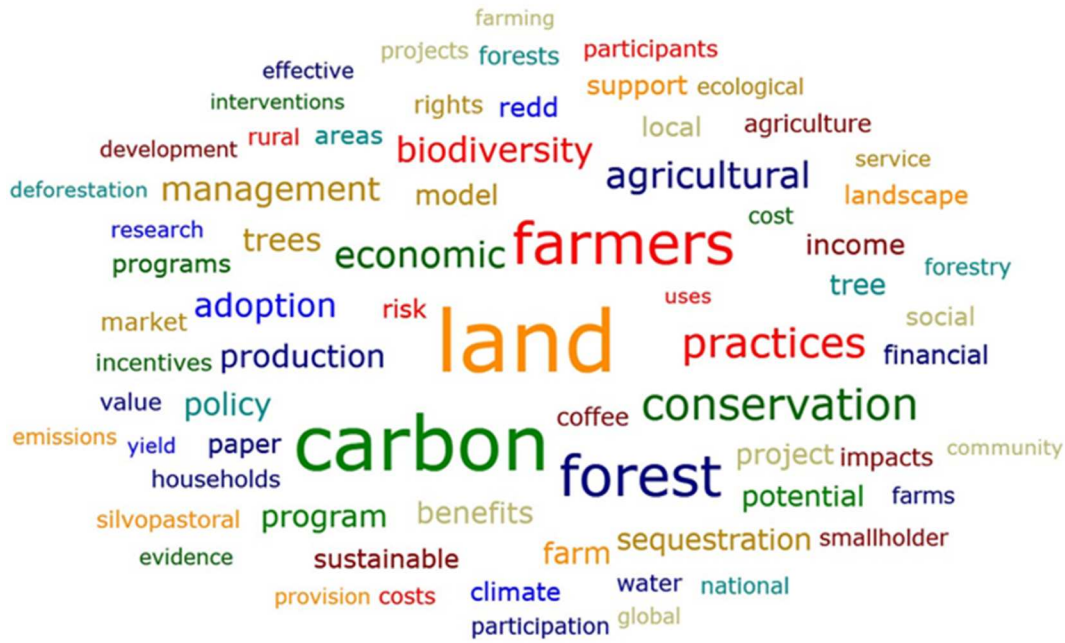

Figure 4. Word cloud of the abstracts of the Agroforestry PES Studies ($N = 111$). Source: Web of Science Core Collection (date of access 22/10/2023) and ATLAS.ti, own assessment.

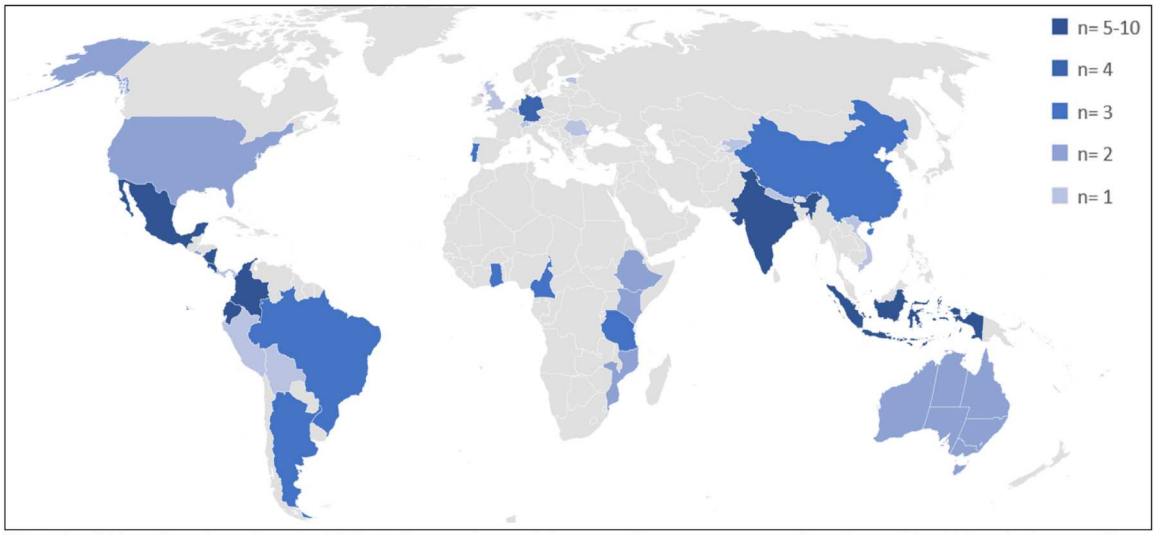

Figure 5. Agroforestry PES studies by country of study ($n = 95$)*. *16 of the 111 analyzed agroforestry PES studies are ignored, because they concern more than 3 countries (11) or lack a specific geographical focus (5). Source: Web of Science Core Collection (date of access 22/10/2023), own assessment.

Silvopastoral agroforestry systems were studied about as often as silvopastoral systems. About one fifth of all studies did not specify any agroforestry sub-type. In terms of PES types and other specifications, the vast majority of studies explicitly referred to cash payments, while only about 25% of studies referred to technical assistance and less than 10% to in-kind payments. Certification of management processes was the focus of about 6% of the studies. 8% of the studies dealt with Agri-Environmental Schemes (AES), with a strong focus on the European Union (EU).

The carbon trading approach was mentioned in about 13% of the studies, although more than 40% of the PES studies referred to carbon as the compensated ecosystem service. Payments for biodiversity services (23%), hydrological services (12%) and land use change (14%) played a less important role. Nearly half of the studies explored agroforestry for carbon removal, whereas only 20% examined its role in carbon conservation. About a fifth of the studies considered both.

3.3. PES characteristics, PES effectiveness and its conditions and causes

The current policy landscape on PES reflects a diverse array of international, supranational and national approaches and frameworks. Internationally, they range from the United Nations Framework Convention on Climate Change (UNFCCC) mechanisms on REDD+ to the post-2020 Global Biodiversity Framework by the Convention on Biological Diversity promoting PES. Both frameworks have their own funding mechanisms such as the Global Environment Facility, the Forest Carbon Partnership Facility or BioCarbon Fund. At the supranational level, the EU's Common Agricultural Policy (CAP) (2023–2027) stands out. It includes AES measures in favour of agroforestry and its recent action plan to develop sustainable carbon cycles and carbon farming to support the proposed 2030 net removal target for the land use sector (EU regulation 2018/841). Developments in Latin America and Africa that promote PES are, for example, the Latin American Water Funds Partnership, the Regional Program for Environmental Services in the Andes, the African Union's Agenda 2063 or the Comprehensive Africa Agriculture Development Programme. In addition, there are multi-stakeholder initiatives such as the Capital Coalition, The Economics of Ecosystems and Biodiversity, or the Global Partnership on Forest and Landscape Restoration, which develop frameworks and tools in favour of PES.

The subsample of 43 empirical agroforestry PES studies (see Supplementary Material) identified information on the effectiveness of PES schemes at the international, national and subnational levels. Furthermore, they identify the conditions and causes of PES effectiveness using both primary ($n = 38$) and secondary ($n = 5$) data collected through qualitative and quantitative methods. The studies were conducted between 2005 and 2022, cover more than 20 countries with a focus on Latin America, and refer to 31 PES schemes or subschemes impacting the enhancement or conservation of agroforestry (see Supplementary Material). While 22 PES schemes are evaluated by only one study, 13 of the 43 studies refer to the World Bank-supported Regional Integrated Silvopastoral Approaches to Ecosystem Management Project (RISEMP) and its three subschemes. RISEMP introduced silvopastoral practices in Colombia, Costa Rica, and Nicaragua over a four-year period. Four other studies relate to the world's first nationwide PES scheme in Costa Rica. Overall, the proportion of agroforestry schemes in the studies ranges from 100% to less than 10%.

A closer look at the PES schemes in these studies reveals different scheme characteristics.

3.3.1. PES characteristics

The reported PES schemes vary widely in the number of service providers, ranging from 24 enrolled households in a scheme in Panama (Shinbrot et al., 2022) to thousands in some African initiatives such as TIST (https://program.tist.org/) or The N'hambita Community Carbon Project (Benjamin et al., 2018; Benjamin & Sauer, 2018; Groom & Palmer, 2012; Nyberg et al., 2020).

Of the 31 schemes analyzed, 14 received public funding, another 14 received private funding, and three (3) received funding from public-private partnerships. Five (5) publically funded and managed schemes are linked to the EU's umbrella AES under the CAP, and two (2) to the AES of Switzerland and the United Kingdom (UK).

Nine (9) of the 31 PES schemes directly remunerate the enhancement or conservation of agroforestry carbon sinks (*results-based payments*) (Guimaraes et al., 2023), of which five (5) are registered under international carbon standards (Plan Vivo; Climate, Community and Biodiversity; Verified Carbon Standard). Such carbon standards enhance credibility and transparency in certifying CDR-related effects. They also facilitate the sale of carbon credits for offsetting emissions but also increase costs.

Schemes targeting ecosystem services that are difficult to measure – such as hydrological services – or aiming to cover all possible services, as is common in AES, often use proxies for compensation. These proxies typically include land-use changes or the number of trees planted (and surviving) (*action-based payments*) (Brownson et al., 2020; Zabala et al., 2017). Indices that combine multiple effects offer an alternative payment design (Pagiola, Agostini, et al., 2005). None of the identified PES schemes integrated action- and results-based payments in a hybrid model.

Several PES schemes offered farmers a choice of land use options and/or agroforestry practices that served to generate the ecosystem services (Pagiola, Agostini, et al., 2005; Ruiz-De-Ona-Plaza et al., 2011; Shinbrot et al., 2022). In our sample, silvoarable and silvopastoral practices were equally well represented.

Most of the PES schemes in our sample are designed to result in new and additional carbon sinks rather than conserving existing ones. Of the 31 reported PES schemes, almost half operate with cash payments only and about another half combine cash payments with technical assistance. The exclusive provision of in-kind payments is rare.

Few studies disclosed the payment durations and level of payments between the PES funder, scheme manager and service provider making the distribution of benefits, transaction costs and conditionality of payments nontransparent. When disclosed, cash payments were denominated in various currencies and linked to different units, such as the number of trees, hectares planted or maintained, or carbon dioxide removed or conserved.

The evidence identified three criteria for determining cash payment levels: (i) opportunity cost, with an optional top-up for ecosystem services (Schleyer & Plieninger, 2011), (ii) investment costs, and (iii) market prices. Most studies applied only one criterion. However, payment structures can incorporate both opportunity and investment costs. In the case of negative opportunity costs, payments are often just needed upfront to overcome initial investment costs (Pagiola et al., 2007, 2020; Pagiola, Arcenas, et al., 2005). They range from seedlings, fertilizers and insecticides to fences and fence posts (Hayes, 2012). Market prices for ecosystem

services are widely used in PES schemes linked to international carbon standards, but their variability poses a risk of not covering the opportunity costs (Nyberg et al., 2020; Otto, 2019).

Technical assistance typically consists of expert support, training, or advisory services to improve skills and knowledge of farmers or farm operations. Further tasks may be the support and guidance on monitoring, reporting and verification (MRV) (Corbera et al., 2009), building relationships with farmers (Ruiz-De-Ona-Plaza et al., 2011) and raising awareness of agroforestry co-benefits (Nyberg et al., 2020). Technicians can be hired by PES scheme managers or by local communities themselves (Jones et al., 2018). Technical assistance is sometimes complemented by extension services in areas such as health, finance, and business management – and vice versa (Benjamin & Sauer, 2018; Hegde & Bull, 2011; Nyberg et al., 2020).

3.3.2. The concept of PES effectiveness

The evaluation of 20 PES schemes highlights that PES effectiveness is a multidimensional concept defined as 'the achievement of stated objectives in addition to what would have been achieved in the absence of the PES intervention' (Martin et al., 2014, p. 217). Since objectives can span multiple dimensions, environmental *additionality* to the baseline (Michaelowa et al., 2019) is a necessary but not a sufficient condition for PES effectiveness. Moreover, even when an effect aligns with an objective, it is only considered *permanent* '[…] if it continues or remains unchanged indefinitely […]' (Oxford Learners Dictionaries, 2023). Based on the findings of the review, other major evaluation criteria of PES effectiveness are *costs* (Benjamin & Sauer, 2018), *participation* in PES schemes and the *timeframe* within which objectives are achieved (Biffi et al., 2022).

In a PES scheme, both funders, which are often also the beneficiaries and scheme designers, and farm households, as service providers, must participate. Household participation, in a narrow sense, is measured by the enrollment rate of eligible land, trees or farms. More broadly, it encompasses the additional ecosystem services and co-benefits generated per unit of land, tree or farm (Santiago-Freijanes et al., 2018; Schleyer & Plieninger, 2011). Thus, participation and additionality are conceptually closely related, especially when 'enrollment' is considered separately.

The additional ecosystem services generated by an agroforestry practice per unit of land becomes objective when compared to those produced by other eligible (agroforestry) practices. A PES scheme with a high enrollment rate (*scaling out*) may still be ineffective if the additional ecosystem benefits at the farm or land unit level (*scaling up*) are minimal. Therefore, while enrollment is a necessary condition for PES effectiveness, it is not sufficient on its own.

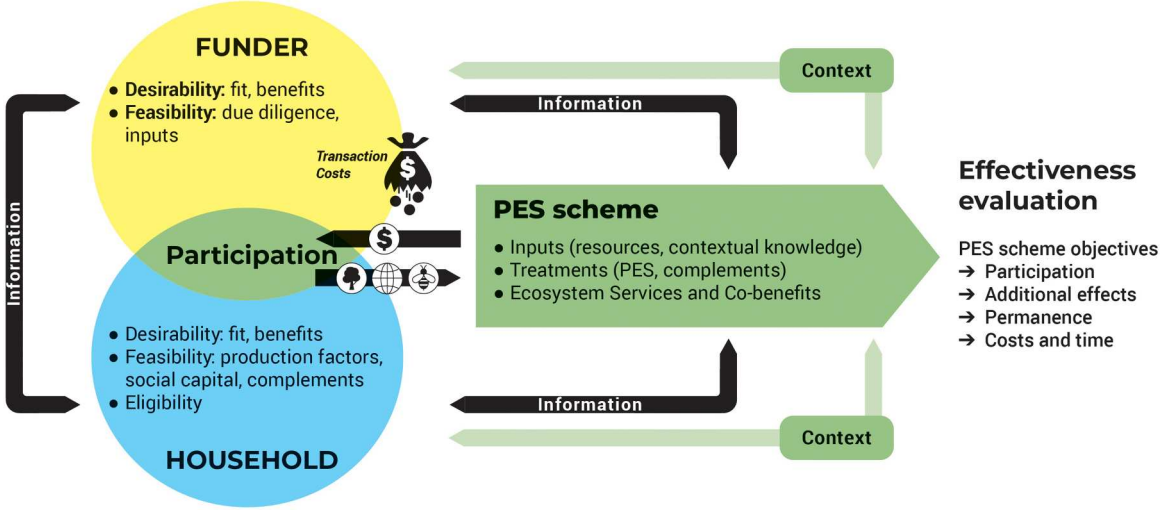

Figure 6. Criteria-based conceptual framework of PES effectiveness. Source: Own development informed by Holland-Cunz and Baatz (2025), Pagiola, Arcenas, et al. (2005) and Wunder et al. (2020).

Building on this understanding and based on our readings, we propose a criteria-based conceptual framework (Figure 6) to guide the following sections. The framework is informed by: (i) (Holland-Cunz & Baatz, 2025) who present a broader framework and criteria for policymakers and PES funders to assess policy instruments supporting CDR methods; (ii) (Pagiola, Arcenas, et al., 2005), who outline the factors influencing a household's decision to participate in a PES scheme; and (iii) (Wunder et al., 2020), who propose a theory of change for PES.

The framework highlights key interactions and conditions necessary for the effective functioning of PES. First, participation hinges on both the funder's willingness to pay for PES and the household's willingness to accept them, including any required land use changes. These decisions are shaped by various criteria and influencing factors, such as desirability – how well PES align with the goals, directions and practices of decision-makers – and the expected and perceived *net* benefits after transaction costs such as information gathering, application/contracting costs or MRV. Funders and households will further only engage in a PES scheme if they are aware of it and if, after exchanging information, their perceptions of these factors and the scheme's offerings align.

Second, certain conditions must be met for a PES scheme to function effectively: (i) *inputs* need to be in place, which include essential resources and contextual knowledge; and (ii) *treatments* are required for both PES introduction and agroforestry implementation. The latter involve PES design-related factors and a broader set of complementary measures (Wunder et al., 2020). The creation of these conditions is based on information about the funders and households and their (anticipated) perceptions.

Finally, PES schemes operate within diverse and dynamic contexts, all of which influence participation decisions, PES scheme design and implementation processes.

Ideally, and taking into account its objectives, a PES scheme's effectiveness is assessed across multiple dimensions such as additional ecosystem services, co-benefits, permanence, participation, costs and time.

3.3.3. PES effectiveness

The review of the sub-sample of 34 studies, covering 20 PES schemes, identified 40 distinct effects based on 70 effect scores. This indicates that many studies assess multiple effect types – including CDR-related, ecosystem services, economic, or social outcomes – and sometimes evaluate more than one PES scheme within the same research. Overall, CDR-related outcomes are less often evaluated than other ecosystem services and socio-economic effects.

The 16 CDR-related effects are more frequently linked to the establishment of new agroforestry carbon sinks (11) than the conservation of existing ones (5). Ecosystem service outcomes are commonly associated to biodiversity, while economic effects are largely tied to changes in PES suppliers' income. Less frequently, studies examine farmers' perceptions of well-being and livelihoods. In terms of social effects, research predominantly focuses on the equitable participation of disadvantaged subgroups in PES schemes, both in terms of enrollment and ecosystem service generation. Additionally, some studies evaluate PES schemes in relation to equity between scheme management and farmers, considering power dynamics (Otto, 2019).

Most PES schemes report positive effects on carbon sequestration and other ecosystem services, including those assessed in studies with control designs (Figure 7). However, the permanence of these effects remains inconclusive in most studies. However, the three RISEMP schemes supported by the World Bank are positively evaluated for the permanence of newly established agroforestry systems. The results suggest lasting benefits for carbon sequestration and biodiversity, as confirmed by control-design studies (Calle, 2020; Pagiola et al., 2016, 2020; Rasch et al., 2021) (see Supplementary Material for indicators, effect scores, and effect sizes from studies with control design).

Eight PES schemes have been evaluated for their economic effects, with 75% yielding positive conclusions. These findings, however, are derived solely from studies without control designs. While the literature offers partially details of the PES scheme design, economic evaluations remain narrowly focused on household impacts and failed to assess the economic effectiveness of PES from a funder's and policy-maker's perspective.

Finally, regarding social effects, the results are mixed. Half of the PES schemes indicate little or negative impacts, particularly concerning the equitable participation of lower socio-economic groups (see also Section 3.3.4.1).

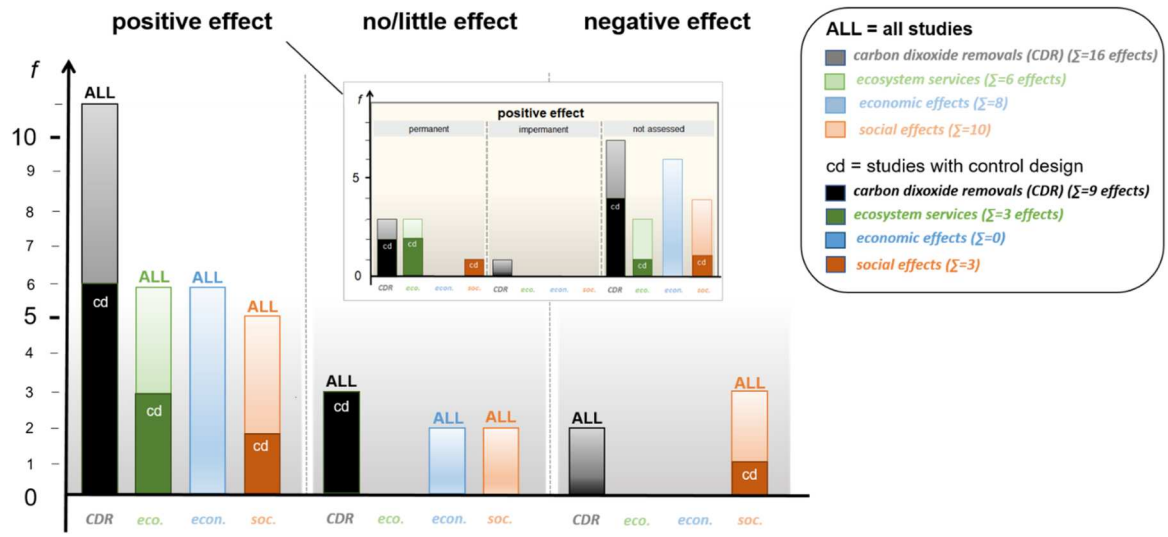

Figure 7. PES outcomes by effect type and study design ($N = 40$ effects). Source: Web of Science Core Collection (date of access 22/10/2023), own assessment.

While the additionality of CDR-related and other types of effects captured through control designs is crucial, it is only a foundation for achieving PES objectives at scale. As the target area, number of eligible farmers, and available funds in a PES scheme increase, enrollment and participation – often central to official PES objectives – become increasingly critical criteria. Given this, it is notable that only three (3) out of 43 studies reported specific targets and corresponding achievement rates for PES schemes (Hegde & Bull, 2011; Nunez et al., 2020; Santiago-Freijanes et al., 2018). Five (5) other studies, covering six (6) PES schemes, used alternative evaluation benchmarks, such as national climate targets or land use changes across eligible areas. Based on these criteria, only two (2) of the eight (8) PES schemes – just 25% – met their targets at the time of evaluation (Biffi et al., 2022; Pinchansky et al., 2021). For example, Nestlé's Milk Plan scheme successfully attracted farmers to enroll and plant hedges in alignment with the UK's net-zero carbon targets by 2050 (Biffi et al., 2022). It is also the only study that explicitly assesses a temporal benchmark in the evaluation.

3.3.4. Conditions and causes of PES effectiveness

All 43 empirical agroforestry PES studies discuss the conditions and causes of PES effectiveness. Among them, 14 explicitly address enrollment decisions, forming the basis for subsection 3.3.4.1 on enrollment. The remaining subsections explore treatment- and input-related conditions, incorporating insights from the remaining literature.

3.3.4.1. Conditions and causes of enrollment into schemes. As the conceptual framework suggests, farmer enrollment is a necessary condition for scaling individual agroforestry impacts through PES. The reviewed studies identify several correlating or causal factors influencing enrollment. First, factors related to the economic benefits of PES participation, namely payment design (6 studies) and transaction costs (5). Second, the availability of production factors making a PES participation feasible, which relates to socio-economic factors and farm characteristics (7). Additionally, access to information on PES schemes (3), which facilitates the participation for both households and funders.

For *PES design*, studies highlight the level of cash payments – and their regular adjustment to market conditions – as a key factor for farmers' willingness to participate (Schleyer & Plieninger, 2011; Sereke et al., 2016; Sibelet et al., 2017; Tsonkova et al., 2018). While Section 3.3.4.2 delves into the specific design of cash payments, research also indicates that not all farmers prioritize financial incentives. Notably, two studies identify

agroforestry co-benefits, such as reduced environmental degradation (Kwayu et al., 2014) and decreased reliance on phytosanitary measures (Calle et al., 2009) as strong 'motivators' for enrollment.

In this context, *transaction costs* have been highlighted as critical. For the World Bank-supported RISEMP studies, they were described as potentially 'greater barriers to participation for poorer households than household-specific constraints' (Pagiola et al., 2008, p. 299, 2010). High transaction costs have also been reported as a barrier to entry in international product certification (Jacobi et al., 2017) and nationwide schemes (Corbera et al., 2009; Tsonkova et al., 2018).

Regarding *farm characteristics*, two studies (Benjamin et al., 2018; Kwayu et al., 2014) suggest that larger farm sizes are positively correlated with enrollment in PES schemes. This correlation may reflect greater capital availability, enabling farmers to invest in new seedlings, equipment, and labour while benefiting from lower transaction costs compared to smaller farms. Larger farms also offer more flexibility, increased opportunities, and a higher tolerance for risk in new business ventures (Kwayu et al., 2014). Additionally, farmers with larger holdings may qualify for payments that require a minimum land size, such as EU subsidies (Martino & Muenzel, 2018). Furthermore, education and experience in agroforestry can be key factors influencing participation (Benjamin et al., 2018).

Finally, another factor that encourages participation is *exposure to information* about PES schemes. Specifically, extension services, consultations during the scheme design phase (Kwayu et al., 2014) and interactions with farmers already enrolled in the scheme (Hayes, 2012) have been identified as influential. The crucial role of direct farmer-to-farmer contact and 'social ties' is further supported by an econometric study in Costa Rica (Rasch et al., 2021). The study also finds that exposure to traditional production paradigms – such as membership in conventional producer organizations – can hinder the flow of new information.

3.3.4.2. Conditions of payment approaches, inputs and complements for effective PES. Payment type conditions encompass the characteristics of cash payments, in-kind contributions, and technical assistance that can impact the effectiveness of PES schemes in delivering additional ecosystem services and co-benefits. Inputs and complementary measures further support these objectives by addressing factors beyond the payment structure itself.

3.3.4.2.1. Cash payments. Regarding payments, more than half of the 43 studies highlight the critical role of appropriate *payment levels* in either facilitating ecosystem services or driving land use changes. Additionally, many studies emphasize the low profitability of agroforestry as a major constraint. Consistent with the findings from the enrollment studies, the remaining literature in our sample underscores the importance of setting payment levels in line with opportunity costs. Cash payments should, at a minimum, compensate for potential income losses from alternative land uses or off-farm work. This is particularly crucial for conservation measures that restrict alternative land uses, as these may (temporarily) reduce benefits compared to less conservation-oriented practices. Therefore, ensuring an appropriate level of cash payments is especially important when they support both productive and non-productive land uses (Guerra et al., 2016; Missall et al., 2022; Nunez et al., 2020).

Even when the returns from agroforestry surpass those from other land uses or off-farm labour, *up-front payments* are crucial to cover the initial investment. These payments can be provided in cash or in-kind, which is particularly important if the agroforestry system does not include short-term cash crops (Bose et al., 2019; Pagiola et al., 2008; Wunder, 2005). For instance, the RISEMP studies highlight that such up-front cash payments, based on the existing tree cover on participating farms, help prevent perverse incentives for pre-project land clearing and enable poorer households to engage in agroforestry initiatives (Calle, 2020; Pagiola et al., 2010). They further help farmers avoid alternative financing options like selling livestock, using personal savings, or applying for loans or complementary programs (Nyberg et al., 2020). In many cases, overcoming investment barriers is a key factor in farmers' decision-making processes (Brownson et al., 2020; Hayes, 2012; Villamor & van Noordwijk, 2011). In our sample, the payment durations vary from 3 to 10 years based on data from about one third of all PES schemes identified.

Mixed evidence from five (5) studies suggests that *flexibility in land use options* is a key factor that promotes not only the provision of ecosystem services but also the decision to enroll and participate in schemes. The more land use options available to farmers for implementation, the better. For instance, the RISEMP studies

indicate that multiple land-use options, extending beyond agroforestry, 'may have played an important role in its success' (Pagiola et al., 2020, p. 11). Multiple agroforestry practice options have also been observed in other effective or long-established PES schemes (Hegde & Bull, 2011; Ruiz-De-Ona-Plaza et al., 2011; Shinbrot et al., 2022). These options may be especially important for lower-income groups seeking to complement subsistence agriculture (Benjamin & Sauer, 2018; Ruiz-De-Ona-Plaza et al., 2011). Conversely, it is reported elsewhere that 'the reduced number of options offered under the scheme, the simplified evaluation process, and the flexibility in the physical implementation of the options on the farm' (Biffi et al., 2022, p. 114484) positively influenced the scheme's effectiveness, as evidenced by the number of hedges planted.

3.3.4.2.2. Technical assistance. The second most emphasized driver of effectiveness is technical assistance. More than ten (10) studies highlight this factor, consistently combined with other measures in all cases studied. It is evident that technical assistance can be particularly crucial at the outset of scheme implementation, helping farmers understand possibly new and complex agroforestry systems (Bose et al., 2019; Calle, 2020; Jones et al., 2018; Pagiola et al., 2008, 2010). Three studies indicate that adequate technical assistance can even substitute for cash payments (Bose et al., 2019; Garbach et al., 2012; Nyberg et al., 2020). It can reduce the need for payments and raise awareness of the benefits of agroforestry as a land-use option (Nyberg et al., 2020). It has also been found that farmers perceive technical assistance as especially relevant for the implementation of complex agroforestry systems and their production functions, but less so for less intensively managed agroforests with high ecological value, such as the establishment of biodiverse, multilayer hedgerows (Garbach et al., 2012). Additionally, it is suggested that technical assistance should consider farmers' local production practices to mobilize their intrinsic innovation potential. For example, instead of cash payments under sustainability certification schemes, Indian coffee farmers expressed a preference for technical assistance to improve their farm management practices (Bose et al., 2019).

The detailed analysis of 34 studies evaluating 20 PES schemes, yielding 40 effects, suggests that cash payments are an effective tool for achieving carbon-related and other environmental outcomes (Figure 8). This may be especially true when farmers can choose from multiple agroforestry practices within PES schemes, allowing them to select those best suited to their expertise and reducing the need for technical assistance.

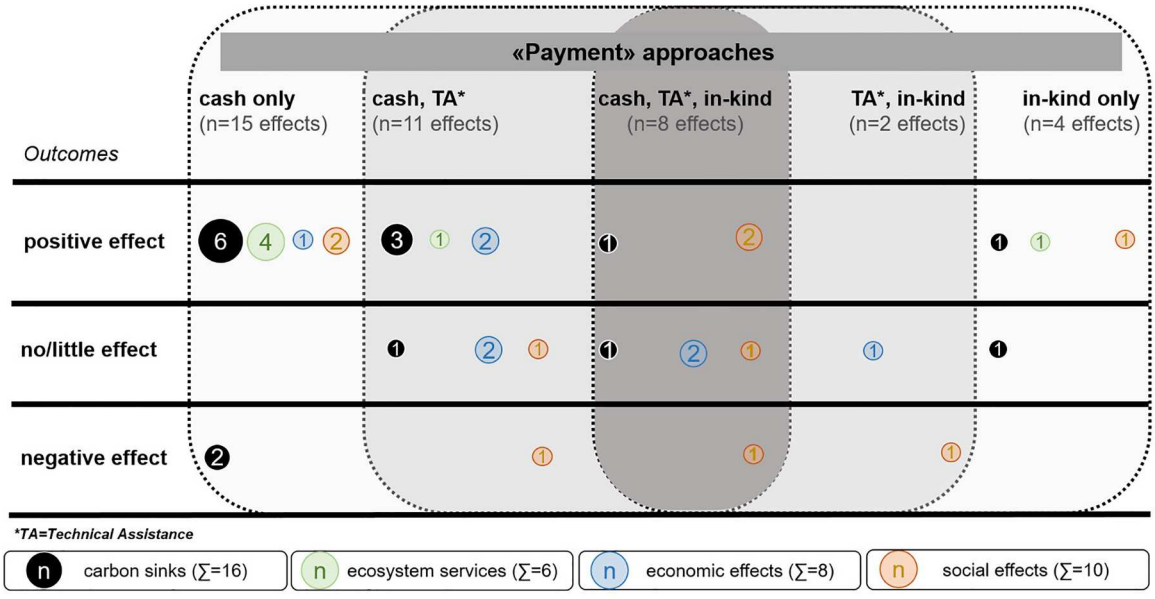

Figure 8. PES outcomes by different «payment» approaches and effect type ($N = 40$ effects).

Source: Web of Science Core Collection (date of access 22/10/2023), own assessment. The effects related to the three RISEMP schemes have been classified as 'cash only' because participants who received both technical assistance and cash payments did not outperform those who received only cash (Pagiola et al., 2010, 2016, 2020).

3.3.4.2.3. Inputs and complements. Including farmers' diverse perspectives, motivations, and knowledge in the development of PES design has been highlighted as a crucial input for PES effectiveness (Bose et al., 2019; Brownson et al., 2020; Hayes, 2012). Considering farmers' contextual knowledge allows for a targeted application of PES and ensures their intrinsic motivation.

Complementary conditions for PES schemes involve the existence of value chains, markets, and legal frameworks for agroforestry and PES. Specifically, three studies underscore the importance of local institutions in developing value chains for agroforestry products, provided that markets for these products exist (Cole, 2010; Jacobi et al., 2017; Jones et al., 2018). Conversely, three other studies highlight the negative impact of inadequate regulation and uncertainty related to land tenure on farmers' long-term investment decisions. For example, issues have arisen with the formal clarification of land tenure rights required for participation in PES schemes (Pinchansky et al., 2021; Santiago-Freijanes et al., 2018), or leasing regulations conflicting with the long-term nature of agroforestry investments (Schleyer & Plieninger, 2011).

3.3.4.3. Conditions and causes of permanent PES effects. Studies evaluating the permanence of effects often cited the same factors that positively influence short-term effects, particularly the combination of short-term cash payments (Pagiola et al., 2016, 2020) and technical support (Calle, 2020). The ability to choose from a wide range of land use options is also highlighted as 'likely' to contribute to permanence, especially since this flexibility has helped exclude less profitable land use options, such as forest conservation, which would have required long-term support beyond the end of the PES (Pagiola et al., 2016, 2020). One study on the RISEMP scheme in Costa Rica found that cash payments alone may not be sufficient to ensure the permanence of land use decisions (Rasch et al., 2021). In this regard, a study of a PES scheme involving indigenous households in Panama found that the increase in income from subsidized agroforests was crucial for farmers, especially the poor, to sustain the land use (Shinbrot et al., 2022). Permanence was negatively affected when the level of payments depended on carbon markets, as shown in an ethnographic study of a PES scheme in Mexico. When payments were suspended in response to decreasing global carbon prices, farmers began to abandon the PES scheme and agroforests (Otto, 2019).

4. Discussion

This study is the first to systematically assess the current research landscape on PES *and* agroforestry based on a scoping review. However, of the 43 empirical studies analyzed, only 10 used control designs and study-specific indicators to assess whether carbon-related effects or co-benefits are truly additional and/or permanent. Despite the limited number of well-elaborated studies, our review presents a relatively clear and positive assessment of the effectiveness of PES in promoting agroforestry.

Our review exclusively considered peer-reviewed journals from the Web of Science Core Collection. It used the umbrella terms 'payment for ecosystem services' and 'payments for environmental services', along with 'agroforestry' and its subtypes: 'silvopastoral', 'silvoarable'/'agrisilviculture', and 'agrosilvopastoral'. However, although we also considered alternative spellings both PES and agroforestry are associated with numerous other terms – such as REDD, carbon credits, certification, shaded coffee or shaded cocoa (see analysis of thematic foci) – which were not necessarily associated to the search terms. Literature from other scientific databases and gray sources was also omitted. Incorporating these additional sources and terms could certainly have increased the number of hits for the quantitative analysis, and led to more robust results of the content analysis. On the other hand, including only some of these alternative terms in a (necessarily) non-exhaustive different search string would have introduced a selection bias and overemphasized them in the analysis, distorting the results for the umbrella terms that were the primary focus of the research.

The limited number of effectiveness dimensions evaluated also influenced the results. Compared to additionality, other key dimensions – such as permanence, enrolment/participation, costs, and time – remain under-researched. Notably, studies on the economic effects of PES have primarily focused on household participants, overlooking factors critical to funders and policymakers. These include investment costs, PES payment levels (and/or opportunity costs), and payment duration – ideally assessed against alternative land-use

investments, such as forestry and other policy instruments. This broader perspective is particularly important given findings from RISEMP studies in Latin America, which suggest that agroforestry sequesters carbon at a lower cost than forests due to lower investment costs and negative opportunity costs. Such effectiveness advantages are especially relevant in addressing the temporal urgency underscored by recent research on irreversible climate tipping points (Armstrong McKay et al., 2022; Lenton et al., 2008).

Despite the above listed methodological limitations, which in a way underscore the complexity of the topic, this review provides valuable guidance for scaling agroforestry carbon sinks through PES. For example, policymakers can strengthen PES schemes by addressing land tenure issues. The effectiveness of PES also depends on attractive and adaptable payment structures as illustrated in RISEMP and follow-up studies (BEIS, 2020). These should cover opportunity costs, support initial investments, and minimize transaction costs. Simplified enrolment, proportionate MRV requirements, and the pooling of smallholders can also reduce transaction costs and thus increase the adoption of PES among the farmers (Cacho et al., 2013; Engel et al., 2008). 'Nudging' (Thaler & Sunstein, 2008), i.e. offering flexibility regarding the choice of agroforestry practices can also enhance participation and lessen the need for technical assistance, despite possibly higher transaction costs. Support should include management, logistics, and marketing in addition to production aspects. Additionally, clear and widespread communication about PES opportunities is essential for farmer enrolment. Finally, the targeted distribution of financial incentives can maximize the cost-effectiveness of PES schemes by ensuring the efficient allocation of scarce resources (Babcock et al., 1997; Engel, 2016; Ezzine-de-Blas et al., 2016; Wunder et al., 2018).

Our results suggest that PES targets can be effectively aligned with farm characteristics, location, management practices, and the type and extent of ecosystem services provided. In general, experienced, well-educated and large-scale agroforestry farmers are strong candidates for PES, as they can make necessary investments and deliver effective and low-risk performance due to their know-how and economies of scale (Brownson et al., 2020). To enhance carbon sinks, it may make sense to give priority to areas with little agroforestry, with less fertile soil to take advantage of the lower opportunity costs and with high and fast biomass growth (Feliciano et al., 2018; Ma et al., 2020). It can be also very meaningful to target those agroforestry practices that offer a competitive advantage over afforestation/reforestation or current land use, but only face investment barriers or knowledge gaps. In these cases, it is sufficient to support initial investment and opportunity costs until profitability is achieved. However, current international carbon standards are not yet geared towards such shorter crediting periods.

A focus solely on carbon offsets should not overshadow the many other benefits of agroforestry in cost–benefit analyses. Agroforestry offers valuable provisioning and regulating services, including climate resilience, wind and soil erosion control, and water regulation – benefits that farmers may value even without financial incentives, especially in the face of climate change (Hanemann, 2005). Therefore, mobilization efforts of farmers for agroforestry systems should communicate not only technical and financial aspects but also non-monetary benefits, potentially reducing reliance on direct cash payments (Bose et al., 2019; Garbach et al., 2012; Nyberg et al., 2020). This approach is particularly worth considering given that existing literature largely overlooks the possibility of insufficient funding (Shapiro-Garza, 2013).

5. Conclusion

Despite the significant CDR potential of agroforestry (IPCC, 2022), this study shows that there is limited research on the combined fields of PES and agroforestry. Most of the peer-reviewed PES literature focuses on agriculture or forestry. The studies that concern agroforestry primarily emphasize technical and production aspects. Empirical data on the effectiveness of PES in scaling agroforestry is still scarce. Of the 43 empirical studies analyzed, only 10 employed control designs and study-specific indicators to assess whether carbon-related effects or co-benefits were truly additional and/or permanent compared to business-as-usual. In general, the research focuses on the Global South – particularly Latin America and Asia – whereas the potential for the Global North (Reed et al., 2014; Rigueiro-Rodríguez et al., 2008; Udawatta & Jose, 2011) is largely overlooked.

Despite these limitations, the interdisciplinary research we reviewed paints a relatively clear and positive picture of PES effectiveness, particularly in terms of additionality for carbon-related and other outcomes. However, findings on permanence, participation, costs, and timeframes remain inconclusive. The studies

highlight several strategies to enhance PES effectiveness in scaling agroforestry, including flexible and attractive payment structures, low transaction costs, and a diverse range of agroforestry practices that farmers can choose to implement. Nonetheless, small farm size continues to be a significant barrier to PES participation.

The identified research gaps highlight the need for further impact evaluations of PES promoting agroforestry and systematic reviews of their effectiveness to better understand whether and how objectives are achieved. Future research should pay particular attention to easily measurable indicators, such as enrollment rates and the duration of PES payments. In some cases, data from national inventories (Schleyer & Plieninger, 2011) and other PES schemes (Biffi et al., 2022) may also serve the formation of alternative control groups or benchmarks, potentially helping advance the subfield effectively. Moreover, ex-post surveys of household participants can offer valuable insights into the additionality of PES (Bose et al., 2019; Calle et al., 2009; Corbera et al., 2009; Pinchansky et al., 2021; Sereke et al., 2016; Sibelet et al., 2017; Villamor & van Noordwijk, 2011).

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Author contributions

Research design: S.M., B.P.; Conceptual Framework, Data collection, Analysis, Interpretation, Writing – original draft preparation: S.M.; Writing – review & editing, S.M., B.P., S.R., F.E.M.O.; All authors have read and agreed to the published version of the manuscript.

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