Current Research in Environmental Sustainability 4 (2022) 100134

Contents lists available at ScienceDirect

Current Research in Environmental Sustainability

journal homepage: www.sciencedirect.com/journal/current-research-in-environmental-sustainability

Carbon accounting in European agroforestry systems – Key research gaps and data needs

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ARTICLE INFO

Keywords:
Climate change mitigation
Soil organic carbon
Biomass carbon

ABSTRACT

In simplest terms, agroforestry involves growing trees on farms for a range of socio-economic and ecological benefits. Agroforestry as a land management technique has been practiced for thousands of years. As climate change and environmental impacts of agricultural intensification have become increasingly evident in recent years, agroforestry has garnered renewed scientific and public interest. Indeed, due to treeś high carbon sequestration potential, their integration into cropland has been highlighted as a promising natural solution for climate change mitigation. In this context, we review research gaps and data needs that constitute barriers to increased agroforestry implementation and improved carbon accounting in temperate regions, with a focus on Europe. A lack of clear agroforestry classification systems, as well as methodological and logistical constraints, emerge as key challenges. We provide recommendations to address these issues and identify future research areas which should be prioritized to support climate change mitigation and agricultural system resilience through agroforestry expansion.

1. Introduction

In Europe, the intentional planting of trees to enhance food security and animal and crop production can be traced back to the Copper Age (2500 BCE) (Fig. 1). In contrast, the separation of forestry and agriculture into discrete activities is a relatively recent phenomenon dating to post-WWII (Eichhorn et al., 2006). Since the 1960s, there has been an acceleration in tree removals from agricultural landscapes to accommodate modern agricultural land management practices. Understanding the extent and nature of currently remaining tree cover constitutes a great scientific and regulatory challenge.

Over the last decade, political and societal interest in the potential of tree-based "solutions" for more sustainable and climate-friendly land-use pathways has increased rapidly. This has contributed to greater research efforts to quantify the current global tree-cover extent (e.g., Zomer et al., 2016). In particular, agroforestry, defined broadly as a land-use practice which combines the integration of livestock or crop production with perennials (e.g., Cardinael et al., 2021), is getting increasing attention.

Indeed, the potential of agroforestry for carbon sequestration and a broad range of other ecosystem benefits is increasingly recognized (e.g., Cardinael et al., 2021; Torralba et al., 2016). The specific effects of temperate agroforestry systems (AFS) on long-term soil carbon sequestration are often system-dependent (e.g., Burgess and Rosati, 2018). Nevertheless, a recent review of relevant literature suggests that temperate AFS can contribute to substantial increases in soil organic carbon (SOC) sequestration (Mayer et al., 2022). Similarly, a recent pan-European assessment identifies "priority areas" in which the implementation of specific agroforestry practices is expected to reduce environmental pressures and significantly increase carbon sequestration (Kay et al., 2019).

At present, the implementation or scaling up of agroforestry practices at local, regional, and national scales is limited, in great part due to a lack of clear definitions and methods. For instance, certain practices considered as agroforestry in one region of the European Union (EU) are considered as "standard" agriculture in other EU regions (Burgess and Rosati, 2018). Additionally, current data availability about temperate agroforestry systems is limited by a low number of studies and a heavy

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https://doi.org/10.1016/j.crsust.2022.100134
Received 15 December 2021; Received in revised form 21 February 2022; Accepted 24 February 2022
Available online 5 March 2022

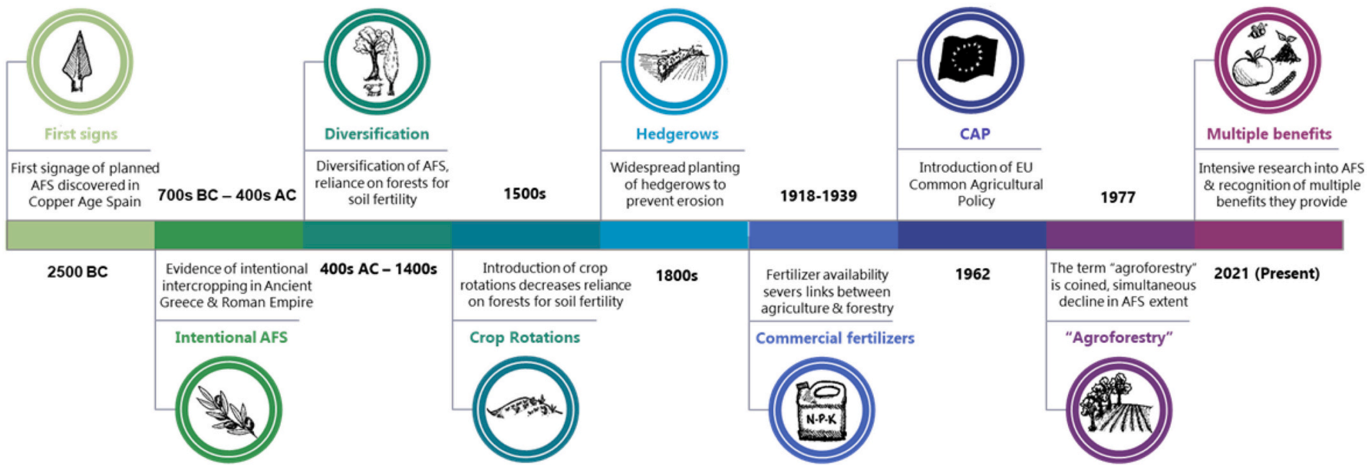

Fig. 1. A simplified timeline of agroforestry development in Europe (based on Eichhorn et al., 2006). The first signs of agroforestry systems (AFS) and intentional intercropping can be traced as far back as 2500 BCE. For centuries, people depended on trees for production of food and fodder, animal forage and timber. Nutrient flows from woodlands onto agricultural fields contributed to the maintenance of soil fertility and consequently agricultural productivity. As technology improved, these nutrient- and energy-cycling relationships between farming and forestry deteriorated. In the mid-20th century, trees began to disappear from European landscapes, replaced by large scale annual monocropping systems. The introduction of the EU's Common Agricultural Policy (CAP) reinforced this trend, as existing CAP measures do not offer adequate incentives for agroforestry conservation or expansion. Nevertheless, recent recognition of the contribution of agriculture to the climate emergency and biodiversity crisis has highlighted agroforestry as an attractive opportunity to diversify and enhance farming operations.

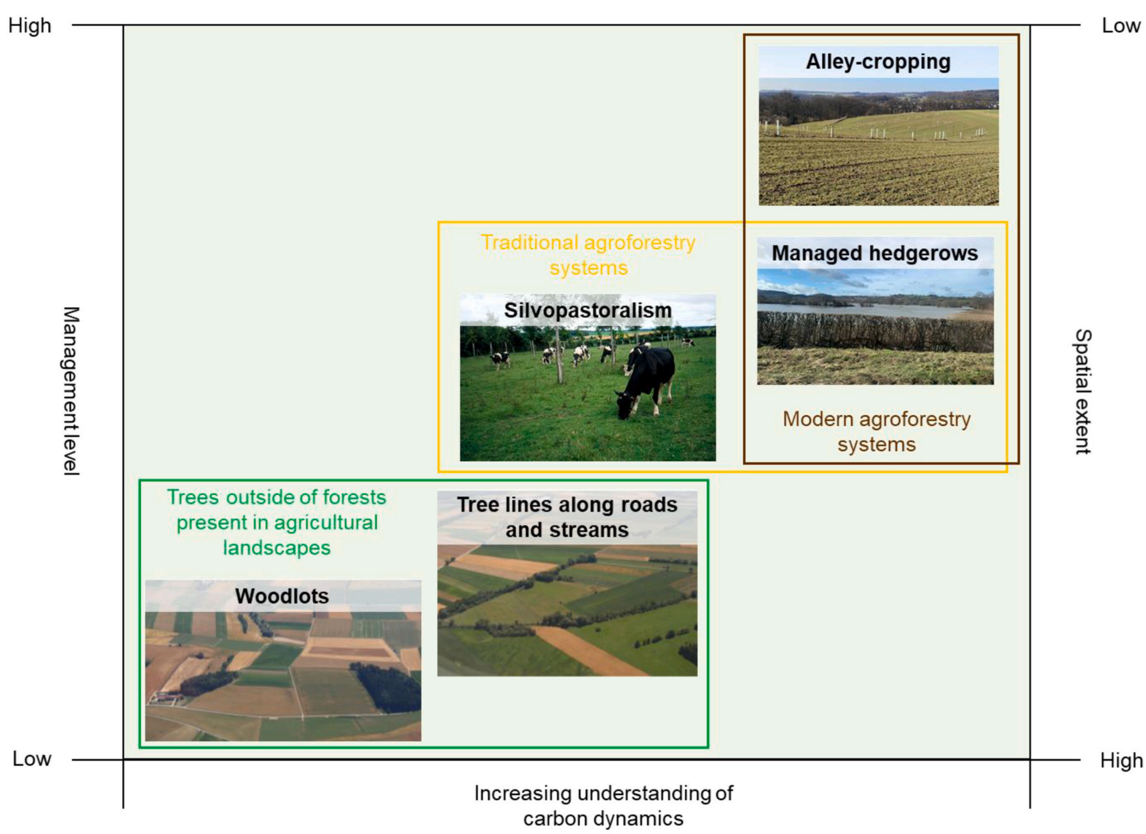

Fig. 2. A simplified representation of interspersed woody components present in European agricultural landscapes relative to their extent, management level and understanding of carbon dynamics. These can constitute 'trees outside of forests' (TOF), located e.g. in groves or along roads, traditional AFS e.g., silvopastoral systems and hedgerows, and modern AFS e.g., alley-cropping and hedgerows managed through coppicing for biomass production. Carbon dynamics in TOF remain largely understudied (Golicz et al., 2021). The carbon storage and sequestration potential of traditional agroforestry systems is better studied; however, these systems are threatened with destruction or abandonment due to low profitability (Eichhorn et al., 2006). Investigations of modern AFS are ongoing and increase our understanding of carbon fluxes in tree-crop systems; nevertheless, multiple spatial and temporal challenges in study design exist, limiting our progress (Cardinael et al., 2018).

focus on alley-cropping and hedgerow systems, despite the existence of many more AFS types (Mayer et al., 2022). Obtaining accurate measurements of carbon sequestration (especially SOC) in field-studies is further constrained by a lack of standardized field and laboratory methods (Mayer et al., 2022).

Here, we review key research gaps and data needs that could facilitate improved agroforestry carbon accounting in temperate regions, with a focus on Europe. We then identify future research priorities to support climate change mitigation and agricultural system resilience through AF expansion.

2. The challenges of accounting for trees in European agricultural landscapes

2.1. Challenge 1: lack of a well-defined classification system that accounts for trees found within "intentional" and "non-intentional" AFS

Most European countries have historically developed some form of "intentional" AFS, which can be silvoarable (crop based) or silvopastoral (animal based) AFS (Eichhorn et al., 2006). Some of the best-known examples are traditional agricultural systems: British hedgerows managed through laying and trimming, German 'Knicks' (shelterbelts) and 'Streuobstwiesen' (grazed or intercropped orchards), or 'dehesas' and 'montados' (oak-dominated grazed woodlands) found across the Iberian Peninsula (Eichhorn et al., 2006). Intentional AFS also include more modern systems (e.g., alley-cropping) developed to facilitate mechanized crop harvest through low tree-planting densities and widely spaced rows, whilst simultaneously providing additional income streams (e.g. from fruit, nuts, or timber) (Kay et al., 2019). In addition, European agricultural landscapes include what the Food and Agriculture Organization (FAO) defines as 'trees outside forest' (TOF), here referred to as "non-intentional" AFS (Rosenstock et al., 2019). This classification refers to trees integrated into farms and rural landscapes; it includes landscape elements such as hedgerows, tree groves, forest patches and other perennial wooden vegetation found outside of forests. TOFs currently do not conform to standard European definitions of AFS as they are not actively managed (for a more detailed discussion on the topic of AFS classification, see McAdam et al., 2008). The lack of clear distinction between intentional AFS and non-intentional TOF systems has resulted in the latter being understudied, including in terms of area distribution or carbon dynamics (Fig. 2). Nevertheless, as TOFs have measurable impacts on adjacent cropland and pastureland (Pardon et al., 2017), more formalized recognition of their roles as agricultural features could inform more accurate and holistic landscape-management approaches.

2.2. Challenge 2: lack of suitable tools to map trees on farms

There have been several recent research efforts focused on developing AFS distribution maps at different spatial scales. For instance, the Horizon2020 funded AGFORWARD project led to the development of the first satellite-based, pan-regional maps depicting the actual extent of agroforestry at landscape-scales in the EU (den Herder et al., 2017). Final maps indicate that agroforestry systems cover about 3.6% of total EU territory and 8.8% of its agricultural area, with particularly high concentrations in Mediterranean countries. At a national scale, Golicz et al. (2021) (Golicz et al., 2021) estimated the extent of small woody landscape features at 4.6% of agricultural land in Germany, confirming their importance and potential for expansion. However, at present, there are no EU-wide land surveys focusing solely on the delineation of AFS area. Remote sensing technologies which have been employed for this purpose in the past tend to underestimate AFS cover: for instance, *CORINE Land Cover* datasets recognize 'agroforestry' only in the Mediterranean region (den Herder et al., 2017) and *small woody landscape features* datasets ignore systems with scattered, low-density tree cover (Golicz et al., 2021). Dynamic mapping approaches that contextualize the landscape effects of agroforestry across different spatial and temporal scales and management regimes are yet to be developed. We highlight the urgent need to develop AFS-specific datasets that will reliably estimate their land-area whilst taking into account their inherent variability.

2.3. Challenge 3: standardization of soil organic carbon accounting

SOC is the largest terrestrial carbon pool and consequently plays a prominent role in European AFS research (Cardinael et al., 2021). However, SOC assessments suffer from methodological shortcomings such as: lacking uniformity in soil sampling depths and baseline definitions; lack of bulk density inclusion in SOC concentration reports that prevent carbon stock estimations; or pseudo replication. These issues were first identified by (Nair, 2012) and subsequently echoed by Cardinael et al. (2018) (Cardinael et al., 2018) and Mayer et al. (2022) (Mayer et al., 2022) whose recent meta-analyses discarded multiple studies due to methodological inconsistencies. Policy-makers and farm practitioners depend on collated scientific findings to better understand soil carbon dynamics in different AFS (e.g., lower carbon gains in silvopastoral vs. silvoarable AFS Fornara et al., 2018) and to refine estimates relating to land use change (such as agroforestry coefficients proposed by the Intergovernmental Panel on Climate Change, see-Cardinael et al., 2018). Improving standardization in AFS research therefore needs to become a priority in the scientific community. This could be achieved, for instance, through development of a set of (EU-wide) guidelines based on the existing sampling protocol formulated by (Cardinael et al., 2017), which is sufficiently flexible to account for high variability of agroforestry systems in terms of size, species composition and planting design/structure. Guidelines could include sampling depth recommendations and minimum data requirement for soil characteristics such as bulk density and soil texture; they could be applied to screen studies for future meta-analyses used to inform national and international policies.

2.4. Challenge 4: estimation of aboveground (ABG) and belowground (BLG) biomass

For carbon accounting, trees serve as SOC sequestration "tools"; the significance of tree biomass carbon, considered transient due to limited tree lifecycles (Cardinael et al., 2017), is often overlooked. Consequently, relatively few region-specific allometric equations are being developed for tree species typical of AFS (e.g., *Prunus avium* L., Morhart et al., 2016), limiting the precision of tree biomass and biomass carbon estimates. This is compounded by scattered information availability and lack of a centralized EU-wide inventory collating existing allometric equations and root to shoot ratios. Technological advances such as ground penetrating radars for belowground assessment, successfully employed in North America (Borden et al., 2014), are yet to be applied in Europe. However, as AFS are being increasingly recognized for their indirect effect on stabilizing carbon pools across landscapes (e.g., evidence of silvopastures contributing to wildfire risk reduction in Southern Europe, seeDamianidis et al., 2021), assessments of tree contributions to AFS carbon budgets merit higher prioritization on research agendas.

2.5. Challenge 5: limited integration of tools and data for AFS carbon accounting

Plot level investigations of AFS carbon dynamics allow for the collection of data that is essential for the development of models such as Yield-Safe, APSIM and EPIC (reviewed in Kraft et al., 2021) to extrapolate carbon sequestration and storage in plant biomass and soils. We expect that increasing the accuracy of carbon accounting tools will lead to increased recognition of the potential of AFS for offsetting agricultural GHG emissions (e.g., from cattle production, fertilizer application

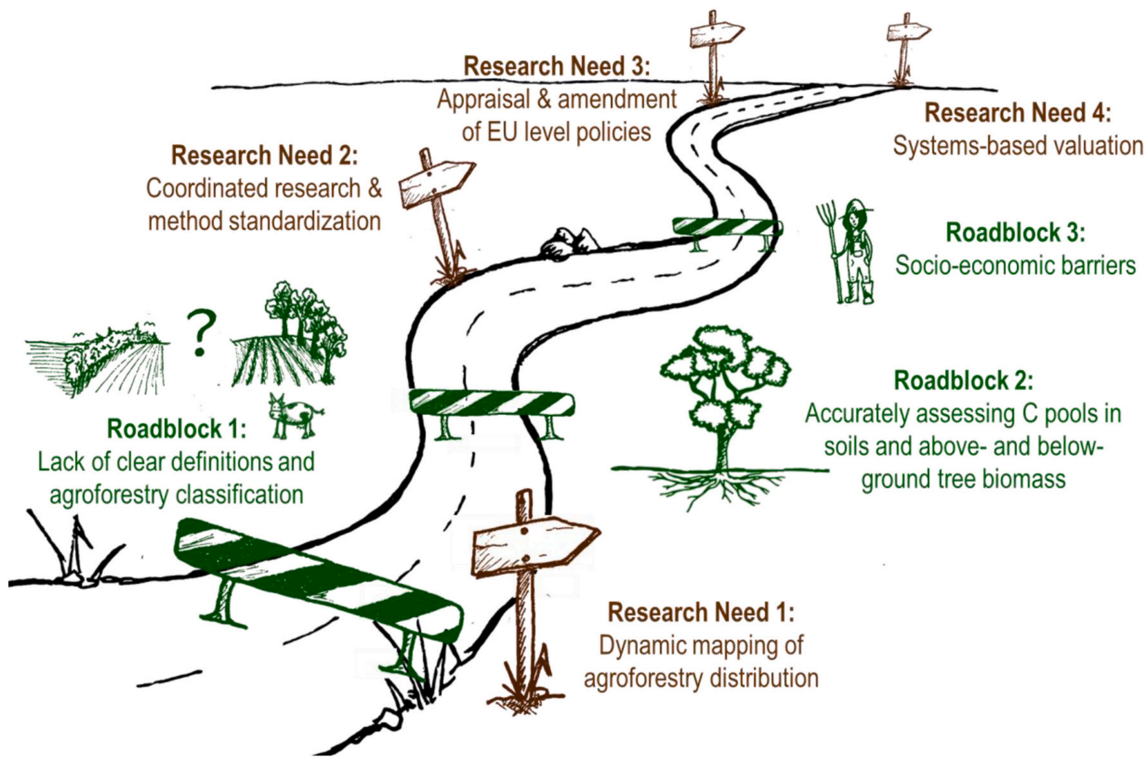

Fig. 3. Visual summarization of the major roadblocks (in green) towards improved carbon accounting and agroforestry implementation in the EU, as well as research needs (in brown) identified in this review. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or soil tillage). Many countries, especially across Latin America and Africa, already recognize that AFS may contribute to national carbon budgets as carbon sinks (Rosenstock et al., 2019). Nevertheless, inclusion of AFS in carbon credit mechanisms may lead to a reduction of farm-level emissions. For example, carbon credits gained through tree planting could offset emission-intensive activities that may require long-term phasing out (e.g., inorganic fertilizer application), thus facilitating sustainability transitions for individual farmers and contributing to farm-scale carbon neutrality.

However, more must be done to integrate available tools and data collected across AFS systems. Future mainstreaming of carbon credits for maintaining and implementing AFS, would require both farmer buy-in and improved monitoring and evaluation infrastructure. This could for instance be facilitated through the development of farmer-oriented decision support systems, as suggested by DeFAF (https://agroforst-info.de/praktische-werkzeuge/). Such tools could allow for farm- or parcel-specific assessments of (i) projected carbon gains from new AFS implementation; or (ii) carbon storage of extant agroforestry systems, helping to map AFS in the process. The former could be achieved by selecting land area, recommended tree species (to prioritize e.g., biomass or fruit production), soil type and management practices, and by then applying regional coefficients similar to agroforestry coefficients proposed by the IPCC (Cardinael et al., 2018). The latter could be achieved by processing georeferenced photos of extant AFS through Google Earth for size assessments and applying machine learning (e.g., Sothe et al., 2022) to estimate carbon storage based on similar systems.

3. Social and regulatory barriers to adoption and maintenance of AFS

Coherent monitoring and evaluation approaches and policy tools relevant for agroforestry are currently lacking at national, EU and global scales (Cardinael et al., 2021; Rosenstock et al., 2019). For instance, several studies have examined shortcomings of current CAP policies regarding agroforestry. (Kay et al., 2019) point out that current measures support either sustainable cropland or grassland productivity while limiting tree density (pillar I), or rural development and forestry (pillar 2), with limited integration between the two. This exemplifies the current lack of centralized policy making designed to support agroforestry (Eichhorn et al., 2006). Across the EU, practitioners are thus left to interpret the relevance of 27 different funding (Zomer et al., 2016; Cardinael et al., 2021) measures on their farms, which ultimately constitutes a significant barrier towards greater farmer adoption of AFS practices (e.g., Burgess and Rosati, 2018). This could be addressed through streamlined and more clearly formulated policy tools incentivizing AFS adoption at EU and national levels.

Still, increased encouragement to maintain traditional AFS (Eichhorn et al., 2006), and likely subsidization of new AFS creation through the European Green Deal, suggest a shift regarding recognition of AFS' importance. To date, no steps have been taken to enable implementation; one potential approach to facilitate this could be the introduction of targeted financial incentives (e.g., as part of CAP) that reward “carbon farming” practices like tree planting and maintenance. The establishment of a pan-European network of lighthouse examples, in combination with practice-oriented educational programmes showcasing innovative AFS practices, may further support AFS uptake among farmers.

In addition, a singular focus on the carbon sequestration potential of AFS fails to account for other benefits provided through the inclusion of trees in agricultural land-use – including wildfire mitigation, microclimate regulation, erosion reduction, biodiversity enhancement, or income diversification (e.g., Damianidis et al., 2021; Plieninger et al., 2021; Moreno et al., 2018; Giannitsopoulos et al., 2020). Despite findings that EU farmers recognize multiple benefits attributed to AFS, the quality and extent of AFS has declined across Europe (Elbakidze et al., 2021). (Elbakidze et al., 2021) identify a potential disconnect between the value systems applied to AFS by farmers versus policy makers, which may constitute an important barrier to further adoption. Improved valuation of the multiple benefits of agroforestry systems through locally relevant indicators may bolster their economic viability and increase adoption rates (e.g., Giannitsopoulos et al., 2020; Elbakidze et al., 2021). More broadly, landscape- and system-based policies, which recognize and account for the wide diversity and multi-functionality of AFS, are urgently needed.

4. Conclusions

Sustaining traditional AFS and farmland TOFs while also expanding modern practices could greatly improve the carbon budget of European agriculture. However, utilizing the potential of trees to sequester carbon in soils and biomass, and thus to mitigate GHG emissions, will require a number of broad actions (Fig. 3). The collection of low and high-resolution data documenting the extent of tree cover on agricultural land must become a priority. Investigating regional differences and identifying relevant AFS characteristics (e.g., farmer acceptance levels, carbon sequestration potential, etc.), could further help inform the design or implementation of future AFS expansion initiatives. Standardizing research protocols and improving data access, for instance through public database development, is essential. Similarly, integration of existing data is crucial, ideally by providing farmers with tools that can optimize agroforestry uptake across the EU with appropriate regulatory support.

Credit author statement

We note that KG and AW contributed equally to this manuscript. KG and AW conceived and wrote the manuscript and created the figures. KG, AW, SBK & LB provided edits on previous versions of the draft, and revised the manuscript and figures for final submission.

Declaration of Competing Interest

Authors do not have any conflict of interest.

Acknowledgements

KG and LB would like to acknowledge funding of the “Agroforstprojekt Gladbacherhof” (VII 5 – 80e04-09-04) through the Hessische Ministerium für Umwelt, Klimaschutz, Landwirtschaft und Verbraucherschutz as part of the Hessische Ökoaktionsplan 2020-2025. AW & SBK would like to acknowledge support from the Digital Agriculture Knowledge and Information System (DAKIS) Project (031B0729A), financed by the German Federal Ministry of Education and Research (BMBF). We thank Raymond Sauvaire for providing us with the photograph illustrating silvopastures included in Figure 2. We further thank our anonymous reviewers for their constructive comments, which led to a much improved version of our manuscript.

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