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RESEARCH ARTICLE

Towards evidence-based biodiversity assessment tools for agroforestry systems

Jari Vandendriessche[1] | Maxime Eeraerts[1] | Pieter De Frenne[1] | Paul J. Burgess[2] | Laura Cumplido-Marìn[2] | Sonja Kay[3] | Margherita Tranchina[4,5] | Paul Pardon[6] | Kris Verheyen[1]

[1]Department of Environment, Forest & Nature Lab, Ghent University, Melle-Gontrode, Oost-Vlaanderen, Belgium; [2]School of Water, Energy and Environment, Cranfield University, Bedford-Cranfield, Central Bedfordshire, UK; [3]Agricultural Landscapes and Biodiversity, Agroscope, Zürich, Switzerland; [4]Scuola Superiore Sant'Anna, Pisa, Toscana, Italy; [5]Scuola Universitaria Superiore Pavia, Pavia, Lombardia, Italy and [6]Flanders Research Institute for Agriculture, Fisheries and Food, Merelbeke, Oost-Vlaanderen, Belgium

Correspondence
Jari Vandendriessche
Email: jari.vandendriessche@ugent.be

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Abstract

1. Agroforestry can help to conserve biodiversity and enhance multiple ecosystem services such as carbon sequestration, microclimate regulation and nutrient cycling. However, in land planning and biodiversity certification schemes it remains difficult to quantify the effect of agroforestry on biodiversity across time and space.
2. Here we combine insights from a second-order meta-analysis, a stakeholder questionnaire, and a review of biodiversity assessment tools to establish a route towards more accurate estimates of agroforestry effects on biodiversity. Via a synthesis of cross-taxa meta-analyses, we evaluated the impact of agroforestry and landscape structure on biodiversity. Complementing the literature evidence, we performed a stakeholder questionnaire to determine the perceptions and preferences of stakeholders with regards to biodiversity.
3. The meta-analyses synthesis indicates predominantly positive or no effects of agroforestry practices on biodiversity, albeit with contextual nuances such as landscape structure and system design. The questionnaire revealed stakeholders' recognition of biodiversity's pivotal role in agroecosystems and a willingness to support methods to assess the effects of agroforestry on biodiversity. There was a preference for user-friendly, web-based tools that integrated mapping features and checklists tailored to diverse agroforestry types. Finally, we evaluated 73 existing biodiversity tools in terms of their capability of incorporating agroforestry components. The tools' review revealed limitations in terms of their specificity, accessibility or capacity to encompass multifaceted agroforestry designs.
4. *Practical implication.* Our three-faceted approach provided comprehensive insights about the building blocks required to develop an evidence-based and

user-friendly tool for predicting the effects of agroforestry on biodiversity. Specifically, our interdisciplinary synthesis underscores the potential of agroforestry in promoting biodiversity while emphasizing the need for an evidence-based, user-centric tool to effectively assess biodiversity within agroforestry systems, accounting for landscape context and system design. Such a tool should be constructed with input data for different agroforestry types, across taxa and updateable when knowledge gaps are filled.

KEYWORDS

agri-environmental measures, biodiversity conservation, decision aid system, ecosystems services, land use, questionnaire, stakeholder perception, sustainable agriculture

1 | INTRODUCTION

Biodiversity is vital for well-functioning ecosystems, in part because of its role in supporting ecosystem services such as pest control, pollination and nutrient cycling (Dainese et al., 2019; Lindemann-Matthies et al., 2010; Millennium Ecosystem Assessment, 2005). Despite its importance, biodiversity is globally under threat (Butchart et al., 2010; Sachs et al., 2009). The problem is increasingly recognized by policymakers (European Commission, 2011) who are taking measures to preserve and restore biodiversity. In Europe, this is now embodied by, among others, the Green Deal and the Biodiversity Strategy to 2030 (European Commission & Directorate-General for Environment, 2021).

During recent decades, the expansion and intensification of agriculture have been key drivers of biodiversity decline, mainly through driving the loss of natural and semi-natural habitats and small landscape elements (Balmford et al., 2012; Tilman et al., 2001; Tscharntke et al., 2012). In many European areas, agricultural landscapes generally consist of a matrix embedding fragmented patches of remnant natural vegetation, often referred to as semi-natural habitats, where non-domesticated biodiversity persists (Goulson, 2021). Maintaining and increasing these semi-natural habitats is critical to halt biodiversity loss in agricultural landscapes (Eeraerts, 2023; Estrada-Carmona et al., 2022; Perfecto & Vandermeer, 2010).

One way of increasing biodiversity in intensive croplands and grasslands is to introduce trees and shrubs (Leakey, 1996). These woody elements may co-produce, for instance, nuts, fruit, cork or wood. Examples of such agroforestry practices include silvoarable (i.e. tree-crop associations) and silvopastoral systems (i.e. tree-livestock associations) and more specifically alley cropping, hedgerows and windbreaks, food forests, forest grazing (FG) practices, scattered solitary trees, etc. (Dmuchowski et al., 2024; Mosquera-Losada et al., 2009). Agroforestry can increase biodiversity-mediated ecosystem services (Udawatta et al., 2019) by providing habitat, food, shelter and the provision of more diverse resources to multiple species (Jose, 2009; McAdam et al., 2009) and might enrich the structure of a landscape. However, Staton et al. (2019) argued that, especially in temperate regions, both the practical knowledge and scientific understanding of the effects of agroforestry on biodiversity are still limited. Published studies on the effects of agroforestry on biodiversity in comparison to monoculture croplands and intensively managed grasslands represent mixed results (Imbert et al., 2020; Pardon et al., 2019; Plieninger et al., 2015; Varah et al., 2020). The net effect of agroforestry on biodiversity is likely to be dependent on the focal crop, the age of the system, the tree species, their management and the surrounding landscape (Kletty et al., 2023). Structurally complex landscapes are reported to have generally high levels of biodiversity as they offer a variety of habitats by forming a complex patchwork of semi-natural habitats (Concepción et al., 2008; Eeraerts, 2023; Tscharntke et al., 2012). Both conceptual and empirical research demonstrate a mediating effect of landscape structure on the net biodiversity effect of agro-ecological measures (Lichtenberg et al., 2017; Scheper et al., 2013; Sirami et al., 2019). It is of expectance that this mediating effect of landscape structure on biodiversity is also present in agroforestry systems.

Given the current biodiversity crisis, it is important to properly account for possible biodiversity gains that could be attained by agroforestry. Additionally, biodiversity is a complex, multi-taxa concept dependent on spatial and temporal scales, which makes it difficult to score it properly. As a result, farmers interested in biodiversity are uncertain about their options to enhance biodiversity (Birrer et al., 2014; Dwyer et al., 2023).

At present, we are unaware of a specific policy or management supporting tool available to assess the biodiversity benefits of agroforestry in Europe. Such a tool might (1) enable farmers to assess and understand the biodiversity on their farms and (2) provide a clear interpretable metric that can be used to report downstream along the value chain. This might enable the appropriate labeling of agroforestry products (e.g. for certification schemes), which is important to both farmers and value chain actors, including the end consumer. Hence, we aim to identify the key building blocks of an evidence-based and user-friendly tool that predicts the biodiversity benefits of agroforestry implementation in agro-ecosystems. To achieve this, we implemented a multifaceted approach to enable us to gain comprehensive insights about the required building blocks.

2 | MATERIALS AND METHODS

Our approach was three-faceted. Firstly, we compiled scientific evidence, based on published meta-analyses, about agroforestry systems in the broad sense and their effect on multi-taxa biodiversity in agroecosystems. As ample evidence of landscape structure influencing biodiversity effects generated by agro-ecological measures (Batáry et al., 2011) is present, our search also included meta-analyses on landscape structure in agroecosystems. Additionally, implementation of agroforestry implicates the landscape context, as structural elements are implemented. Thus, some landscape metrics could be used as a proxy for agroforestry implementation (applied on a bigger scale). The collected data will serve as the scientific proof for biodiversity effects provoked by either agroforestry or landscape structure (i.e. landscape complexity, configuration and composition). Secondly, a questionnaire was distributed to different stakeholders in the agroforestry value chain within Europe to explore the qualitative and quantitative requirements and preferences concerning a biodiversity tool for agroforestry systems. This aspect can serve as a wish list potential users have for a biodiversity-targeted agroforestry tool. Thirdly, we compiled a database of available biodiversity tools that are used to predict biodiversity in agroecosystems. With this third aspect, we evaluated the collected tools upon the criteria established by the meta-analyses and questionnaire.

2.1 | Meta-analyses: Literature search and processing

Existing meta-analyses are valuable in this sense as they provide a quantitative summary of published scientific research on a specific topic. In the meta-analyses, the estimated effects of case studies are converted to comparable effect sizes, which can be contrasted and used to summarize the effects across a large range of contexts, taxa and scales. Over time, the number of meta-analyses has increased, even within one particular topic; thus, several efforts have already led to the combining of multiple meta-analyses into comprehensive articles focusing on agricultural practices (Beillouin et al., 2019; Bonfanti et al., 2023; Dmuchowski et al., 2024; Makowski et al., 2021).

We performed a systematic literature search to identify suitable meta-analyses for our objectives. Our search was performed on 29 February 2024, using the following search terms:

(biodiversity OR agrobiodiversity OR arthropods OR contributions) AND (agriculture OR agroecosystem OR agroecosystems OR farmland OR silvopastoral OR landscape OR forest) AND (agroforestry OR silvopasture OR hedgerows OR hedges OR "scattered trees" OR woody OR "forest grazing" OR "livestock disturbances" OR "food forest" OR "landscape complexity" OR "landscape structure") AND (meta-analysis OR "meta analysis" OR meta-analyses OR "meta analyses" OR "systematic review" OR "meta-synthesis").

We opted for a single query designed with four compartments to screen the literature we wanted, implying the following: (i) a filter on biodiversity as a topic, (ii) a filter on the ecosystems a study should be carried out in, (iii) a filter on the specific cases (i.e. agroforestry and landscape structure) and (iv) the study being a meta-analysis.

Inserting this query in ISI Web of Science Core Collection and in Scopus resulted in 217 and 128 articles, respectively, of which 244 unique records. Title and abstracts were screened to see if they were relevant to this study's key objectives: (1) the study quantitatively synthesized existing literature (i.e. a meta-analysis), (2) the study includes either agroforestry elements or landscape structure effects (i.e. landscape complexity, landscape configuration and landscape composition) and (3) the study used one or more biodiversity metrics as response variables. Studies focusing on genetic biodiversity were excluded (e.g. intra-specific genetics or genetic biodiversity). This approach resulted in 53 suitable meta-analyses.

Hereafter we assessed the full texts and excluded meta-analyses (1) in which less than 50% of the underlying studies were performed in ecosystems relevant to the European scope (i.e. temperate, boreal and Mediterranean), (2) did not compile data for agroforestry elements or landscape structure meta-analytically (e.g. narrative reviews), (3) used non-agroecosystem comparators (e.g. forests) or (4) fell beyond our particular scope of agroforestry systems or landscape contexts (e.g. interaction effects of agri-environmental measures like organic farming or implementing wildflower strips across landscape gradients, effects of mowing). More information about these decisions is available in Text S1, along with the PRISMA diagram of our approach. This resulted in a final set of 12 meta-analyses. We also identified seven meta-analyses assessing interaction effects between landscape structure and agri-environmental measures (e.g. flower belts, hedgerows, grass strips, crop diversification). Not one identified meta-analysis specified an interaction between landscape structure and agroforestry implementation; thus, the available evidence represents the closest link possible.

From the studies that were identified as suitable meta-analyses for our study, we extracted the overall effect sizes as determined by each meta-analysis. Effect sizes of interest were the effect of either agroforestry or landscape structure on biodiversity (i.e. richness, abundance). When extracting the effect sizes, the highest level of detail was retained regarding biodiversity functional groups (i.e. overall biodiversity, plants, soil fauna and microbiota, pollinators, natural enemies and pest species), types of agroforestry (e.g. agroforestry in the broad sense, silvoarable, silvopastoral, hedgerows, scattered trees) and landscape characteristics (i.e. composition,[1] configuration[2] and complexity[3]). The degree of replicates and standard error per overall effect size was extracted to calculate comparable study-level effect sizes. Details are given in Text S1. We represented these values qualitatively with individual effect sizes.

[1]That is, the ratio of different building blocks in a landscape (e.g. reduction of intensive agriculture, higher percentages of seminatural habitat).

[2]That is, the spatial arrangement of landscape building blocks (e.g. smaller plot area, better connectivity of seminatural habitats).

[3]Encompassing a variety of landscape structure factors (including compositional and configurational factors).

Next, we carried out a second-order meta-analysis for the agroforestry part as our main interest. Most of the considered studies used either log-response ratio effect sizes (agroforestry meta-analyses) or Fisher's Z effect sizes (landscape structure meta-analyses). Therefore, we recalculated all other effect sizes to these, if possible (a detailed approach is available in Text S1). We calculated the mean response ratio across all studies according to Hedges et al. (1999):

$$\text{Pooled effect size: } \theta^* = \frac{\sum_{i=1}^{k} w_i^* \theta_i}{\sum_{i=1}^{k} w_i^*}$$

All related formulas are available in Text S1, k represents the number of studies and w_i^* and θ_i represent respectively the random-effects weights and the effect size for study i. We visualized pooled effect sizes along with corresponding 95% confidence intervals.

2.2 | Questionnaire design and collection

Second, we undertook a questionnaire in which we sought to disentangle the stakeholders' needs and wishes for a biodiversity tool designed to aid biodiversity estimation in European agroforestry systems. We specifically targeted four actors' groups: (1) Policymakers and administrations concerned with applying agroforestry-related regulations at regional, national and European levels, who set the scene for the adoption (or not) of agroforestry; (2) farmers, landowners and by extension, farm advisers (who were categorized separately) playing an active role in designing and managing agroforestry and whose choices determine the agronomic, economic, environmental and social performance at farm level and beyond; (3) stakeholders in the value chain including wholesalers, retailers, organizations trading the carbon sequestration and biodiversity benefits of agroforestry, and final consumers seeking verification of the benefits of agroforestry in clear and accessible terms; and (4) researchers who help to assess the performance of agroecosystems and communicate their results. The questionnaire was distributed within seven stakeholder groups linked to the DigitAF project (https://digitaf.eu/). These were situated in Finland, Czechia, the Netherlands, Germany, the United Kingdom, Italy and Belgium (Tranchina et al., 2024). The biodiversity-related questionnaire consisted of four segments, encompassing questions upon (1) the importance of biodiversity and its assessment, (2) the required specifications and relevance of an agroforestry-based biodiversity tool, (3) the design of such a tool and (4) interests concerning its validation (see Text S2 for the full questionnaire). Summary results of the questionnaire are presented.

The questionnaire was completed by 82 stakeholders across the seven regions between April and September 2023. Respondent characteristics and respondents' opinions on the inclusion of agroforestry types can be retrieved in Figures S1 and S2.

2.3 | Biodiversity tools: Search and processing

We performed a broad search of biodiversity tools between November 2022 and December 2023 to build a comprehensive database of tools used to assess biodiversity in agroecosystems. A detailed description of this process, an overview table and the corresponding PRISMA diagram are available in Text S3. From this database, totaling 73 tools, we selected 37 tools that are able to assess biodiversity in agroforestry systems (process also described in Text S3). For the 37 selected tools, we categorized the input–output relations in different categories, distinguishing between the input variables required by the tools and the outputs they provide. As such, there are tools using habitat characterization (structure quality), biotic indicators (sampling of species group) or both as inputs. Additionally, we highlighted the typology concerning different agroforestry structures incorporated in the tools, referring to their applicability in specific agroforestry types. Furthermore, the tools were evaluated on their open source availability. Text S3 provides any additionally required clarifications.

We also established a point of view (POV) of the stakeholders to compare the tools efficiently, which we assessed by means of the questionnaire outputs, assigning to each category the percentage of stakeholders valuing that particular category. To best display this dataset on tool-type, scale, applicability, input and output, we performed Nonmetric Multidimensional Scaling (NMDS) using the function metaMDS with Bray–Curtis distance in the package vegan (Oksanen et al., 2022). We explored and plotted both the tools space (sites of metaMDS-output) and the underlying variables (species of metaMDS-output). All packages and programs used for data handling are available in Text S4.

3 | RESULTS

3.1 | Meta-analyses

We identified six meta-analyses (totaling 19 effect sizes; 3 of these were not convertible to log-response ratios) that assessed the effects of agroforestry on biodiversity in agroecosystems, relevant to a European context (Figure 1a). Only a limited number of agroforestry features were assessed through meta-analyses for different taxa. We retrieved studies wherein agroforestry was presented as agroforestry in general, silvoarable, silvopastoral, hedgerows and scattered trees were represented. However, the low number of meta-analyses and the highly variable nature of agroforestry lead to highly variable results in the quantitative second-order recalculation techniques. As such, we obtained insignificant results for agroforestry in the broad sense (overall: 0.30 ± 0.54, plants: 0.83 ± 0.91, natural enemies: 0.22 ± 0.55, pest species: -0.33 ± 0.67). On the other hand, panels consisting of only one study tended to have smaller confidence intervals (e.g. silvoarable + natural enemies: 0.22 ± 0.17, hedgerows + overall: 0.41 ± 0.05). Therefore, we additionally visualized the effects qualitatively per study (Figure 1b).

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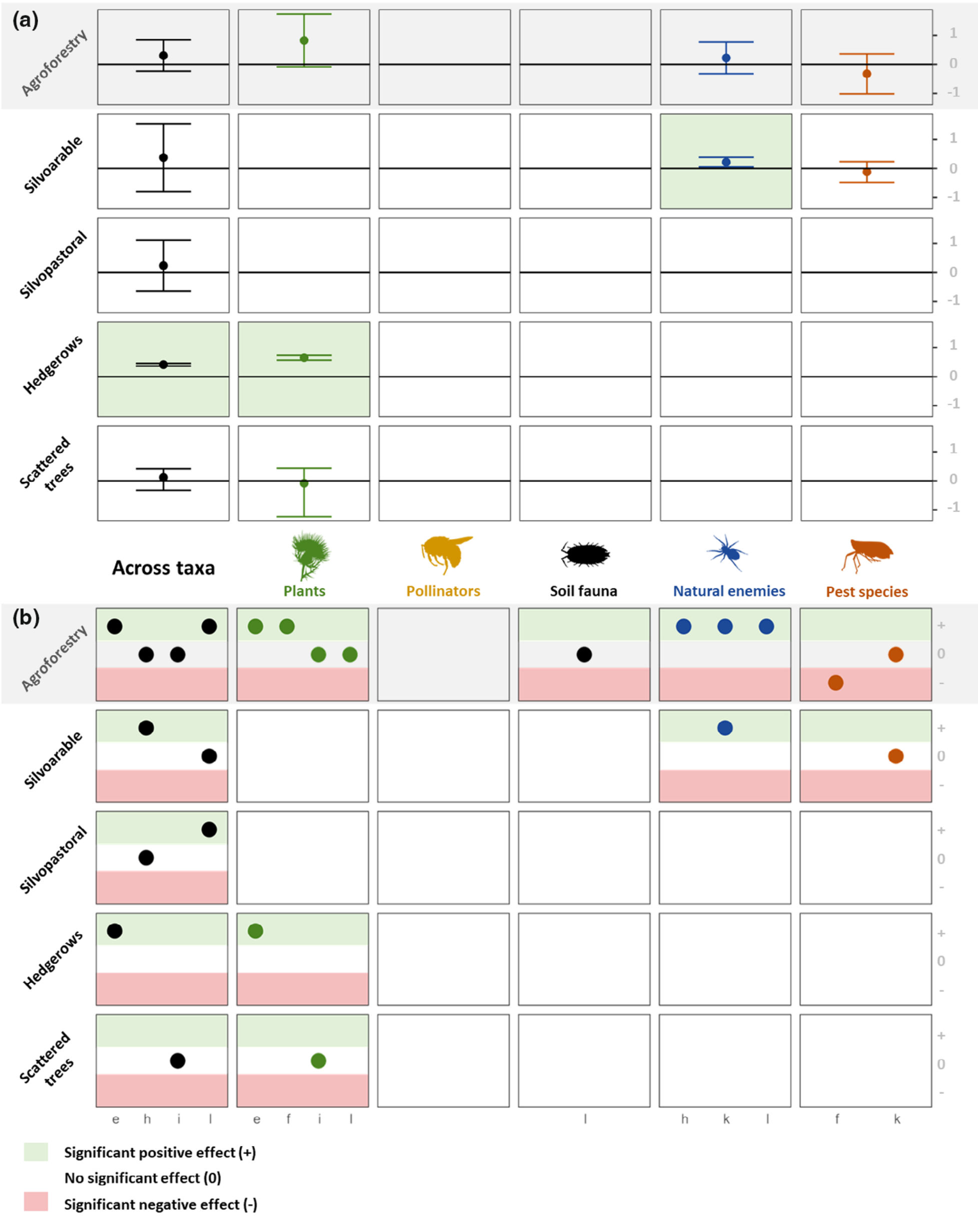

FIGURE 1 Effects of different agroforestry types on biodiversity levels of different taxonomic groups. (a) The second-order effect sizes (log-response ratios) with 95% confidence intervals as calculated with 16 effect sizes (3 effect sizes represented by hedge's *g* values were deleted in this analysis, see Section 2). (b) 19 effect sizes concerning agroforestry type and functional group as reported or recalculated from subindices in the meta-analyses, representing positive, negative or non-significant results. The underlying effect sizes are based on abundance, diversity and richness metrics and are compared to their baselines (agroecosystems without agroforestry). The grey shaded row represents a summary view on agroforestry in general. The colours of the dots and silhouettes appoint a taxa's functionality in agricultural context: Green, plants; black, soil fauna and microbiota; orange, pollinators; blue, natural enemies and red, pest species. e, García de León et al. (2021); f, Koellner and Scholz (2008); h, Mupepele et al. (2021); i, Prevedello et al. (2018); k, Staton et al. (2019); l, Torralba et al. (2016). Taxa symbols were retrieved from phylopic.org.

Qualitative results overall supported the premise of mostly positive or neutral effects: only one effect size reported negative results on biodiversity (pest species). Thus, the identified meta-analyses support the hypothesis that agroforestry generally enhances or maintains biodiversity.

We also identified another six meta-analyses that assessed the effect of landscape structure on biodiversity in agroecosystems (i.e. not necessarily implying agroforestry), accounting for 35 effect sizes. Landscape structure effects on biodiversity were mostly positive, meaning that an increase in landscape structure is beneficial for biodiversity, and more consistent when compared to the results of the agroforestry part (Figure S3). Following the limited number of meta-analyses for both agroforestry context and landscape structure, we could also not detect any meta-analysis detecting the interaction between both.

However, seven meta-analyses in our review tackled interactions between agro-ecological measures (of which agroforestry implementation might be considered an example) and landscape structure, and these all agreed that landscape structure mediates the effect of these measures on biodiversity (Batáry et al., 2011; Lichtenberg et al., 2017; Marja et al., 2019, 2024; Pérez-Sánchez et al., 2023; Sánchez et al., 2022; Tuck et al., 2014). Landscape structure here mainly influenced the magnitude of the effects of agro-ecological measures on biodiversity, rather than the level of significance. The general observation is that effects are greatest in simple landscapes compared to cleared and complex landscapes, as in the latter the baseline biodiversity is already too low or very high, respectively, for measures to be effective.

We detect mostly positive effects of increasing landscape structure by influencing landscape composition (except for no effect in pest species) and landscape configuration (except for pest species and natural enemies). Similarly, in most cases, landscape complexity has a positive effect on biodiversity. This evidence supports the general finding that landscape structure influences local biodiversity, with higher biodiversity levels in more diverse landscapes.

3.2 | Questionnaire

Most of the 82 respondents recognized the importance of biodiversity in agroecosystems (Figure 2a), with 79.3% valuing biodiversity as 'very important' and an additional 13.4% valuing biodiversity as 'important'. About 60% of the stakeholders indicated that a biodiversity assessment tool concerning agroforestry was important (very important = 34.2% and important = 26.8%; Figure 2c). However, despite the acknowledged importance of biodiversity, most of the respondents did not have experience with existing biodiversity tools: only nine respondents (11.0%) claimed to use or to be familiar with existing tools.

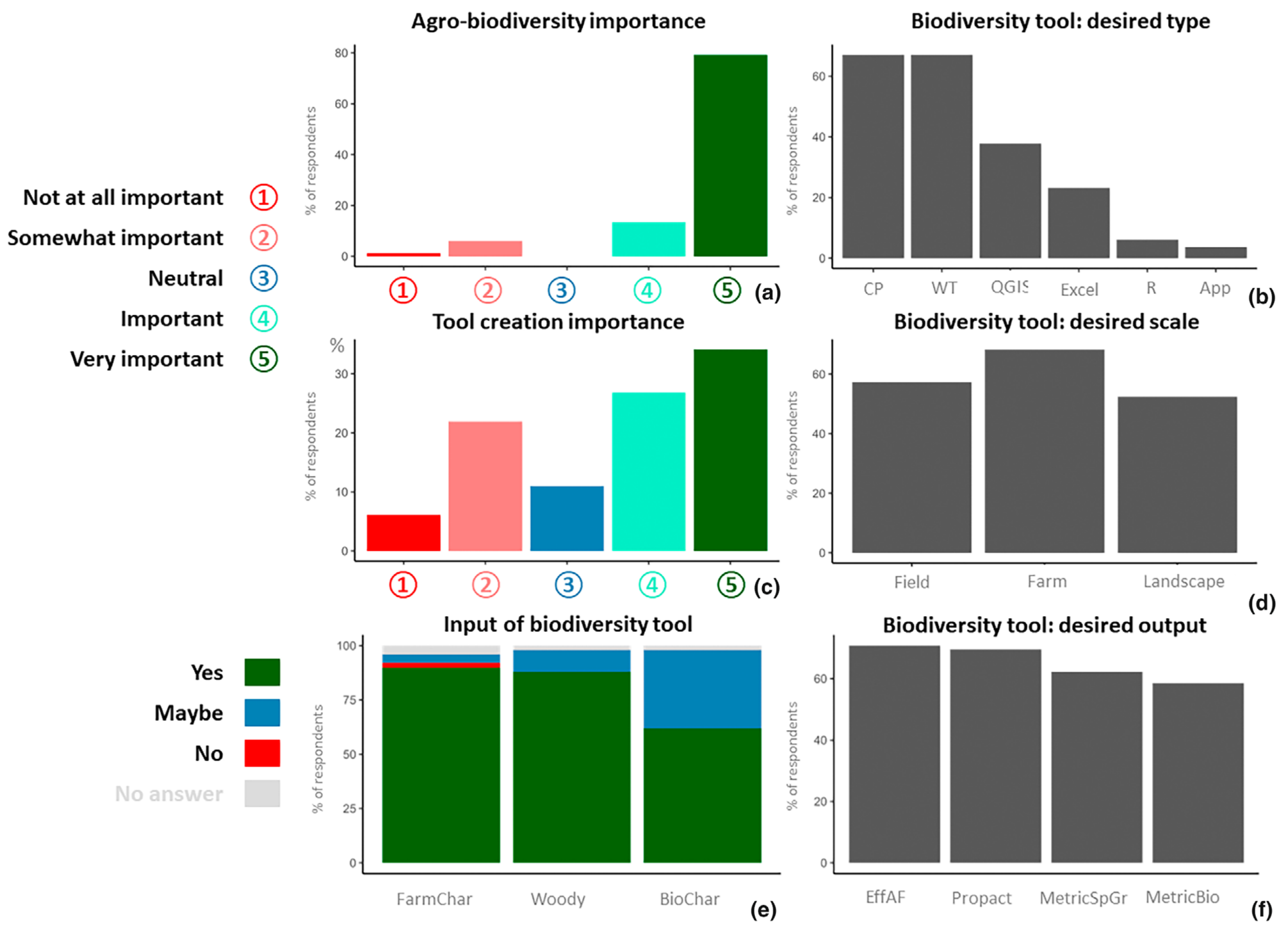

FIGURE 2 The relevance of biodiversity and a tool assessing biodiversity according to stakeholders, expressed in percentage of stakeholders. (a) Importance of agrobiodiversity according to 82 stakeholders. (b) Perceived importance of a tool designed to assess biodiversity in agroforestry systems, according to the stakeholders. (c) Desired interfaces the stakeholders want for a biodiversity tool. CP, computer program; Excel, spreadsheet tool; QGIS, geographic information system tool; R, programming-wise tool; WT, website tool. (d) Geographic scale for which the stakeholders want a biodiversity tool to work with. (e) Practices that might be incorporated in a biodiversity tool (addressed to farmers and advisors only). BioChar, checklist for presence or absence of several charismatic and easy-to-record key species; FarmChar, checklist for management practices and habitats on/close by the farm or field; Woody, the amount/characterization of woody species at the farm/field. (f) Needs of stakeholders in relation to a helpful output of a biodiversity tool (EffAF, effects of different agroforestry types; MetricBio, total biodiversity; MetricSpGr, metrics for taxa; PropAct, proposed actions towards improving biodiversity).

Concerning the functioning of a tool, most stakeholders expressed preferences towards tools accessible through websites or specifically designed computer programs (Figure 2b). The most preferred scale for the operation of a tool was at the farm scale, but without a lot of distinguishment as approximately half of the stakeholders were interested in a tool that could operate at a field or landscape scale (Figure 2d). Stakeholders expressed a desire for the tool to integrate mapping features (79.3%) and checklists for farm characteristics (89.0%) as inputs (Figure S4).

About 70% of stakeholders identified the biodiversity effects of different agroforestry types (EffAF) and proposed actions towards improving biodiversity (PropAct) as useful outputs for a biodiversity tool. 62.2% and 58.5% of respondents identified, respectively, metrics for taxa (MetricSpGr) and total biodiversity (MetricBio) as desirable (Figure 2f).

A separate part of the questionnaire was directed towards farmers and advisors, the likely assessors of farm-scale biodiversity, where we tried to disentangle the effort that they were willing to invest to assess biodiversity. The stakeholders reported that they were prepared to allocate time (13.8 h/year on average) for the assessment of biodiversity, and 89.0% expressed an interest in using a checklist for on-farm habitats, structures and management practices in combination with specifications of the agroforestry elements. However, more than half of the respondents were still interested in assessing basic biodiversity metrics (e.g. with a checklist of charismatic species to encounter on a farm; Figure 2e). In a free-form section of the questionnaire, some respondents suggested options to enable farmers to assess farmland biodiversity by using either a checklist of several species or enabling photograph identification. Other detailed suggestions indicated interests towards biodiversity differences in agroforestry designs.

3.3 | Tools

We identified 37 tools that were considered usable in agroecosystems and integrated at least one form of woody characterization, or were solely built upon on-site biotic metrics, meaning they could be applied in agroforestry systems (Text S3). However, most of the tools are unable to evaluate diverse agroforestry designs. Within the 37 tools in our database, only 17 were able to accommodate more than one distinct agroforestry type, thereby allowing comparison of different agroforestry options. Particularly noteworthy tools were the capacity of the Biodiversity Metric, SALCA-BD and Ecological Focus Area calculator (EFA) to account for six and two times five agroforestry types, respectively (of seven types defined in Text S3). An important observation is that most of these tools only use a presence/absence criterion for agroforestry; more detailed agroforestry characterizations are as of yet not present in biodiversity estimation toolkits.

These selected tools used different approaches to assess biodiversity: some of the key approaches being used and potential pitfalls are illustrated below with examples of tools in the database. The Biodiversity Metric (Natural England) differentiates over 100 habitats and requires a detailed mapping of the area that will be assessed (Panks et al., 2022). However, this complicated distinction of habitats could impede accessibility for non-experts. Towards agroforestry application, this broad scope (i.e. going far beyond agroecosystems) and impeded accessibility are major limitations. The Credit Point System (IP-SUISSE & Schweizerische Vogelwarte) implements an entirely different approach. It makes use of an exhaustive and user-friendly questionnaire format (Birrer et al., 2014). However, this approach falls short in providing quantitative values for separate species groups, and its narrow agroforestry design-related implementation options limit its applicability from an agroforestry perspective. These first two tools provide deterministic, evidence-based outputs. Conversely, GLOBIO (PBL Netherlands Environmental Assessment agency) adopts a data-driven output for predicting different habitat types based on its access to a global biodiversity database, offering an empirical estimation for habitat assessment. Its global approach, however, imposes limitations on the number of assessable habitats, rendering it incapable of accommodating various agroforestry types and lacking distinctions among ecosystem regions (Alkemade et al., 2009). Another approach to avoid the use of deterministic inputs or the need for yet established empirical databases is the use of actual, in-situ biodiversity data (Freyman et al., 2016), but the data gathering for such tools might require expert knowledge. Using data from open-source biodiversity databases like the implementation of the Greenspace Bird Calculator (Australian Museum Research Institute; Callaghan et al., 2020) can solve this. A theoretical setup like this was also discussed by Bimonte et al. (2021). The incorporated processes, however, disconnect from in-situ habitat specifications, troubling the comparison of agroforestry implementation with baseline systems. To enhance this connection, high-resolution data have to be available to enable parcel-wise biodiversity estimates.

In our NMDS-analysis of biodiversity tools, we observed distinct patterns of tool relationships (Figure 3). Cool Farm Tool, Ecosystem Services Assessment Tool for Agroforestry (ESAT-A) and Habitat and Biodiversity Assessment Tool were identified as having distinct characteristics, suggesting substantial differences in the approaches used by these three tools. This distinction in tool relationships was primarily influenced by programming tool (R), maps, and EffAF types. FG, app and GIS were also important variables, but only had presence in the StakePOV variable. We refer to Text S3 for the interpretation of the variables mentioned. The presence or absence of these variables substantially impacts the positioning of tools along the first axes of our analysis (Figure S5). The NMDS analysis also highlights the stakeholder's POV (stakePOV). Whereas Biodiversity Metric, Nature Smart Cities[4] and BPI coincided most with stakePOV, the three tools showing the least coincidence were ESAT-A, EII and Birdscalculator.

[4]Nature Smart cities incorporates two approaches, for further information, we kindly refer to Text S3.

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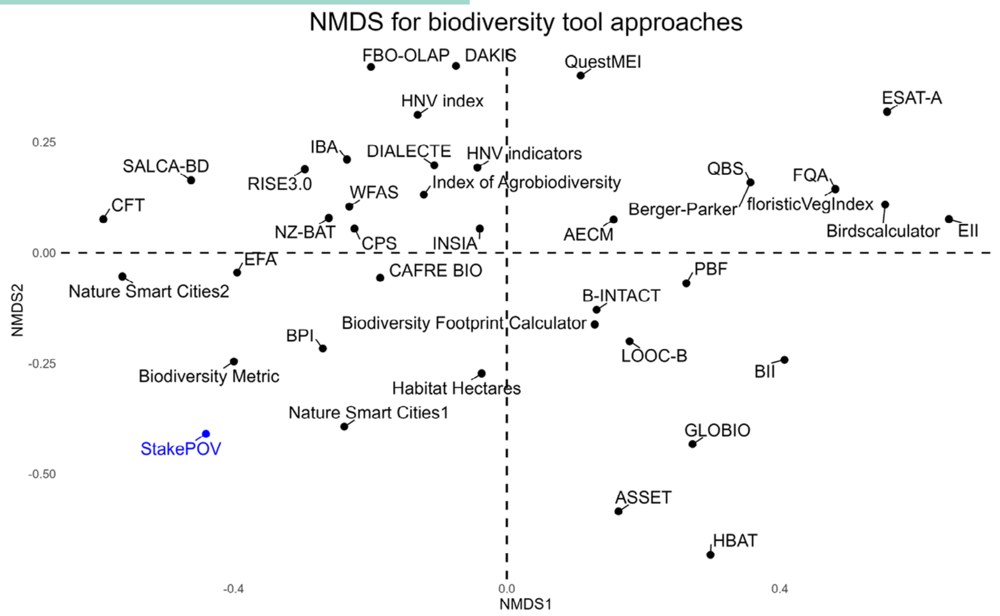

FIGURE 3 Nonmetric Multidimensional Scaling (stress = 0.196) of the different categorizations of the biodiversity tools. StakePOV (in blue) represents the stakeholders' point of view based on the questionnaire.

All of these latter tools are almost solely built on biotic characterization.

4 | DISCUSSION

In this study, we identified the key building blocks of an evidence-based tool that can be used to predict the biodiversity benefits of agroforestry implementation in agroecosystems. From the questionnaire, stakeholders who have an interest in agroforestry reported that they would like a tool (1) to provide guidance on measures that can promote biodiversity, (2) to assess the effects of different types of agroforestry and (3) to address a range of target species groups. Additionally, stakeholders articulated a desire for tools that integrate mapping data and checklists for farm characteristics, mainly focused on woody characterizations to define agroforestry and stressed the need for enriching functionalities within agricultural tools and the need for adapting to uncertainty and dynamic factors. According to our questionnaire, stakeholders are also willing to spend time to assess biodiversity, preferring comprehensive tools adapted to their intended end-users, ideally available through websites or computer programs in simplified graphical interfaces. Accessibility and usability are an often-occurring shortcoming in agricultural tools (Zhai et al., 2020). Stakeholders also expressed the utility of integrating both checklists for farm characteristics and mapping features. Farm characteristics could encompass specific habitat features and management strategies, mainly tailored towards agroforestry.

Unfortunately, a tool encapsulating all these features is presently unavailable (NMDS output in Figure 3; see also Stewart et al. (2022)). The tools most closely aligned with these preferences (e.g. the Biodiversity Metric, Nature Smart Cities, BPI, EFA and Habitat Hectares) are relatively challenging in terms of user complexity and—most importantly—are not specifically tailored to agroforestry. This additionally means that they are not properly capable of accounting for effect differences between different agroforestry types, one of the main concerns for stakeholders. Therefore, there appears to be an identifiable need for either a new or an adapted biodiversity assessment tool for agroforestry systems that is both evidence-based, but still sufficiently user-friendly to facilitate implementation and application. This kind of tool should (1) inform farmers about potential biodiversity implementations, (2) report these potential effects to policy actors, urging the rewarding of agroforestry implementation.

Our study highlights that agroforestry stakeholders acknowledge the importance and value of biodiversity (García de Jalón et al., 2018; Herzog et al., 2012). We do acknowledge the fact that the pool of stakeholders here (i.e. highly educated and involved in an agroforestry project) probably causes bias (however, they are probably also the target public to facilitate the use of a future biodiversity tool). Previous research has shown that biodiversity perception changed especially with farmers that first had in-depth interactions with biodiversity researchers about the role of biodiversity and wildlife (Gabel et al., 2018; Noe et al., 2005), underpinning that a citizen science approach could be beneficial towards creating farmer–researcher interactions (e.g. FrameWORK's farming clusters; Banks et al., 2023; Hager et al., 2022). These scientist–practitioner interactions are important to 'build bridges'. This also confirms the findings that farmers and advisors consider the output of proposed measures to be very valuable. Also, rewarding farmers for the potential biodiversity outcome of nature-friendly management practices (e.g. agroforestry implementation) might give more flexibility in management, hence promoting farmers' engagement and autonomy, but also emphasizes the need for an assessment tool enabling self-assessment of these potential outcomes (Tasser et al., 2019).

Any future tool should start from a baseline context where agroforestry implementation is being considered and should determine generated biodiversity effects. The stakeholder-appointed criteria require well-suited input data for different agroforestry types, compared with these baselines, across taxa. However, such detailed scientific information is not yet available in existing meta-analyses (Figure 1). These do acknowledge the positive biodiversity value of agroforestry interventions as in line with results from the tropics (De Beenhouwer et al., 2013; Schroth et al., 2004) and the work of the European Joint Research Center (Makowski et al., 2021; Schievano et al., 2025) for landscape features (including agroforestry)[5] supporting the premise that structurally and functionally more complex land-use systems result in greater biodiversity. However, two major challenges were identified with our approach.

Firstly, gaps on the meta-analysis level occur concerning different agroforestry types and in distinguishing different functional groups. No pollinator-focused meta-analysis was available (however, there are certain studies addressing the topic; e.g. Varah et al., 2020) and a lack of data on several other functional groups (e.g. soil fauna, natural enemies, pest species) occurred. We could only retrieve meta-analyses for agroforestry in general, silvoarable, silvopastoral, hedgerows, scattered trees and FG (Li & Jiang, 2021). Other practices (e.g. food forest approaches) were not covered. Most meta-analyses combined comparisons among agroforestry types or among agroecosystems and (semi-)natural habitats (e.g. forest). This variety in baselines makes it impractical to estimate the effect of agroforestry compared to baseline agroecosystems as the net effect can depend on the baseline land use selected for the comparison (Boinot et al., 2022). The more useful approach for the question addressed here would be to compare an agroforestry treatment with a pure control.

Second, the low number of available meta-analyses limits the power of the performed second-order analyses as variation within the results is considerable. This is an indication of context dependency in the magnitude of the effects, perhaps influenced by the agroforestry design or management factors (Jose, 2009; Kletty et al., 2023) and the limited data available. Kletty et al. (2023) reported, as such, unequivocal, but most often positive, biodiversity effects of silvoarable agroforestry and identified aspects influencing biodiversity outcomes. They defined affecting aspects such as the taxa, diversity metrics, management, age, site location, environment, climate, landscape structure, comparison type and sampling method. Agroforestry in the broad sense can encompass many different system types (Dmuchowski et al., 2024; Mosquera-Losada et al., 2009), which will generate additional variation. These effects might be partly extractable with data available on a case-study level, but are as of now not available on a meta-analysis level, either due to variability in baselines (e.g. forests, agroecosystems) and/or a difference in scope (i.e. the primary target is to express the overall added value of agroforestry instead of comparing it to baselines only or representing system differences) (Boinot et al., 2022; Mupepele & Dormann, 2022). Additional case studies followed by complete meta-analyses, starting from primary studies, are thus needed to establish a database better suited towards cross-taxa EffAF types and landscape contexts. This is particularly relevant given that surrounding landscape structure generally has an influence on biodiversity. This observation is relevant, as the implementation of agroforestry systems inherently contributes to increased landscape quality. Notably, several meta-analyses have identified interactions between landscape structure and agri-environmental measures with respect to biodiversity outcomes (Batáry et al., 2011; Scheper et al., 2013). However, it is important to acknowledge that meta-analytic data specifically addressing these interactions within the context of agroforestry remain unavailable to date. Also, very few case studies account for this landscape interaction in an agroforestry context (Kletty et al., 2023), highlighting the need for additional research and compiling efforts.

If we translate these observations from our second-order meta-analysis to applicability for a tool input, we argue that some characteristics (e.g. agroforestry type, age, tree and crop species) might need to be assessed empirically. However, current empirical evidence would not meet the data requirements needed to account for highly variable moderators (e.g. detailed agroforestry designs and management strategies). The main reason for this lies in the wide range of agroforestry application modalities in combination with the relatively low number of studies (Kletty et al., 2023). One way to include these factors is to use expert opinion. Another way to achieve this is by composing dynamic models, but at present, their functioning is still limited (Rahman et al., 2023). Additional inclusion of mapping features could enable remote habitat (quality) and landscape assessment. Furthermore, this option enables landscape structure inclusion to account for mitigating effects between agro-ecological measures and landscape structure as literature suggests.

This way, targeted inputs can be straightforward and tailored to agroforestry systems; therefore, enhancing easy application for agroforestry stakeholders, if at least these stakeholders are aware of the existence of a tool. The questionnaire highlighted that only a low number of stakeholders know any biodiversity tool. Existing literature confirms the importance of having tools to aid decision-making alongside video tutorials and technical guides for communication purposes (Bliss et al., 2019) and determining the potential need for a tool, along with required/desired criteria (Graves et al., 2005). Also, insights in farmers' and advisors' information behaviour are crucial to distribute knowledge. Peer-to-peer communication still seems to be the most important facet, but website information, images, printed materials and video tutorials are valued highly as well (Kiraly et al., 2023). Thus, synergizing tool releases with workshops, guidelines and tutorials might ensure successful utilization (De Vetter et al., 2022).

[5]https://datam.jrc.ec.europa.eu/datam/mashup/JRC_FP_EVIDENCE_LIBRARY/index.html.

Currently, certain efforts are being made to improve existing biodiversity tools for agroecosystems in the European context. Farmland Ecosystem Assessment Support Tool, a tool currently being constructed, includes the framework of its predecessor EFA (Douglas & Tzilivakis, 2022) and will additionally include a mapping interface and citizen science biodiversity data, often open source and rapidly expanding (Hobern et al., 2019; Pocock et al., 2017), although the quality of this data is still questionable[6] (García-Roselló et al., 2023), and spatial resolution is currently better suited to landscape-scale application.[7] Simultaneously, TAPE, a tool that as of yet does not integrate woody features (FAO, 2019), aims at introducing the BioBio-indicators (indicators at farm scale that are relevant to estimate agrobiodiversity value). These indicators were evaluated as proper indicators to reflect farmland biodiversity (Herzog et al., 2012). Although both approaches might come close, their complexity for users still needs to be evaluated, and neither of these tools will specifically target agroforestry. There is still a gap for a tool that explicitly meets the needs and wishes of agroforestry stakeholders, enabling a straightforward application and making it easy to retrieve with proper communication. Updateability might be of importance as well, since the rapid evolvements in this research area. A proper approach might be to create a field-scale tool accounting for the biodiversity gains that may be achieved due to different agroforestry systems implementation in comparison with a treeless baseline. This kind of tool can be integrated afterwards into farm-scale tools. Underlying databases should be developed with an identical aim.

AUTHOR CONTRIBUTIONS

Jari Vandendriessche, Maxime Eeraerts, Pieter De Frenne and Kris Verheyen conceived the ideas and methodology for this study. Jari Vandendriessche collected the data and led the data processing and writing of the manuscript in collaboration with Maxime Eeraerts, Pieter De Frenne and Kris Verheyen. Paul J. Burgess and Laura Cumplido-Marín gave valuable feedback in the process and aided in the finalization of this study. Jari Vandendriessche, Pieter De Frenne and Kris Verheyen designed the biodiversity-focused part of the questionnaire, while Sonja Kay, Margherita Tranchina and Paul Pardon led the construction of the questionnaire in collaboration with Jari Vandendriessche, Paul J. Burgess, Laura Cumplido-Marín and others outside the scope of this study. All authors contributed substantially, were involved in critical revision in the final stages and gave final approval for publication.

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[6](i) Observer effects (misidentifications, taxonomic bias), (ii) faulty geographic referencing and (iii) degree of presence of active observers.

[7]There could be a potential in carrying out low-scale parcel-based citizen science bioblitzes (Meeus et al., 2023) to distinguish these small-scale effects.

CONFLICT OF INTEREST STATEMENT

None declared.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70133.

DATA AVAILABILITY STATEMENT

All data are archived via Figshare along with the R code and are publicly available: https://figshare.com/s/e51c87dd073dbb02faf5, DOI: 10.6084/m9.figshare.24776298 (Vandendriessche et al., 2025). Regarding the questionnaire, no personal data have been stored in the course of this research. The data utilized in this study exclusively consist of anonymized or aggregated information, ensuring the privacy and confidentiality of individuals involved. Respondents gave informed consent on data collection, storage and utilization in compliance with the GDPR framework.

STATEMENT ON INCLUSION

Our study brings together a review and information based on a questionnaire across the whole of Living Labs established within the DigitAF consortium and extended with a Belgian cluster, without reaching any further. Authors from a number of different countries were engaged to give feedback on the study design to ensure that the diverse sets of perspectives they represent were considered. Whenever relevant, literature published by scientists from the region was cited. Our study was a global review and was based on a meta-analysis of secondary data rather than primary data. As such, there was no local data collection. However, the geographical distribution of the authorship team broadly represents the major regions of interest in the meta-analysis, supporting the inclusion of data from peer-reviewed studies published in local languages and ensuring the appropriate interpretation of data and results from each region.

ORCID

Jari Vandendriessche https://orcid.org/0000-0003-3845-6655
Maxime Eeraerts https://orcid.org/0000-0003-2739-9704
Pieter De Frenne https://orcid.org/0000-0002-8613-0943
Paul J. Burgess https://orcid.org/0000-0001-8210-3430
Laura Cumplido-Marìn https://orcid.org/0000-0003-4672-3047
Sonja Kay https://orcid.org/0000-0003-0531-4407

Margherita Tranchina https://orcid.org/0009-0006-3037-1752
Paul Pardon https://orcid.org/0000-0002-2836-9198
Kris Verheyen https://orcid.org/0000-0002-2067-9108

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SUPPORTING INFORMATION

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

Figure S1. Respondent characteristics for the questionnaire.

Figure S2. The relevance of proposed agroforestry practices according to stakeholders.

Figure S3. Effects of landscape complexity, composition and configuration on biodiversity levels of different taxonomic groups.

Figure S4. Tool construction preferences according to questionnaire respondents.

Figure S5. Underlying variables for the Nonmetric Multidimensional Scaling (stress = 0.196).

Data S1. Second screening of selected meta-analyses, PRISMA-diagram and potential bias assessment.

Data S2. DigitAF survey - Biodiversity and overall respondent characteristics.

Data S3. Biodiversity-assessment tools.

Data S4. Data handling.

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