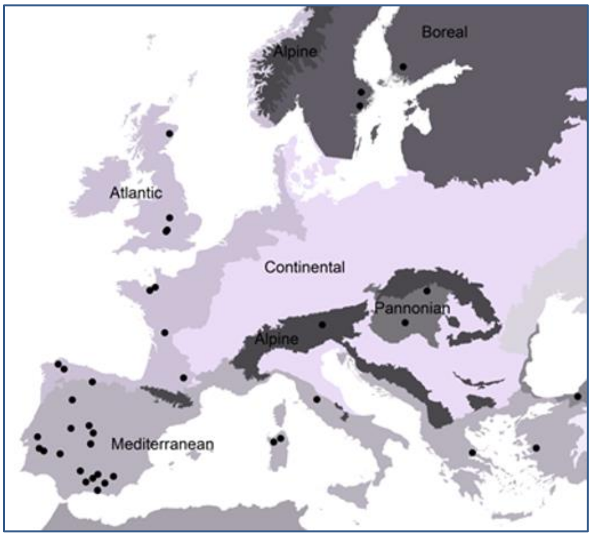

Synthesis of Existing European Agroforestry Performance

Project name	AGFORWARD (613520)
Work-package	7: Landscape Evaluation of Innovative Agroforestry
Deliverable	Deliverable 7.19 (7.1): Synthesis of existing European agroforestry performance
Date of report	13 November 2015 (updated 7 July 2016)
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Contents

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1 Context

The AGFORWARD research project (January 2014-December 2017), funded by the European Commission, is promoting agroforestry practices in Europe that will advance sustainable rural development. The project has four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations (through participatory research) to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices at a field-, farm- and landscape scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

This report comprises Deliverable 7.19 in the project, which contributes to the first and third objectives as it improves our understanding of the context of European agroforestry and the effects of agroforestry on biodiversity, ecosystem services and farm profitability, using systematic reviews and meta-analysis. The deliverable has been produced in the form of three papers, which have all been published in highly-ranked scientific journals:

Fagerholm, N., Torralba, M., Burgess, P.J., Plieninger, T. (2015). A systematic map of ecosystem services assessments around European agroforestry. Ecological Indicators 62: 47-65 http://dx.doi.org/10.1016/j.ecolind.2015.11.016

Torralba, M., Fagerholm, N., Burgess, P.J., Moreno, G., Plieninger, T. (2016). Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agriculture, Ecosystems and Environment 230: 150-161. http://dx.doi.org/10.1016/j.agee.2016.06.002

Plieninger, T., Hartel, T., Martín-López, B., Beaufoy, G., Bergmeier, E., Kirby, K., Montero, M.J., Moreno, G., Oteros-Rozas, E., Van Uytvanck, J. (2015). Wood-pastures of Europe: Geographic coverage, social-ecological values, conservation management, and policy implications. Biological Conservation 190: 70-79. http://dx.doi.org/10.1016/j.biocon.2015.05.014

2 Description of three papers

Agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions (Burgess et al., 2015). The diversity of practices behind the term agroforestry is vast and includes land uses such as silvoarable systems, forest farming, riparian buffer strips, improved fallow, multipurpose trees and silvopasture systems (Mosquera-Losada et al. 2009, den Herder et al. 2015). These agroforestry systems have played an important role in Europe in the past and many current traditional land-use systems involve agroforestry. Economic conditions and a drive to produce cheap food decreased the importance of these systems during the twentieth century, but in recent years agroforestry has regained attention in Europe as a means of maintaining food production and profitability whilst enhancing the environment.

This multi-functional role has been captured in scientific and grey literature through the years in a continuous but unsystematic way, based on multiple different approaches and typically focused on single and specific practices, geographical ranges or ecosystem services (i.e. alley cropping in Tsonkova et al., 2012; silvopasture in Rivest et al., 2013; silvoarable systems in Eichhorn et al., 2006;

soil carbon sequestration in Lorenz and Lal, 2014; temperate climate agroforestry systems in Smith et al., 2013). Hence, this deliverable aims to provide a qualitative and quantitative synthesis of the existing knowledge on the outcomes of European agroforestry systems in terms of biodiversity and ecosystem services. The outputs provide evidence of the social, economic and environmental benefits of both modern and traditional agroforestry at different scales and give insights on the form of land use management and institutional policies that encourage beneficial agroforestry. The outputs also highlight lines of research to address detected knowledge gaps.

The first section within the deliverable has the aim of providing an overview of how agroforestry has been studied in Europe and of identifying potential knowledge gaps and biases in the ecosystem service research agenda within agroforestry. It is based on a systematic review of the scientific literature on ecosystem services and European agroforestry (Fagerholm et al., 2015).

The results show how European research has focused on the agroforestry systems covering the largest areas (such as extensive wood pastures in the south of Europe and continental agricultural mosaic landscapes), using a monetary and biophysical approach and quantitative indicators, and typically focusing on no more than one or two services at a local or regional scale. Fagerholm et al (2015) suggest a need to diversify both the research approaches and the ecosystem services covered for a better understanding of European agroforestry. This paper also points to key actions which can contribute to making future agroforestry research more relevant for decision makers, such as enhancing stakeholder participation in mapping and valuing ecosystem services, introducing broader scales to ease the transfer of research outcomes to policy schemes, and to increase the use of emerging explicit mapping tools.

One of the objectives in the AGFORWARD project is to upscale site-specific results such as described in Fagerholm et al (2015) to wider geographic regions in a statistically robust way. Hence Torralba et al (2016) presents a meta-analysis on the effects of agroforestry on ecosystem service provision and on biodiversity levels in comparison with other specialized land uses such as forestry or arable land. It applies the hypothesis that complementary resource use by different components in an agroforestry system increase resource capture (Carnell et al., 1996) to biodiversity and a wider range of ecosystems services. The results reveal an overall positive effect of agroforestry through increasing ecosystem service provision and biodiversity enhancement; indicating that relative to conventional agriculture or forestry, agroforestry can maintain productivity whilst increasing other ecosystem services.

The third paper (Plieninger et al. 2015) focuses on wood pasture (the integration of grazing livestock with scattered trees), which is the dominant type of agroforestry across Europe (den Herder et al. 2015). Wood pastures are the most common traditional agroforestry systems in Europe and their existence contributes to the cultural heritage in many European rural landscapes. The review presents an in-depth estimation of the extent of European wood pastures and a qualitative revision of the cultural values and main threats associated with them, suggesting potential solutions in rural planning which could help to correctly allocate and address them in the European policies.

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3 Paper 1: A systematic map of ecosystem services assessments around European agroforestry

This is a pre-print version of the following paper:

Fagerholm, N., Torralba, M., Burgess, P.J., Plieninger, T. (2015). A systematic map of ecosystem services assessments around European agroforestry. Ecological Indicators 62: 47-65
http://dx.doi.org/10.1016/j.ecolind.2015.11.016

Abstract

Agroforestry offers proven strategies as an environmentally benign and ecologically sustainable land management practice to promote ecosystem services. In this literature review, we systematically consider the agroforestry and ecosystem services literature with the aim to identify and catalogue the knowledge field and provide the first systematic synthesis of ecosystem services research in relation to European agroforestry. We reviewed 71 scientific publications from studies conducted in farmland and forest ecosystems with various types of agroforestry management. Each publication was systematically characterised and classified by agroforestry practice and research approach in order to provide an insight into the current research state in addressing ecosystem services (including methods, indicators, and approaches). Spatial distributions of the case study sites in Europe were also explored. In addition, typical clusters of similar research approaches were identified.

The results show that ecosystem service assessment of European agroforestry is currently focused on the spatially extensive wood pastures in the Mediterranean, Atlantic, and Continental agricultural mosaic landscapes. A specific emphasis has been on regulating, supporting, and provisioning services, such as provision of habitat and biodiversity, food, climate regulation, fibre, and fuel, and the consideration of cultural services has been largely limited to aesthetic value. There is a bias to biophysical and monetary research approaches. The majority of the studies focus on quantitative methods and biophysical field measurements addressing the assessment of only one or two services. Monetary approaches have been applied in less than one fifth of the studies but form a distinctive group.

Our results highlight gaps and biases in the ecosystem service research agenda within agroforestry based on which we conclude that research should aim to diversify from the biophysical and monetary approaches, towards a wider variety of approaches, especially socio-cultural, and a wider coverage of ecosystem services. Stronger consideration of stakeholder participation and introduction of spatially explicit mapping are also important key actions. We make suggestions to advance the promise of ecosystem services provision from European agroforestry in decision making including various actors, stakeholders and institutions, with strong links to policy processes, such as the EU Biodiversity Strategy and Common Agricultural Policy.

Keywords: agroforestry management, decision making, environmental services, literature review, silvoarable, silvopastoral

3.1 Introduction

The ecosystem services framework has become the most widely adopted integrated framework to study the relations between ecosystems and people. Conceptually it describes how biophysical systems provide a variety of important benefits to human well-being and ultimately it can guide decision-making towards halting or reversing ecosystem degradation (Daily, 1997; Haines-Young & Potschin, 2010; MA, 2005). For this reason the assessment of ecosystem services is important, as it creates the knowledge to understand the supply and demand of ecosystem services, to support awareness raising, and to achieve priority on the political agenda, for example in the European Union (EU) (Cowling et al., 2008; Crossman et al., 2013; Maes et al., 2012).

Assessments of ecosystem functions and their potential provision of services to people have been dominated by natural sciences and economics (Seppelt et al., 2011; Vihervaara et al., 2010). The common approaches to assessment have been identified as biophysical, socio-cultural and monetary (Cowling et al., 2008; de Groot et al., 2010) or alternatively as habitat, system and place-based approaches (Potschin & Haines-Young, 2013). A general tendency in ecosystem service assessments, depicted by the recent literature, is that the measurement of cultural services lags behind regulating, provisioning, and supporting services' categories (Crossman et al., 2013; Martínez-Harms & Balvanera, 2012; Seppelt et al., 2011).

The ecosystem services concept also offers a transformative lens for agroecosystems, the most common anthropogenic ecosystem on the planet (Swinton et al., 2006). While agricultural intensification and expansion are among the most important drivers of ecosystem services degradation (MA, 2005), several multifunctional land-use systems hold the promise to safeguard ecosystem services within commodity production (O'Farrell & Anderson, 2010; Tscharntke et al., 2005). Agroforestry, widely adopted in the world's tropical and subtropical regions, is one of such land-use systems that provide multiple ecosystem services, combining the provision of agricultural and forestry products with non-commodity outputs, such as climate, water and soil regulation, and recreational, aesthetic and cultural heritage values (McAdam et al., 2009). The main trait of agroforestry is the deliberate combination of trees/shrubs with agricultural crops or livestock, with people playing a key management role (Mosquera-Losada et al., 2009). The principal forms of agroforestry in Europe include wood pastures, the use of hedgerows, windbreaks, and riparian buffer strips on farmland, intercropped and grazed orchards, grazed forests, forest farming, and more modern silvoarable and silvopastoral systems. Agroforestry has traditionally formed an important element of European landscapes, but many of these systems have disappeared due to economic and social changes (among others, land abandonment and agricultural intensification), and the remaining ones are highly vulnerable (Nerlich et al., 2013).

An assessment of the current spatial extent of agroforestry by den Herder et al. (2015) shows that agroforestry is most widely practised in southern Europe, especially in Spain, Portugal, Greece, and Italy. Wood pastures cover an extensive area and are distributed around Europe from the Mediterranean oak tree systems to Boreal wood pastures (Plieninger et al., 2015). Most fruit tree systems are found in central and Mediterranean Europe, with mixed olive cultivation in the Mediterranean being the most area-extensive expression of this agroforestry type. Also the traditional temperate fruit orchards are prominent (Herzog, 1998). Currently, agroforestry in the European Union is practiced at least on an area of 25 million hectares, which is equivalent to about 5.7% of the territorial area and 14.2% of the utilized agricultural area (den Herder et al., 2015).

Agroforestry has the potential to advance sustainable rural development in Europe (Primdahl, 2013). A key environmental benefit of agroforestry is the possibility to diversify agricultural landscapes with trees and to increase overall biodiversity (Mosquera-Losada et al., 2009; Nerlich et al., 2013). The key agricultural benefits include the opportunity to significantly increase land resource efficiency and productivity compared to the separation of agricultural and tree systems (Cannell et al., 1996; Graves et al., 2007), and to improve animal welfare. Jose et al. (2009) have raised awareness for the ecosystem services that are mediated by global agroforestry not only to farmers and landowners, but to society at large. The evidence supporting the promotion of agroforestry specifically in Europe has been reviewed by Smith et al. (2013) with the conclusion that temperate agroforestry balances both productivity and environmental protection through multiple ecosystem services. The challenge, however, lies in mainstreaming this land use practice. A meta-analysis on the role of scattered trees occurring throughout farmland matrix and their role as keystone structures maintaining ecosystem services by Rivest et al. (2013) also concluded that management options exist to conserve and restore trees but farmers need to be supported by relevant policies. In addition, Tsonkova et al. (2012) reviewed the ecosystem services provided by a specific type of temperate agroforestry, named alley cropping systems, and identified benefits in terms of increased carbon sequestration, improved soil fertility, enhanced biodiversity and increased overall productivity on marginal lands. Other reviews regarding European agroforestry practises have been published, for example, by Eichhorn et al. (2006) where the focus was on listing and quantifying the existing systems of silvoarable agroforestry and to document the recent changes and by Nerlich et al. (2013) who characterized traditional agroforestry practices and their disappearance from farmland. These recent reviews do not, however, systematically consider the agroforestry and ecosystem services literature in Europe.

The current review addresses this gap and produces a systematic and comprehensive evaluation of the knowledge field through mapping the conducted studies and applied research approaches for ecosystem services assessment around European agroforestry. The aim of this literature review is to identify and catalogue the knowledge field and provide the first systematic synthesis of ecosystem services research in relation to European agroforestry. The specific questions to address include: 1) What agroforestry systems and ecosystem services have been studied in Europe? 2) What approaches to ecosystem service assessment have been applied in research? 3) How are agroforestry systems, ecosystem services and research approaches interlinked? Based on the findings, the existing research gaps and biases are discussed. We then interpret our results from the perspective of the Daily et al. (2009) framework on "Ecosystem services in decision making" to derive recommendations on how to make research on ecosystem services from European agroforestry more relevant for land use policy and practice.

3.2 Material and methods

We reviewed scientific publications from studies conducted in farmland or forest ecosystems in Europe with various types of agroforestry management. Our review followed established guidelines for systematic review and systematic mapping (Bates et al., 2007; Collaboration for Environmental Evidence, 2013; Pullin & Knight, 2009, Pullin & Stewart, 2006) and was oriented along previous review exercises in the field of ecosystem services (Milcu et al., 2013; Nieto-Romero et al., 2014; Seppelt et al., 2010; Smith et al., 2013; Vihervaara et al., 2010). Evidence-based formalized systematic review frameworks were initially developed in the health sciences and have recently started to raise interest also within conservation and environmental management to guide research and policy-making (Bilotta et al., 2014; Pullin & Stewart, 2006). The advantages of such a formalized methodology for literature review stems from the rigour and objectivity in the process combined with the underlying philosophy of transparency and independence. The systematic review approach aims to build new knowledge from a rigorous analysis of existing research findings. Systematic mapping, the approach used in this review, has similarities with the systematic review but has a focus on gathering existing literature into a searchable database and provide a transparent evidence base (Bates et al., 2007).

Electronic academic databases used in the search for relevant items comprised ISI Web of Science, Scopus, CAB Abstracts (Ovid), BIOSIS Citation Index, and Geobase (Ovid). Publication search combined three search strings in English with the following topics: (1) agroforestry and related definitions describing agroforestry systems, structures and practices, (2) ecosystem services and related definitions such as the equivalent of environmental services, and (3) Europe and specific countries. A scoping exercise was performed to pilot search terms and strings to iteratively revise the search terms, presented in detail in Appendix A. We covered a wide variety of terms applied for European agroforestry systems and practices and also aimed to include diverse search terms for ecosystem services. It is nevertheless likely that some relevant publications were not captured in this data search. The use of single ecosystem service types (e.g., nutrient cycling) as search words would have yielded an extensive amount of results but we were interested in those studies that were clearly linked to ecosystem services research. Hence, we covered only studies that defined themselves as ecosystem services research, in line with the literature researches applied by Martínez-Harms & Balvanera (2012), Nieto-Romero et al. (2014) and Seppelt et al. (2010). We did not include grey literature, as we aimed to review internationally published studies on agroforestry and multiple ecosystem services. Titles and abstracts were stored in an Endnote database and duplicates removed.

The searches were performed in August 2014 and resulted in a total of 286 references including journal articles, reports, books, book chapters, and conference papers. From these we manually selected those studies which (1) address one or more agroforestry practices within the European biogeographical regions and (2) provide assessment of biodiversity or one or more ecosystem services. Items were selected through a three step filtering process (Pullin & Stewart, 2006) during which, in the first instance, the inclusion criteria were applied on title. Secondly, items remaining were filtered by abstract (or introduction section or equivalent if an abstract was not available) and, further, by viewing remaining items at full text content. We applied the inclusion criteria conservatively at the different stages of the filtering process, especially title and abstract were in most cases read together, in order not to exclude any relevant publications. If a study and the results were covered in several publications, only one of them was included. To check for data quality and consistency of application of the inclusion criteria, another reviewer went independently through the first filters of title and abstract on a random subsample of 10% of references (Pullin & Stewart, 2006). A kappa value of 0.729 (p=0.000) was calculated, which indicates a substantial level of agreement between reviewers (Cohen, 1960: < 0.5). In addition, the review by Smith et al. (2013) was searched for relevant publications. Finally, 71 publications published in English, Spanish, German, and Swedish were considered in the analysis (Appendix B).

To characterize the context of agroforestry and ecosystem service assessment literature, each publication was classified according to publication characteristics, study location and context, and characteristics of agroforestry practice studied (Figure 1). To classify agroforestry practices we developed a typology based on previously suggested categorisations (Mosquera-Losada et al., 2009; Nerlich et al., 2013) and our interpretation of the agroforestry practices appearing in the data, including wood pastures, woodlots and scattered farm trees, forest grazing, hedgerows, orchards, riparian buffer strips, and modern agroforestry systems (systems often based on traditional practices, modified by research and experience and well adapted to modern farming. e.g. modern tree-pig systems, cf. Nerlich et al., 2013). A spatial data layer was produced for study site locations. Data on biogeographical region (EEA, 2011) and land system archetype (Levers et al., submitted) were extracted to each site. Subsequently, to identify and classify the research approaches to ecosystem service assessment, each study was coded based on methods, ecosystem services under assessment, data sources, indicators, and analytical approaches. Classification of ecosystem services followed that of the Millennium Ecosystem Assessment (MA, 2005). Data extraction variables are presented in detail in Appendix C. All categories were pretested to guarantee repeatability and consistency.

Characterization of the studied variables was approached through descriptive statistics. Cluster analysis was applied to identify typical clusters of studies approaching ecosystem services and their assessment in similar ways. To reach this goal seven key variables were specified after testing with various amounts of variables (Appendix C). Agglomerative hierarchical clustering with Ward's method and squared Euclidian distance was applied for this purpose in SPSS22 (Everitt et al., 2011; Murtagh & Legendre, 2014; cf. Milcu et al., 2013). Clustering sorts the publications based on the specified key variables starting from n clusters (n=71 publications) and continues to sort these into clusters of sameness, following a bottom up logic, until one cluster remains. Ward's clustering was selected as it is widely understood and readily interpretable. Four clusters were chosen as a meaningful interpretation balancing the inner homogeneousness of a cluster and the external heterogeneousness in relation to other clusters. Clusters were examined using descriptive statistics.

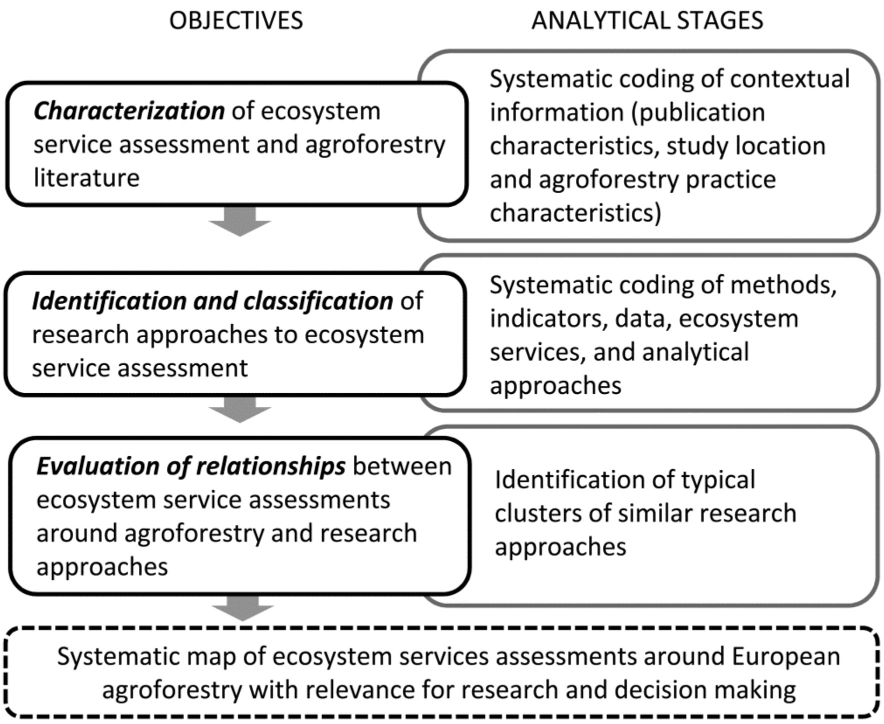

Figure 1. Objectives of the systematic mapping of ecosystem services assessments around European agroforestry with related analytical stages.

3.3 Results

3.3.1 Characteristics of agroforestry and ecosystem service assessment literature

The 71 reviewed publications are peer-reviewed journal articles (83%) and book sections (17%) published between 1993 and 2014 (Figure 2B). More than 80% of the publications have appeared since 2007 (Figure 2B). The publications cover 151 study sites in a total of 12 European countries (Figure 2A and C). Most of the study sites are located in Spain (45%), the UK (15%) and France (14%) and mainly in the Mediterranean (44%), Atlantic (36%) and Continental (17%) biogeographical regions, the majority of them being patch (38%) and local (37%) scale studies rather than regional or national scale (25%) (Figure 2A and D). Two studies are performed at European scale (Reisner et al., 2007, Schulp et al., 2014) and two address modelled landscapes (Brownlow et al., 2005; Kaeser et al., 2011). The number of study sites per publication varies between 1 and 20 (mean 2.7, SD 4.1), with most studies (79%) focusing on 1-2 sites.

In total, 21 different ecosystem services including biodiversity have been studied. The most common services assessed in the sample are provision of habitat and biodiversity, food, fiber, climate regulation and fuel (Figure 3). In general, provisioning, regulating and supporting services are equally addressed (with 29%, 27% and 27% share of all studied services respectively), with 17% share including an assessment of cultural services. Addressing more than one ecosystem service category in a study has become more prominent after the mid-2000s (Figure 2B, category mixed).

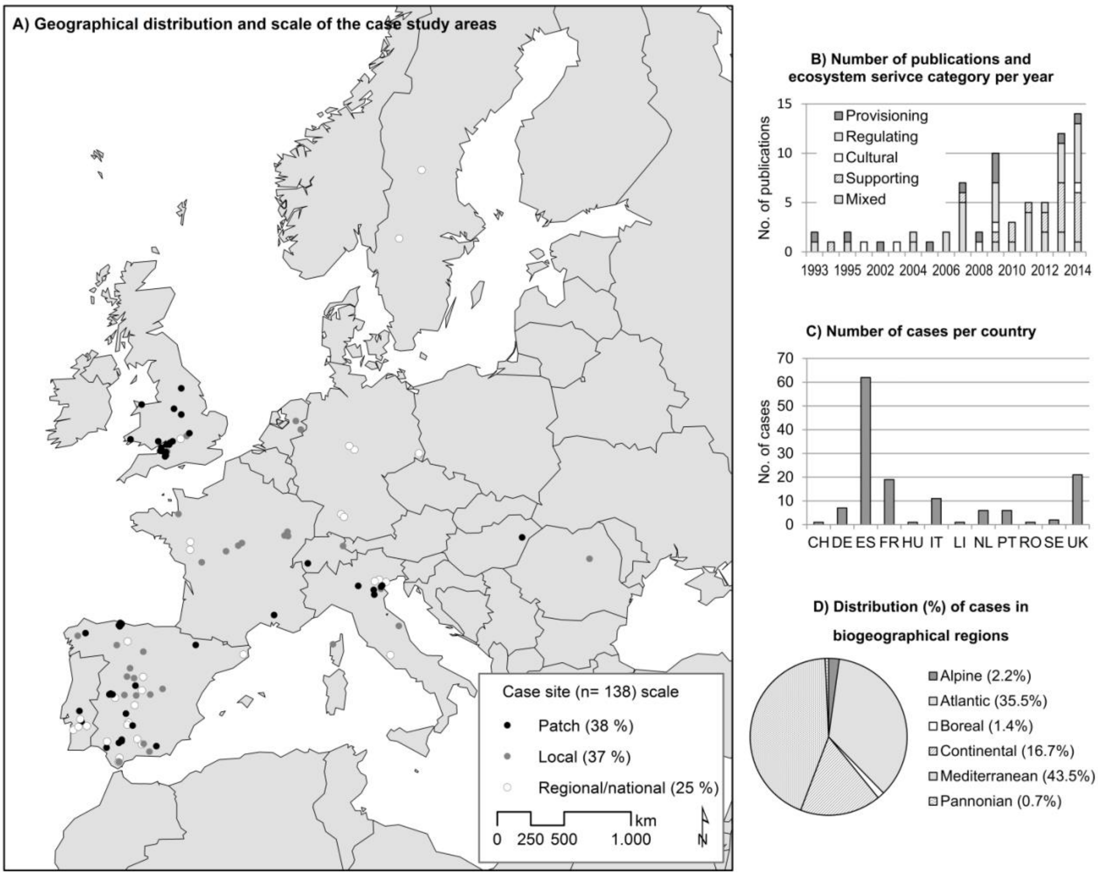

Figure 2. Geographical distribution and the scale of the case study sites (n= 138, 13 sites missing due to lack of data) addressed in the 71 publications: (A) geographical distribution and scale of study areas, B) number of publications and ecosystem service category per year, (C) number of case study sites per country, and (D) distribution of case in the European biogeographical regions.

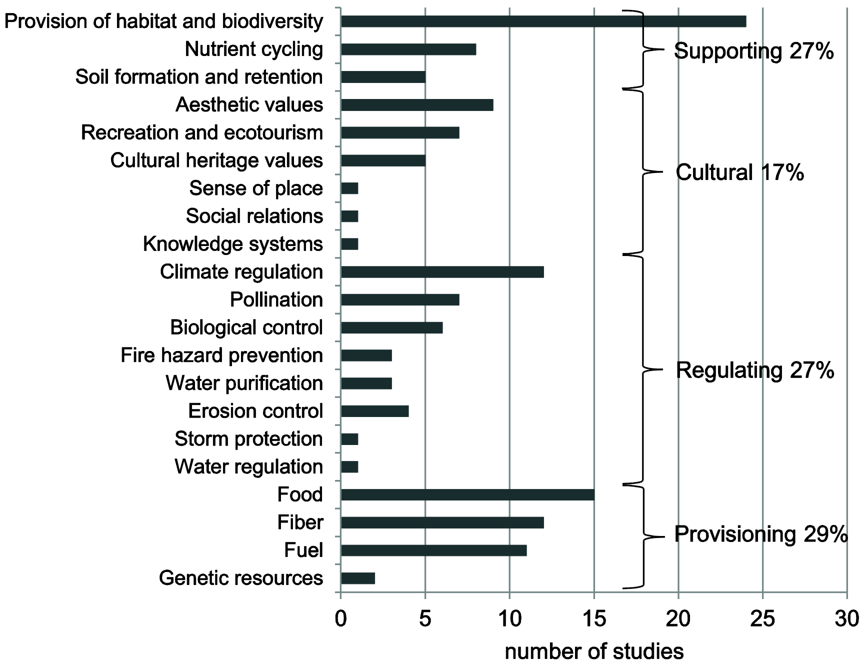

Figure 3. Frequency of the different ecosystem services appearing in the 71 publications and their share (%) in ecosystem service categories.

3.3.2 Characteristics of agroforestry practices

The studied agroforestry practices are dominated by wood pastures (44%) including Spanish *dehesa* and Portuguese *montado* landscapes and other grazed woodlands (Figure 4). Silvoarable systems are also prominent, most often characterised by agricultural mosaic landscapes with woodlots and scattered farm trees (21%), hedgerows systems (20%), and riparian buffer strips (6%). Forest grazing, orchards, and modern agroforestry systems have gained less attention in the reviewed literature (4%, 3% and 3% of studies respectively). Wood pastures are mainly addressed in the Mediterranean biogeographical region (81%) and silvoarable systems mostly in the Atlantic and Continental regions (Figure 5). Hedgerow systems are the most heterogeneous type in terms of biogeographical regions, whereas orchards have been studied only in the Continental region.

Approximately half (48%) of the studies are based on extensive management, with only 14% categorised as intensively managed. Mixed productive management (e.g. both organic and intensively managed conventional farms) and organic management comprise 24% and 3% respectively (Figure 4). In terms of land system archetypes, a significant share of the patch and local scale study sites are located on arable cropland (classes 3, 4 and 5: 41.3%) or on grassland (classes 7, 8 and 9: 25.7%, Table 1). Both of these land systems are represented 15% more compared to their spatial extent in Europe. Then again, studies located in areas defined as forest systems are less present compared to their spatial extent (classes 11 and 12: 3.1% vs. 27.6%). Of the publications 30% consider an assessment of ecosystem services in agroforestry as compared to pure forms of agriculture, forestry or to another agroforestry system. However, in the majority of the studies this is not done (Figure 4). Most studied agroforestry sites are delineated by biophysical (55%) borders such as watersheds, valleys and forest areas. Furthermore, drivers of ecosystem change, as stated by the authors, are prevalent, with direct drivers threatening 30% of the study areas, indirect 14%, and both direct and indirect drivers noted for 15% of these study areas (Figure 4). Among the direct drivers land abandonment in silvopastoral systems, agricultural intensification or conversion to agricultural land are frequently mentioned. Commonly cited indirect drivers are EU and national policies that incentivise afforestation and intensification of European agriculture.

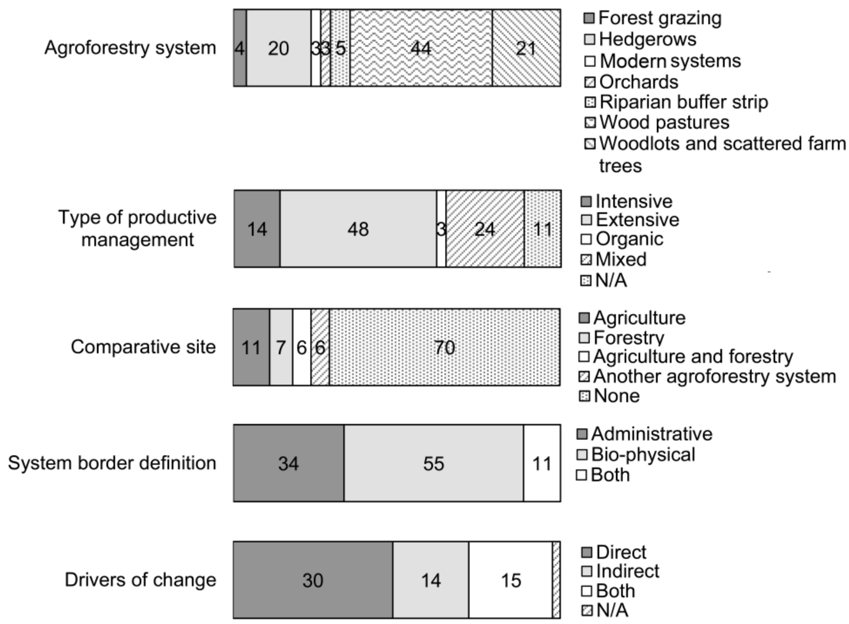

Figure 4. Variables characterising agroforestry systems with relative proportions (%) of studies (category labels with value less than 3% are not shown in the figure).

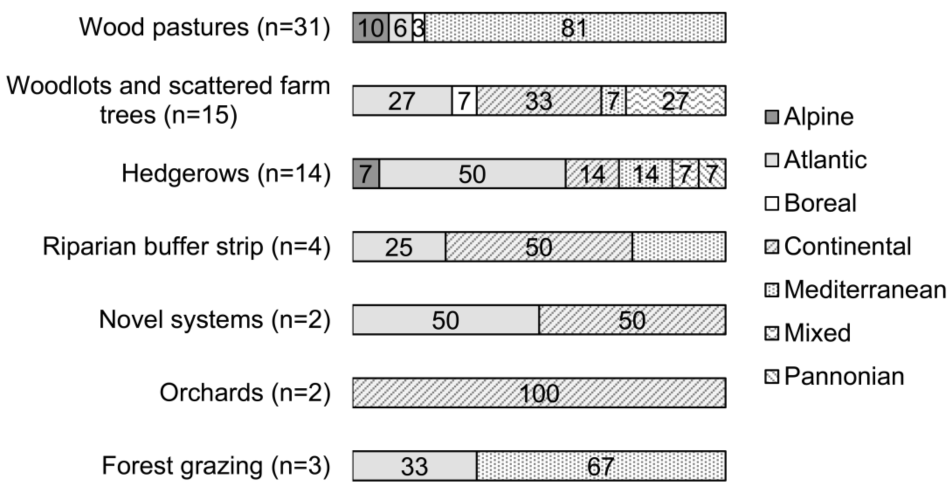

Figure 5. Distribution of agroforestry systems addressed in the studies (n=71) within the European biogeographical regions (in %).

3.3.3 Research approaches to ecosystem service assessment around European agroforestry

In the reviewed literature, the most common approach applied to ecosystem service assessment within European agroforestry is biophysical assessment (79% of all studies), followed by monetary (13%), socio-cultural (6%) and mixed approaches (3%) (Figure 6). Mixed approaches appearing in our sample combine the biophysical with socio-cultural or monetary approaches (Baumgärtner & Bieri, 2006; Borin et al., 2010). Following these figures, the clear majority (93%) of the studies is based on quantitative methods for ecosystem service elicitation and to lesser extent on qualitative (4%) or mixed (3%) methods. In the majority of studies, the assessment focuses on only one ecosystem service (58%) or two to five services (37%) (mean 2.3, SD 3.4). More than six services are assessed only in a few studies (3 studies, 4%) with the highest number amounting to 27 services (Plieninger et al., 2013).

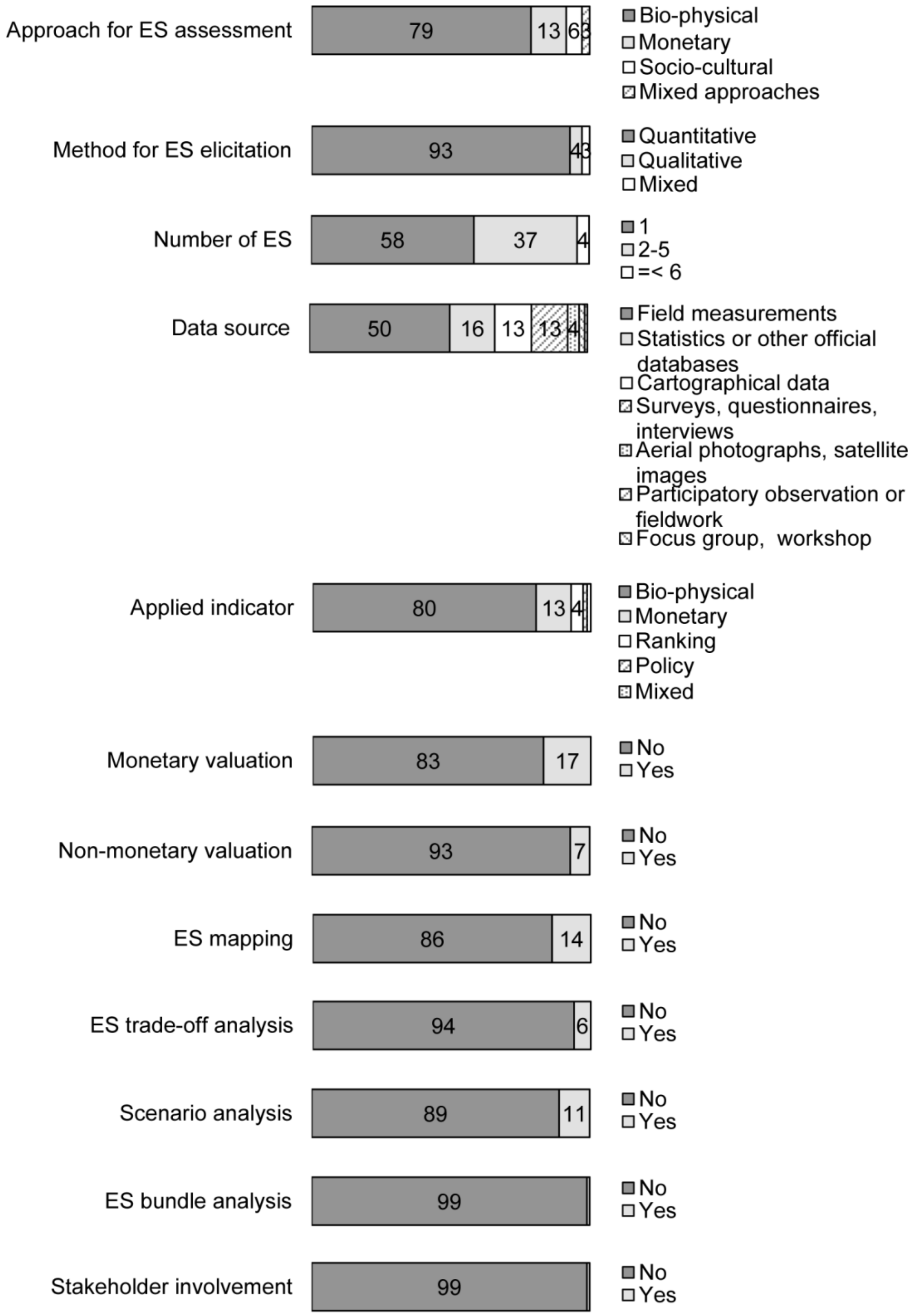

Figure 6. Variables characterising research approaches to ecosystem service assessment with 16 relative proportions of studies (category labels with value less than 3% are not shown in the figure).

Table 1. Relative proportion of land system archetypes (LSA, Levers et al., submitted) characterising patch and local scale study sites and their distribution in the European Union.

Class	Land system archetype	Study areas (%) (n=97[1])	Areal coverage (%) in European Union
1	High-intensity cropland	1.0	1.3
2	Large-scale permanent cropland	6.2	3.8
3	High-intensity arable cropland	13.4	7.5
4	Medium-intensity arable cropland	17.6	11.9
5	Low-intensity arable cropland	10.3	6.2
6	Fallow farmland	1.0	3.9
7	High-intensity livestock farming	8.2	0.9
8	Medium-intensity livestock farming	8.2	4.0
9	Low-intensity livestock farming	9.3	5.9
10	Low-intensity grassland area	11.3	9.2
11	High-intensity forest	1.0	8.3
12	Low-intensity forest	2.1	19.3
13	High-intensity agricultural mosaic	5.2	4.5
14	Low-intensity mosaic	5.2	11.5
15	Urban built up	0.0	1.8

[1] Regional/national scale studies (n=34) were excluded from analysis to appreciate the spatial resolution (3x3 km cell size) of the land system archetype data. Also, case study sites not spatially covering the LSA data (n=7, e.g. studies located in Switzerland) were excluded.

Of the data used in the studies, 70% were derived from primary data sources, mainly from field measurements (50% of all data sources) and surveys, questionnaires and interviews (13%) (Figure 6). Aerial photographs and satellite imagery (4%), participatory observation or participatory fieldwork (2%) and focus groups or workshops (1%) were not widely applied. The remaining 30% consisting of secondary data sources include statistics and other official databases (16%) and cartographical data (13%).

The applied indicators for ecosystem service assessment are dominated by biophysical indicators (80%), followed by monetary (13%), ranking (4%), and policy (1%) indicators or the combination of the previous (1%) (Figure 6). The only study applying mixed indicators combines biophysical, monetary and ranking (Borin et al., 2010) and the only one applying policy indicators uses official databases to find indicators on supranational policies and regional institutional structures (Thiel et al., 2012). Biophysical indicators are especially related to studies measuring one indicator, and monetary or mixed indicators applied in the studies including two to five indicators (Figure 7). Studies that adopt six or more indicators apply biophysical, ranking, or policy indicators. Subsequently, around one fifth (17%) of the studies apply monetary valuation, mainly market price and cost approaches (90% of studies applying monetary valuation) or contingent valuation (27%) (Figure 6). Choice experiments (Hasund et al., 2011) and deliberative valuation (Johansson, 1995) are both applied in one study. Additionally, some studies (7%) undertake non-monetary valuation, which can include ranking of importance of ecosystem services and sceneries in landscape photographs.

Mapping of ecosystem services is rarely adopted and only used in 14% of studies. Also, ecosystem service trade-off analysis is applied only in a few studies (6% of studies) and analysis of service bundles is even less common (1%, Palma et al., 2007) (Figure 6). Scenario analysis is performed in 11% of studies with the main approaches of behavioural scenarios applied in seven studies and scenarios addressing behavioural changes and climate change in one study. Active involvement of stakeholders in the design, implementation or analysis of the scientific research regarding ecosystem services is rare (1%). It is applied in one study, where the local level landscape users (farmers, shepherds, entrepreneurs, hobby gardeners, local policy makers) assessed the possible future drivers of cultural landscape changes and their likely impacts on ecosystem services provision through stakeholder-based scenarios (Plieninger et al., 2013).

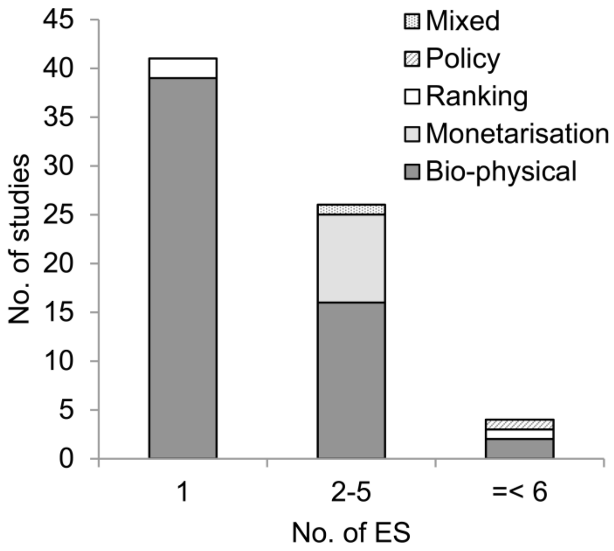

Figure 7. Number of studies according to the number of ecosystem services assessed with the applied indicators for ecosystem service assessment.

3.3.4 Relationships between ecosystem service assessments and research approaches around European agroforestry

In the cluster analysis we identified four groups of publications. The largest cluster A (n=25) has the majority of publications with the principal focus being Mediterranean wood pastures and woodlots and scattered farm tree systems in Continental and other biogeographical regions (e.g. Boreal and Alpine) (Figure 8). Quantitative methodologies and biophysical approaches based on field measurements for the assessment of mostly a combination of different ecosystem services or only regulating and supporting services, including provision of habitat and biodiversity, nutrient cycling, soil formation and retention, climate regulation, food, and fiber, are dominant (e.g. Corral-Fernandez et al., 2013; Garcia-Tejero et al., 2013; Hussain et al., 2009; Lozano-Garcia & Parras-Alcantara; 2013, Moreno Marcos et al., 2007). In addition, monetary approaches and especially use of mixed data sources, such as surveys, questionnaires, interviews and statistics, are found in group A. These are applied in the assessment of multiple especially provisioning and cultural ecosystem services including food, fuel, fiber, and recreation and ecotourism (Campos & Caparros, 2006; Campos et al., 2007; Campos et al., 2008; Fernandez-Nunez et al., 2007; Hasund et al., 2011; Johansson, 1995).

In the second largest group B (n=21) the majority of publications have a dominance of quantitative methodologies and biophysical approaches based on field measurements to study mainly wood pastures in the Mediterranean and Continental regions (Foldesi & Kovacs-Hostyanszki, 2014; Graves et al., 2007; Guerra et al., 2014; Joffre & Rambal, 1993; Parras-Alcantara et al., 2014). Group B also includes publications addressing the assessment of cultural services, such as aesthetic values, recreation, cultural heritage values and knowledge systems, approached through surveys, questionnaires, interviews, participatory observation and participatory fieldwork by applying ranking and monetary indicators (Babai & Molnar, 2014; Campos et al., 2009; Franco et al., 2003; Gomez-Limon & Lucio Fernandez, 1999).

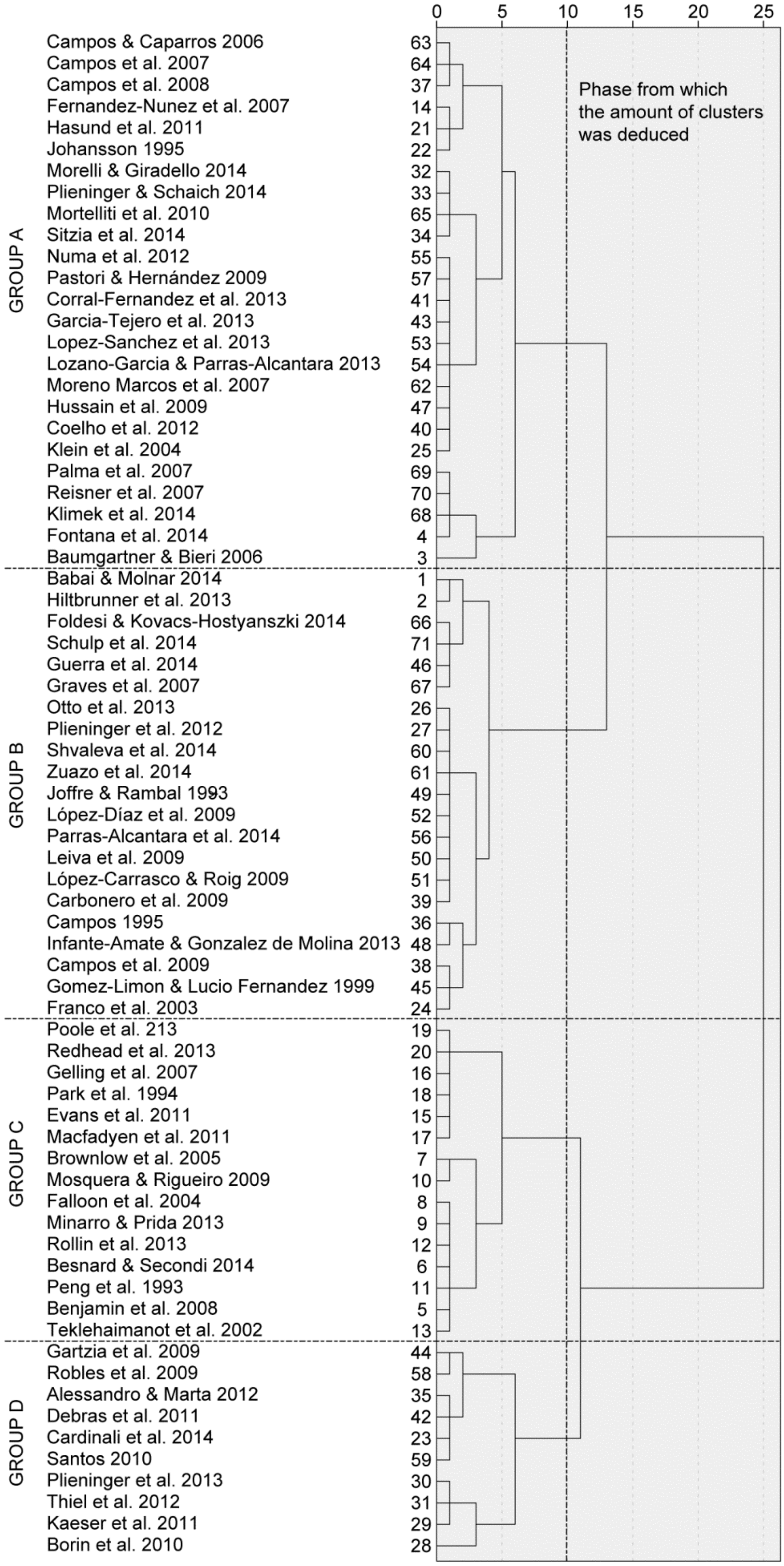

Figure 8. Dendrogram showing the four groups of publications deduced from the cluster analysis.

Group C (n=15) comprises exclusively Atlantic agricultural mosaic landscapes with mainly hedgerow, woodlot and scattered farm tree systems. These are approached through field measurements of biophysical indicators to assess regulating, supporting and provisioning ecosystem services, such as provisioning of habitat and biodiversity and pollination (e.g. Gelling et al., 2007; Macfadyen et al., 2011; Minarro & Prida, 2013; Rollin et al., 2013).

Group D (n=10) addresses Continental and Mediterranean silvoarable and silvopastoral systems, including riparian buffer strips, orchards, forest grazing, hedgerows and modern agroforestry systems. Ecosystem service assessment of these systems is characterised by field measurements of biophysical indicators for regulating or supporting services, e.g. for the provision of habitat and biodiversity, fire hazard prevention, and soil formation (Alessandro & Marta, 2012; Cardinali et al., 2014; Robles et al., 2009). However, focus groups and official databases have also been used to measure a diversity of ecosystem services through policy and ranking indicators (Plieninger et al., 2013; Thiel et al., 2012).

3.4 Discussion

This review has been motivated by calls for multifunctional landscapes and land-use systems (O'Farrell & Anderson, 2010; Wu, 2013) in which agroforestry plays a major role. We revealed a substantial and rapidly growing number of studies on agroforestry and ecosystem services in Europe. However, this body of literature is small when compared to the vast extent of agroforestry lands in Europe. Hotspots of research were Mediterranean Europe, the UK, and France (Fig. 2), whereas agroforestry systems in the Nordic Countries and Eastern Europe (e.g., the diverse wood pasture systems described by Bergmeier et al., 2010) received little attention. A broad range of agroforestry systems was considered, both silvopastoral and silvoarable systems and intensively and extensively managed systems (Fig. 4). While grassland, livestock, and arable cropland systems were well-covered, the role of agroforestry in forest lands and land mosaics of different intensities were clearly understudied (Table 1).

To incorporate ecosystem services into decision making around land use is a commonly identified challenge (Maes et al., 2013; Nieto-Romero et al., 2014; Robertson & Swinton, 2005). At the same time, public policies (for example, the Common Agricultural Policy (CAP) and in particular the rural development programmes of the EU) offer options to enhance rural development through the establishment of agroforestry. The conceptual framework by Daily et al. (2009) specifies leverage points for mainstreaming ecosystem services into decision making along five key nodes, comprising of *Decisions, Ecosystems, Services, Values*, and *Institutions.* Three key actions have been defined for each link between the nodes (Daily et al. 2009). In the following, we use this framework to identify the key limitations of current agroforestry research on ecosystem services (as revealed by our systematic review) and to reflect on how agroforestry research can contribute more comprehensively to decision making on ecosystem services.

3.4.1 Decisions → Ecosystems: Actions and scenarios

The first action in the Daily et al. (2009) framework stresses that to inform decisions that affect ecosystems, (1) collaboration with stakeholders that define important scenarios of alternative future uses of land, water, and other natural resources is needed. Also, there is a need for (2) improved methods for assessing the current condition, and predicting the future condition, of ecosystems and (3) state-of-the-art programs for long-term monitoring of biodiversity and other ecosystem attributes.

The agroforestry research covered in our review frequently identified direct and indirect drivers of ecosystem change (Fig. 4), but both long-term monitoring and forward-looking scenario development was rare (Fig. 6) and the number of ecosystem services addressed was small (Fig. 7). Future research could provide the needed information by putting stronger focus on ecosystem services provision under alternative future policy and/or behavioural scenarios in collaboration with stakeholders, following established standards (Oteros-Rozas et al., in press).

This requires, firstly, a proper inclusion of agroforestry into existing European monitoring systems such as LUCAS (Land Use and Land Cover Aerial Frame Survey) and CORINE (Coordination of Information on the Environment) land cover data (den Herder et al., 2015). Formal designations of land use and cover in the EU are typically separated into land which falls within the remit of the CAP, and areas such as woodland and forests which do not. This artificial separation has limitations as the integration of trees with agriculture frequently provides landscape-level benefits such as enhanced biodiversity, runoff control, and soil conservation (Jakobsson & Lindborg, 2015; King, 2010; Plieninger et al., 2015). A better way would be to monitor agroforestry practices within a continuum of agriculture and forestry systems.

Secondly, agroforestry assessments need to include a broader set of ecosystem services. Agroforestry studies frequently measure the efficiency of agroforestry through "land equivalent ratios" (Graves et al., 2010), which are based on only two or three provisioning services. More comprehensive metrics that also account for cultural, regulating, and supporting services are needed and stakeholder involvement to define future scenarios for these. The approach by Agbenyega et al. (2009) which (focusing on community woodlands) also included ecosystem dis-services could be applied more generally to agroforestry as well (dis-services considered as "negative" aspects of regulating, provisioning, supporting and cultural services. i.e. an increase in recreational use of an area usually involves an increase of dog excrement and litter disposal) For regions rich in agroforestry (such as Mediterranean Europe) such assessments of biodiversity and ecosystem services may be advanced toward long-term monitoring programs that would allow longitudinal studies. Also, better use should be made of data repositories of completed agroforestry studies to share information (cf. Crossman et al., 2013).

3.4.2 Ecosystems → Services: Biophysical models

According to the Daily et al. (2009) framework, translation of ecosystem condition and function into ecosystem services (1) requires collaboration with stakeholders to define services that people care about. It also builds on (2) development of transparent, flexible models of ecological production functions at scales relevant to decision making and testing, and (3) refining of these models in different social and agro-ecological zones.

Stakeholder involvement was very low in the agroforestry studies we reviewed (Fig. 6). Also studies were mostly performed at plot to local scales, and typically in one study site only. Compared to broader ecosystem service assessments (Seppelt et al., 2010), mapping approaches received minimal attention in agroforestry research. As ecosystem services are per definition the benefits provided by ecosystems to society (MA, 2005), future agroforestry research has to build more strongly on the participation of farmers, landowners, residents, and other relevant actors (cf. Díaz et al, 2015; Scholte et al. 2015; Seppelt et al., 2011). Such collaboration is promoted, for example, through landscape-level stakeholder workshops (such as those established in EU FP7 project AGFORWARD, http://www.agforward.eu/index.php/en/). More citizen science approaches that appreciate the capabilities of various actors to collect valuable data as citizen sensors or share their local knowledge (including traditional ecological knowledge, land management practices and experiential knowledge dealing with landscape values) related to ecosystem services would be helpful as well.

Currently, it is not clear which agroforestry practices contribute which kinds of ecosystem services and at what levels of provision, with some agroforestry systems being more multifunctional than others. Production models of agroforestry (such as Farm-SAFE and Yield-SAFE, cf. Graves et al., 2007) do exist, but they need to be advanced toward the inclusion of a broad and relevant set of ecosystem services at multiple spatial scales. To match the scales of decision making, upscaling of insights to national and EU levels is particularly required. Stronger development of mapping approaches is another desideratum to help creating spatially explicit models of service supply and demand across spatial and temporal scales (Crossman et al., 2013; Martínez-Harms & Balvanera, 2012; Willemen et al., 2015).

In addition, it would be beneficial to establish Pan-European networks of study sites that include land management practices of different types and intensities within varying biogeographical settings to refine existing models and to obtain generalized insight into ecosystem services provision from agroforestry.

3.4.3 Services → Values: Economic and cultural values

In order to make the societal value of an ecosystem explicit, according to the Daily et al. (2009) framework (1) direct biophysical measurements need to be complemented with monetary and socio-cultural valuation at the spatial and temporal scales that are relevant for decision-making. Also, (2) developing non-monetary methods for valuing human health and security, and cultural services, and incorporating these in easy-to-use, easy-to-understand, but rigorous tools for valuing ecosystem services is required. Another need is (3) the development of methods for identifying who benefits from ecosystem services, and where and when those who benefit live relative to the lands and waters in question.

Our review confirms that agroforestry followed the larger trend of ecosystem services research (as observed by Vihervaara et al., 2010) of generally focusing on regulating, supporting, and provisioning services, while paying less attention to cultural services, which are mainly limited to assessments of aesthetic values (Fig. 3). Also, there was a strong dominance of biophysical assessment approaches and indicators, and a low representation of monetary and socio-cultural approaches and indicators (Fig. 6). Trade-offs and bundles among ecosystem services were rarely analyzed (Fig. 3). For more comprehensive understanding of the importance of ecosystem services, empirical research should be directed to a wider variety of research approaches and to a wider coverage of ecosystem services (Martín-López et al., 2014). There is a clear need for more studies of cultural ecosystem services and also for the direct contributions of agroforestry to human well-being (e.g. in terms of public health benefits), with inspiration derived from the various methods and indicators developed (cf. Hernández-Morcillo et al., 2013; Milcu et al., 2013). Identifying service trade-offs between land management practices, assessing ecosystem services for particular actor groups, and analyzing bundles of ecosystem services may be one important way toward understanding how different stakeholders have access to and benefit from ecosystem services (Felipe-Lucía et al., 2015). Studies considering trade-offs and bundles allow better understanding of the complex dynamics, interactions, resilience, and adaption of landscape structure into functions and finally to valued benefits (Setten, 2012; Termorshuizen & Opdam, 2009). They are also a prerequisite for expanding current production models toward social-ecological production functions that take into account the social factors underpinning ecosystem services (Reyers et. al., 2013).

3.4.4 Values → Institutions: Information

To embed the values of ecosystems in institutions, the Daily et al. (2009) framework calls for (1) piloting initiatives that include incentives for the protection of ecosystem services and fostering recognition of the value of these services. It also demands (2) determining the merits and limitations of various policy and finance mechanisms and (3) developing institutions to achieve representation and participation by stakeholders.

The body of literature that we reviewed generally did not elaborate such initiatives. This topic is nevertheless relevant for agroforestry, as institutional changes toward agroforestry often do not generate direct benefits for land users and landowners, which typically depend on marketed provisioning services. To foster change toward agroforestry, markets need to be developed for the specific ecosystem services provided by agroforestry as identified in this review. This comprises existing products (e.g., jamón ibérico from Spanish wood pastures or apple juice from orchard meadows), brands, development of labels (e.g., organic agriculture, Forest Stewardship Council, protected geographic origin), and a general move toward “landscape labelling” (Ghazoul et al., 2009). There are also excellent examples of upscaling of existing pilot initiatives (e.g. by integrating forest certification, high conservation value, and payment for ecosystem services conservation tools in Mediterranean cork oak savannas, Bugalho et al., 2011; Bugalho & Silva, 2014; Dias et al., 2015).

Various policy and finance mechanisms can also be capitalized on. For example, the capacity of agroforestry practices to enhance ecosystem service provision can be encouraged through public policies such as the EU Biodiversity Strategy to 2020 (the major strategy of the EU to protect biodiversity and ecosystem services). The second target of the strategy, out of six, is to ‘maintain and restore ecosystems and their services (incorporation of green infrastructure in spatial planning)’, and the third target is to ‘increase the contribution of agriculture and forestry to biodiversity’ (EU, 2011). Also, agricultural support schemes, such as the CAP, can promote practices such as agroforestry toward co-delivery of ecosystem services and multifunctional land use (e.g., Plieninger et al., 2012). The legal and administrative separation between agriculture and forestry in current EU thinking (and in current monitoring systems, as described above) is a limitation to such efforts. An example of policy mechanism which forms a particularly important barrier for agroforestry is the limited eligibility of wood-pastures for receiving CAP subsidy payments (Plieninger et al., 2015). Here, not only the EU, but also member states should use more flexibility to create a supportive framework for agroforestry.

3.4.5 Institutions → Decisions: Incentives

To understand the incentives by institutions that promote decision making incorporating the role of ecosystem services, Daily et al. (2009) suggest: (1) enlarging the discussion and inquiry into what motivates people and how social norms evolve, especially when the context of nature is required. Also, (2) incorporating traditional knowledge and practices into modern conservation approaches and (3) developing a broader vision for conservation are proposed.

Though these guidelines are much broader in scope than our systematic review, we suggest that more research on the connections between values and land management actions is needed for an improved uptake of agroforestry practices by farmers, focusing on collaboration, capacity-building and learning. Financial flows and tangible incentives motivating behaviour towards fostering ecosystem services and conservation may be especially important for business-minded land managers and farmers (Raymond et al., 2015). Also, as mentioned above, practical / local / traditional / non-scientific knowledge in agroforestry and ecosystem service assessments could be acknowledged more widely (Hernández-Morcillo et al., 2014; Turnhout et al., 2012). This calls for participation of various stakeholders, including different age groups, ethnicities, and power asymmetries.

3.5 Conclusions

Agroforestry has been recognized as a sustainable land management practice that realigns commodity production with safeguarding ecosystem services (Jose, 2009), but research on the linkages between agroforestry and ecosystem services has not been fully explored. Reviewing published literature from Europe, we provide a systematic insight into this research field. Agroforestry and ecosystem services are mission-oriented research fields. For successful up-take by land use policy and practice, insights from research on ecosystem services need to meet the requirements of individuals, communities, corporation, and governments making decisions. Advancing the directions by Daily et al. (2009) (and specifying these directions for European agroforestry), we propose that the following key actions can contribute to making future agroforestry research more relevant for decision making:

- Stronger consideration of stakeholder participation to define, map, value, and foster ecosystem services;
- Introduction of spatially explicit mapping into agroforestry research, building on existing platforms such as InVEST (www.naturalcapitalproject.org);
- Adoption of multiscale and upscaling approaches that particularly address the scales of national and EU policy making;
- Diversification of assessment approaches and methods that go beyond biophysical assessment and monetary valuation;
- Coverage of a broader suite of ecosystem services, in particular integration of cultural ecosystem services and aspects of human well-being as well as consideration of trade-offs, synergies, bundles, beneficiaries, and power relations around ecosystem services.

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APPENDIX A for Fagerholm et al (2016): Search terms applied in the review**.**

Publication search for the review consisting of three search strings with the following search terms applied to title, abstract and keywords in the specified databases:

1) Agroforestry and related definitions:
   agroforestry OR silvoarable OR silvopastoral OR agrosilvopastoral OR "farm woodland*" OR "forest farming*" OR "forest grazing" OR "grazed forest*" OR "isolated trees" OR "scattered tree*" OR "tree outside forest*" OR "farm tree*" OR woodlot* OR "timber tree system" OR dehesa OR montado* OR "oak tree*" OR "olive tree*" OR "fruit tree*" OR pré-verger OR Streuobst OR pomarada* OR Hauberg OR Joualle OR "orchard system" OR "orchard intercropping" OR parkland* OR "alley cropping" OR "wooded pasture*" OR "wood pasture*" OR pollarding OR "fodder tree*" OR pannage OR hedgerow* OR windbreak* OR "riparian woodland*" OR "riparian buffer strip*" OR "buffer strip*" OR "riparian buffer*" OR "shelter belt*"

2) Ecosystem services and related definitions:
   "ecosystem service*" OR "ecosystem function*" OR "ecosystem good*" OR "ecosystem benefit*" OR "ecosystem value" OR "ecosystem valuation" OR "environmental service*" OR "environmental function*" OR "environmental good*" OR "environmental benefit*" OR "environmental value"

3) Europe and specific countries:
   Europe* OR EU OR Albania OR Andorra OR Armenia OR Austria OR Azerbaijan OR Belarus OR Belgium OR "Bosnia and Herzegovina" OR Bulgaria OR Croatia OR Cyprus OR Czech* OR Denmark OR Estonia OR Finland OR France OR Georgia OR Germany OR Greece OR Hungary OR Iceland OR Ireland OR Italy OR Kazakhstan OR Latvia OR Liechtenstein OR Lithuania OR Luxembourg OR Malta OR Moldova OR Monaco OR Montenegro OR Netherlands OR Norway OR Poland OR Portugal OR Romania OR Russia OR "San Marino" OR Serbia OR Slovak* OR Slovenia OR Spain OR Sweden OR Switzerland OR Macedonia OR Turkey OR Ukraine OR "United Kingdom" OR England OR Wales OR Scotland

APPENDIX B for Fagerholm et al (2015): List of the 71 publications included in the review.

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APPENDIX C for Fagerholm et al (2015): Data extraction variables applied for each publication included in the review. Column Cluster analysis indicates whether the variable was included in the clustering or not.

Variable	Description and/or source	Classes	Reference	Cluster analysis
Publication characteristics				
Author	Author(s)	1-n		No
Type of publication	Type of publication	Journal Article Book Section		No
Year	Year in which the study was published	1990-2014		No
Study location and context				
Biogeographical region	Biegeographical regions in Europe	Alpine Anatolian Arctic Black Sea Continental Macaronesia Mediterranean Pannonian Steppic Atlantic Boreal Mixed	EEA, 2011	Yes
Country	Country in which the study area is located	Text		No
Number of study sites	Number of study sites considered in the study	1-n		No
Comparative site	Comparative assessment of ecosystem service(s) in agriculture and forestry systems	Agriculture Forestry Agriculture and forestry Another agroforestry system No		No

Characteristics of agroforestry system				
System border definition	Definition of the limits of the study area(s)	Administrative Bio-physical Both Other	Nieto-Romero et al., 2014	No
Agroforestry system	Main agroforestry types. Hedgerows includes clear hedgerows, Woodlots and scattered farm trees includes mosaic landscapes where hedgerows can also exist, and Orchards includes fruit tree meadows.	Wood pastures Hedgerows Forest grazing Orchards Woodlots and scattered farm trees Riparian buffer strip Modern Agroforestry systems	Mosquera-Losada et al., 2009; Nerlich et al., 2013	Yes
Spatial scale of the study	Scale of the study site(s); patch less than 1 km2, local 1 - 10 km2, more than 10 km2	Patch Local Regional/national		No
Productive management	Type of productive management	Intensive Extensive Organic Mixed N/A	Nieto-Romero et al., 2014	No
Drivers of change	Natural or anthropogenic factors that directly or indirectly cause an ecosystem change <u>explicitly stated by the authors.</u> Direct (improper management and overexploitation of resources, land use/cover change, climate change, pollution, invasive species), Indirect (socio-political, economic, science and technology, demographic, culture and religion)	Direct Indirect Both N/A	MA, 2005; Milcu et al., 2013; Nieto-Romero et al., 2014	

Methodological approach				
Method	Method for ES identification/elicitation	Quantitative Qualitative Mixed	Milcu et al., 2013	Yes
Approach	Approach for ES assessment based on three approaches for assessing ecosystem services: biophysical, socio-cultural and monetary (Groot et al. 2002, Cowling et al. 2008)	Bio-physical Socio-cultural Monetary Mixed approaches	Nieto-Romero et al., 2014	Yes
Category of ES	ES catogorised as in MA (2005) typology	Provisioning Regulating Cultural Supporting Mixed	Nieto-Romero et al., 2014; Seppelt et al., 2011	Yes
Ecosystem service	Ecosystem service by MA typology	P1 Food P2 Fresh water P3Fuel P4 Fiber P5 Biochemicals, natural medicines and pharmaceuticals P6 Genetic resources P7 Ornamental species R1 Climate regulation R2 Air quality maintenance R3 Water regulation R4 Erosion control R5 Water purification and waste treatment R6 Regulation of human diseases R7 Biological control	MA, 2005	No

		R8 Pollination R9 Storm protection R10 Fire hazard prevention C1 Cultural diversity C2 Spiritual and religious values C3 Knowledge systems (traditional and formal) C4 Educational values C5 Inspiration C6 Aesthetic values C7 Social relations C8 Sense of place C9 Cultural heritage values C10 Recreation and ecotourism S1 Soil formation and retention S2 Nutrient cycling S3 Primary production S4 Water cycling S5 Production of atmospheric oxygen (photosynthesis) S6 Provisioning of habitat		
Number of ecosystem services assessed	Defined by authors and based on the defined classification for the review, the authors of an article might use an alternative classification system	1-n	Nieto-Romero et al., 2014; Seppelt et al., 2011	No
Data source	Data source (main)	Field measurements Surveys/questionnaires Interviews	Nieto-Romero et al., 2014; Seppelt et al., 2011	Yes

		Aerial photographs Satellite images Cartographical data Statistics Census data Other official databases Participatory observation Participatory fieldwork Focus group / workshop		
Applied indicator	Indicators used for the assessment: Bio-physical (bio-physical quantities e.g. kilogram/year pollen transported by pollinators, tonnes/year sediment lost by erosion), ranking (e.g. which ecosystem service has been rated highest by experts/policy makers/the general public), monetary (monetary value for the service produced)	Bio-physical Ranking Monetary Policy Mixed	Seppelt et al., 2011	Yes
Economic valuation	Undertake and applied method for economic valuation	Contingent valuation Market price and cost approaches Travel cost method Hedonic pricing Benefits transfer Choice experiment Deliberative valuation None	Milcu et al., 2013	No
Non-economic valuation	Undertake of non-economic valuation	Yes No	Milcu et al., 2013	No
ES mapping	Undertake of ES mapping	Yes No	Milcu et al., 2013	No
ES trade-off analysis	Undertake of ES trade-off analysis	Yes	Milcu et al., 2013	No

		No		
ES bundle analysis	Undertake of analysis of ES bundles	Yes No	Milcu et al., 2013	No
Scenario analysis	Undertake of and applied approach for scenario analysis: Policy scenarios, behavioural scenarios (which assume a behavioural change by the people using the service or threatening the service, e.g. a change of the fishing strategy or a change in the intensity of land use), demographic scenarios and climate change scenarios	Policy scenario Behavioural scenario Demographic scenario Climate change scenario Mixed No	Nieto-Romero et al., 2014; Seppelt et al., 2011	No
Stakeholder involvement	Actively involving stakeholders (e.g. residents or institutions in the study area) in the design, implementation or analysis of the scientific research regarding ES	Yes No	Milcu et al., 2013; Nieto-Romero et al., 2014; Seppelt et al., 2011	No

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4 Paper 2: Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis

This is a pre-print version of the following paper:

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Abstract

Agroforestry has been proposed as a sustainable agricultural system over conventional agriculture and forestry, conserving biodiversity and enhancing ecosystem service provision while not compromising productivity. However, the available evidence for the societal benefits of agroforestry is fragmented and does often not integrate diverse ecosystem services into the assessment. To upscale existing case-study insights to the European level, we conducted a meta-analysis on the effects of agroforestry on ecosystem service provision and on biodiversity levels. From 53 publications we extracted a total of 365 comparisons that were selected for the meta-analysis. Results revealed an overall positive effect of agroforestry (effect size=0.454, $p<0.01$) over conventional agriculture and forestry. However, results were heterogeneous, with differences among the types of agroforestry practices and ecosystem services assessed. Erosion control, biodiversity, and soil fertility are enhanced by agroforestry while there is no clear effect on provisioning services. The effect of agroforestry on biomass production is negative. Comparisons between agroforestry types and reference land-uses showed that both silvopastoral and silvoarable systems increase ecosystem service provision and biodiversity, especially when compared with forestry land. Mediterranean tree plantation systems should be especially targeted as soil erosion could be highly reduced while soil fertility increased. We conclude that agroforestry can enhance biodiversity and ecosystem service provision relative to conventional agriculture and forestry in Europe and could be a strategically beneficial land use in rural planning if its inherent complexity is considered in policy measures.

Keywords: land use management, systematic review, silvopastoral systems, silvoarable systems, agroecosystem

4.1 Introduction

Agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions (Mosquera-Losada et al., 2009). Agroforestry has played an important role in Europe in the past, and traditional agroforestry practices, such as wood pasture and grazed or intercropped orchards, are still practised widely in Europe (Mosquera-Losada et al., 2009). However, during the 20th century, the area of many European agroforestry systems decreased while the remaining agroforestry practices are vulnerable (Nerlich et al., 2013). The Common Agricultural Policy (CAP) and other public policies have frequently accelerated a transition to specialised forms of agriculture and forestry (van Zanten et al., 2013).

The requirement to conserve biodiversity has been agreed on at an international level, and the Europe 2020 strategy for a "resource efficient" Europe (European Comission, 2011) highlights the necessity of protecting, valuing, and restoring biodiversity and ecosystem services. One of the key concepts for examining the interactions between biodiversity and ecological systems such as agriculture and forestry is the ecosystem service framework (Millennium Ecosystem Assessment, 2005). This framework highlights how biodiversity leads to a range of services that benefit human well-being, including food and fibre production and regulating and cultural services.

The need to combine production with environmental enhancement can provide an opportunity for a renaissance of agroforestry. Agroforestry can sometimes increase land productivity as the combination of tree and crop systems leads to a more efficient capture of resources (such as solar radiation or water) than separated tree or crop systems (Cannell et al., 1996, Graves et al., 2007, Jose 2009). However neutral and negative interactions have been also reported (e.g. Jose et al., 2004; Rivest et al., 2013). Agroforestry has also been found to improve regulating ecosystem services such as nutrient retention, erosion control, carbon sequestration, pollination, pest control and fire risk reduction, and cultural services such as an increase in recreational, aesthetic, and cultural heritage values (McAdam et al., 2009; Smith et al., 2012; Tsonkova et al., 2012). In line with this, in 2005, the European Union provided opportunity for national and regional governments to financially support the establishment of new agroforestry systems (European Union 2013).

The interactions between biodiversity, ecosystem services, and agroforestry have been previously explored. Tsonkova et al. (2012) reviewed the ecosystem services supplied by alley cropping in temperate regions, but this is only one type of agroforestry. Lorenz and Lal (2014) described the role of agroforestry systems in soil carbon sequestration estimating that agroforestry might may be sequestering up to 2.2 Pg of Carbon above- and belowground over 50 years, but did not consider other ecosystem services. After two decades of research on agroforestry functioning in Europe, the aim of this paper is to report on a formal meta-analysis of the evidence that agroforestry systems increase the provision of ecosystem services in Europe compared to other conventional agriculture and forestry systems. Within the ecosystem service framework used by the Millennium Ecosystem Assessment (2005), biodiversity is assumed to be the source of ecosystem services. Schneiders et al. (2012) describes biodiversity and ecosystem service provision as being intricately linked, and within the UK National Ecosystem Assessment (2011) wild species diversity is included as a provisioning/cultural service. Hence this current study considers both biodiversity and ecosystem services in relation to agroforestry. It is anticipated that this analysis will help to identify the generality of existing case-study findings and the presence of large scale patterns. Specifically we raise the following research questions:

Does European agroforestry enhance biodiversity and ecosystem services relative to conventional agriculture or forestry (natural and planted forest)?

Which species groups and which categories of ecosystem services are most supported by agroforestry?

What differences arise among different kinds of agroforestry (e.g. silvoarable systems, silvopastoral agroforestry)?

Do biophysical system properties such as temperature and precipitation drive inter-site differences?

This study can contribute to empower agroforestry towards future agricultural policies providing policy makers and practitioners concrete examples where agroforestry could be a sustainable solution over conventional agriculture and forestry.

4.2 Material and methods

4.2.1 Study selection

The methodology followed existing guidelines for systematic review and literature mapping (Pullin & Stewart, 2006; Pullin & Knight, 2009; Centre of Evidence-based Conservation, 2010; Bilotta et al., 2014). The benefit of a systematic review, as opposed to one unsystematic, is that it uses a process that is more objective and transparent. A review protocol was produced following recommendations describing the systematic literature search and inclusion criteria (Annex A). The systematic literature mapping sought to include all scientific publications that provide quantitative data comparing agroforestry with an alternative land use system in a European study area and using indicators that assess biodiversity and ecosystem services (Table 1).

Table 1. Inclusion criteria

Agroforestry systems	Every kind of system that follows this definition: agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions. This means that the following systems were included: silvoarable systems, silvopastoral agroforestry, agro-silvopastoral systems, buffer strips (which use woody elements) and multipurpose trees systems (Mosquera-Losada et al., 2009).
Types of comparable land use	The compared system must be a conventional farmland or a forestry system with very low cover of agroforestry within the same region.
Geographical scope	The study areas were limited to Europe in a geographical sense
Methodologica approach	Only studies that perform quantitative biodiversity and ecosystem service assessment based on primary data.

Initially, the meta-analysis aimed to analyze the effect of agroforestry on the provision of ecosystem services categories present in the Millennium Ecosystem Assessment (Annex A). However, we early found in initial tests that our analysis would need to be narrowed due to a lack of primary studies analyzing the effect of agroforestry on many ecosystem service categories. The need of at least three primary studies targeting the same ecosystem service reduced the initial scope which included a wider range of ecosystem services (including air and water purification, pollination, pest regulation and all cultural ecosystem services) to the final selection: timber production, food production, biomass production, soil fertility and nutrient cycling, erosion control and biodiversity.

The literature search was performed in August 2014 by generating combinations of keywords in three databases: ISI Web of Science, SCOPUS and CAB Abstracts. We additionally included the first 50 documents provided by Google Scholar and in the end of the process added five papers recommended by three experts in the field. The systematic search included three strings in English: 1) definitions and terms used to describe European agroforestry systems, 2) terms describing ecosystem services and biodiversity indicators used to measure them, and 3) Europe and a set of European countries (Table 2). Titles and abstracts were stored in an EndNote database where duplicates were removed. To ensure the inclusion criteria were consistently followed during the publication selection process, a 10% subset of the whole database was assessed by an independent reviewer.

Table 2. Search terms applied to title, abstract and keywords in the specified databases

Search string	Terms
1	agroforestry OR silvoarable OR silvopastoral OR agrosilvopastoral OR “farm woodland*” OR “forest farming*” OR “forest grazing” OR “grazed forest*” OR “isolated trees” OR “scattered tree*” OR “tree outside forest*” OR “farm tree*” OR woodlot* OR “timber tree system” OR dehesa OR montado OR “oak tree*” OR “olive tree*” OR “fruit tree*” OR pré-verger OR Streuobst OR pomarada* OR Hauberg OR Joualle OR “orchard system” OR “orchard intercropping” OR parkland* OR “alley cropping” OR “wooded pasture*” OR “wood pasture*” OR pollarding OR “fodder tree*” OR pannage OR hedgerow* OR windbreak* OR “riparian woodland*” OR “riparian buffer strip*“ OR “buffer strip*” OR “riparian buffer*” OR “shelter belt*”
2	Product* OR Provision* OR “Soil formation” OR “soil organic carbon” OR “soil carbon” OR “soil C” OR “soil organic C” OR SOC OR “carbon pool” OR “carbon stock” OR “carbon storage” OR “soil organic matter” OR SOM, “carbon sequestrat*” OR “C sequestrat*” OR “Nutrient cycling” OR “Nutrient retention” OR “soil services” OR Nitrogen OR Phosphorus OR Erosion OR “soil loss” OR "water quality" OR "water regulation" OR "water purification" OR "hydrological regulation" OR Biodiversity OR richness OR “species abundance” OR “species composition” OR “biological diversity”
3	Europe* OR EU OR Albania OR Andorra OR Armenia OR Austria OR Azerbaijan OR Belarus OR Belgium OR “Bosnia and Herzegovina” OR Bulgaria OR Croatia OR Cyprus OR Czech* OR Denmark OR Estonia OR Finland OR France OR Georgia OR Germany OR Greece OR Hungary OR Iceland OR Ireland OR Italy OR Kazakhstan OR Latvia OR Liechtenstein OR Lithuania OR Luxembourg OR Malta OR Moldova OR Monaco OR Montenegro OR Netherlands OR Norway OR Poland OR Portugal OR Romania OR Russia OR “San Marino” OR Serbia OR Slovak* OR Slovenia OR Spain OR Sweden OR Switzerland OR Macedonia OR Turkey OR Ukraine OR “United Kingdom” OR England OR Wales OR Scotland

The final number of primary studies included in the analysis was refined through a three-step process: 1) the title and keywords, 2) the abstracts and 3) the full publication content. In each phase, publications that fulfilled the inclusion criteria (Table 1) were promoted to the next step. The initial search provided a total of 5,235 publications that after the first filter were narrowed down to a total of 604 publications. Ultimately, 53 publications were included in the meta-analysis.

4.2.2 Data collection

A meta-analysis compares the quantitative outcomes of different treatments in multiple studies. The contrast between the means is used to summarize the results of the primary studies. Ideally, three values are necessary for this comparison: a mean, a standard deviation and a sample size. Values of each group were extracted directly from the text and tables, taken indirectly from graphs using the DataThief (Tummers, 2006) software, or calculated from raw data when the summary statistics were missing but the original data available. Standard errors were not available in several studies but some were obtained after contacting the authors. Most studies included comparisons of more than one land use or more than one indicator. We considered each comparison as an independent observation in the primary study and use the primary studies as a random factor to control potential correlations between comparisons within a primary study.

For every data record, we derived eight explanatory variables (nine variables in cases where biodiversity was assessed, c.f. Table 3) that served to characterize the properties of those observations and were used as independent variables grouping similar studies in the analysis. If temperature and precipitation were not available in the publication, the study location was used to gather the information from other sources (Global Climate Data - WorldClim, Google Earth). We found that many publications, while not assessing a particular agroforestry system, were interested in comparing two areas or landscapes where the main difference was the high/low proportion of agroforestry. These publications were classified under the category of “mixed” for the explanatory variable of agroforestry system type. Although the search strings included terms for agro-silvopastoral systems, buffer strips, and multipurpose trees systems, there were insufficient publications to include these types in the analysis (View Review Protocol, Annex A). This meant that the final categories analyzed for the variable agroforestry system were silvopastoral (trees and livestock), silvoarable (trees and arable crops) and mixed.

Table 3. Explanatory variables extracted from the primary studies and other data sources that were included in the meta-analysis

Explanatory variable	Description	Source
Agroforestry system	Agroforestry system on which the study was conducted: silvoarable systems, silvopastoral systems, and mixed systems	Primary studies
Comparator	Conventional land-use system that the publication used to compare the agroforestry system against. The three categories employed were: agricultural land, pasture land, and forestry land	Primary studies
Study scale	Extent of the study area (km^2)	Primary studies/Google Earth
Woody element	Main woody species of the agroforestry system	Primary studies
Biodiversity[a]	Taxa studied (Plants/arthropods/fungi/birds)	Primary studies
Biogeographic region	Biogeographic region in which the study was conducted: Boreal/Continental/Atlantic/Pannonian/Mediterranean/Alpine	Primary studies
Ecosystem service	Ecosystem service category assessed according to the Millennium Ecosystem Assessment (2005) framework	Primary studies
Temperature	Mean annual temperature (°C)	WorldClim/Primary studies
Precipitation	Mean annual precipitation (mm)	Worldclim/Primary studies

[a] Studies in which biodiversity is assessed.

4.2.3 Response variables

Two different indices of effect size were used for the meta-analysis: response ratios (Borenstein et al., 2009; Hedges et al., 1999) and Hedges’ g (Hedges and Olkin, 1985). Response ratio (lr) is an unweighted index widely used for meta-analysis in ecology where primary studies differ in the indicators and methods used (De Beenhouwer et al., 2013; Meli et al., 2014; Barral et al., 2015). The response ratio index was defined as the difference between the natural logarithm of the value of a specific indicator in the agroforestry system (ln(µAF)) minus the natural logarithm of the value of the same indicator in the comparison (ln(µC)) (Equation 1). Positives values for lr indicate positive effects of agroforestry, while negative values for the lr indicate negative effects.

$$lr = \ln(\mu AF) - \ln(\mu C). \qquad \text{Equation 1}$$

An increase in the value of an indicator may not always mean benefit. For example if the indicator is soil loss then a decrease in the indicator would usually be preferred. To ensure that high values are correlated with attributes that are desirable from a land management perspective, the algebraic signs of some values were changed.

Hedges’ g was used on a subset of publications to analyze the effect of agroforestry on biodiversity. Indicators used to assess biodiversity were homogenous, only including biodiversity richness and abundance. This allowed us to use a more restrictive but precise effect size index. Hedges’ g was selected as it as it is not biased by small sample sizes and therefore has been previously used to perform meta-analyses based on biodiversity indicators (Paillet et al., 2010; Batáry et al., 2011; De Beenhouwer et al., 2013; Plieninger et al., 2014). Hedges' g is defined as the difference between the means of biodiversity between plots in agroforestry systems (µAF) and the land use compared (µC), divided by the standard pool deviation of µAF- µC corrected by the sample sizes (s) (Equation 2; Borenstein et al., 2007).

$$g = (\mu AF - \mu C)/s \qquad \text{Equation 2.}$$

Positives values for g indicate positive effects of agroforestry on biodiversity, while negative values point to negative effects. All the studies included in this biodiversity subgroup analysis were also comprised in the rest of the meta-analysis to see the overall and the explanatory variables effect.

4.2.4 Statistical analysis

To calculate the overall effect of agroforestry on ecosystem service provision and biodiversity, effect sizes were used as dependent variables to construct a random-effect model (effect sizes nested within studies) and calculate the mean effect size assuming random variation among the observations. Hence 95% confidence intervals were calculated around the mean effect size with bootstrapping of 999 iterations. To assess the effect of the different response variables, sub-group analyses were performed using the explanatory moderators as independent variables (ecosystem service assessed, extent area, agroforestry system, comparator, woody element, biogeographical region, and taxon for comparison regarding biodiversity indicators).

The null hypothesis was examined for the overall meta-analysis and for the subgroup analyses with a two-tail Z-test (i.e. the effect size equals 0) and the heterogeneity was analyzed using a Q-test. Finally, a meta-regression was conducted to assess the effect of precipitation and temperature. All of the analysis were performed using Metawin 2.1 (Rosenberg et al., 2000).

In this meta-analysis we compared relatively homogenous subgroups which included almost no variation in the indicator (such as biodiversity with only two kinds of indicator, richness and abundance) with relatively heterogeneous subgroups (like soil fertility with more than 10 different indicators). This artificial grouping should be taken into account when interpreting the results.

We used the fail-safe N method (Rosenthal, 1979) and calculated a funnel plot comparing effect sizes and variance to visually explore the publication bias (Gurevitch et al., 2001). The Rosenthal fail-safe N method gives us the number of potential missing studies we would need to include before the p-value became non-significant, large numbers (much bigger numbers than the amount of publications assessed in the meta-analysis) suggest absence of bias. In funnel plots, the presence of strong the asymmetries suggest bias. The funnel plots are shown in Annex B.

4.3 Results

4.3.1 Overall results

53 publications (Annex C) were finally included in the meta-analysis incorporated an overall of 365 comparisons. These primary studies were conducted in ten countries encompassing each of the five principal European biogeographical regions. Most studies were carried out in the Mediterranean region (59%) (Figure 1A and 1B), and 61% of the studies focused on silvopastoral systems (Figure 1C). Approximately similar proportions of publications focused on provisioning services, supporting and regulating services, and biodiversity (Figure 1D).

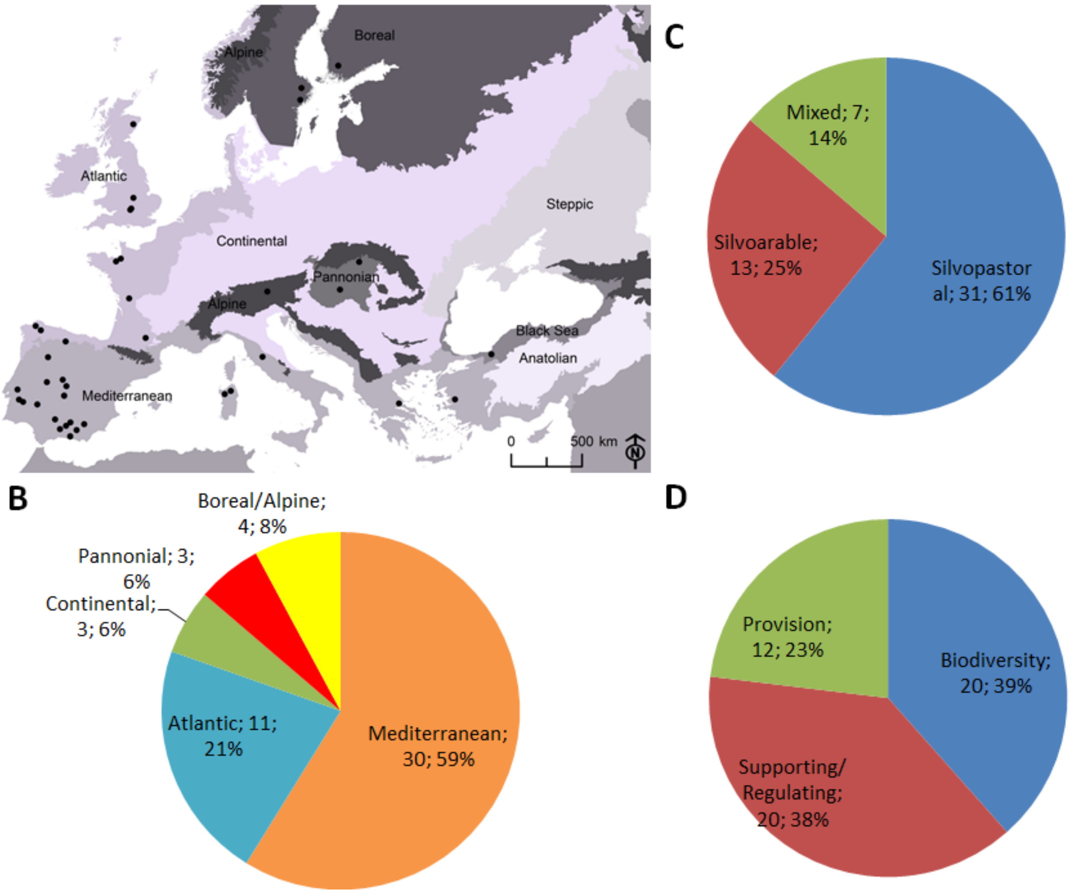

Figure 1. A. Geographic distribution of the case study sites B. the number and proportion of publications per region. C. The number and proportion of publications per agroforestry system type. D. the number and proportion of publications focused on provisioning, supporting/regulating ecosystem services, and biodiversity. Information in the pie charts: number of studies; percentage of studies.

The meta-analysis for the whole data-set using response ratios also revealed a significant positive effect of agroforestry on ecosystem service provision (mean effect size = 0.454; 95% confidence interval = 0.393 to 0.516; Table 4A). Heterogeneity values reveal high diversity in study outcomes, methodologies and indicators used (Z = 1070; p<0.01). This pattern was visually confirmed in the funnel plot (Annex B). Fail safe number analysis showed no effect of publication bias (fail safe number = 1054288.4).

4.3.2 Explanatory variables results

In every subgroup analysis, the random-effect model for the different explanatory variables revealed a significant positive effect of agroforestry (Table 4B-J). When compared with conventional agriculture and forestry, agroforestry had a significant positive effect on soil fertility/nutrient cycling, erosion control, and biodiversity (mean effect size = 0.426; 95% confidence intervals = 0.382 to 0.469; Figure 2; Table 4B). There were non-significant effects of agroforestry on food and timber production. The only significant negative effect of agroforestry was on biomass production (Figure 2; Table 4B).

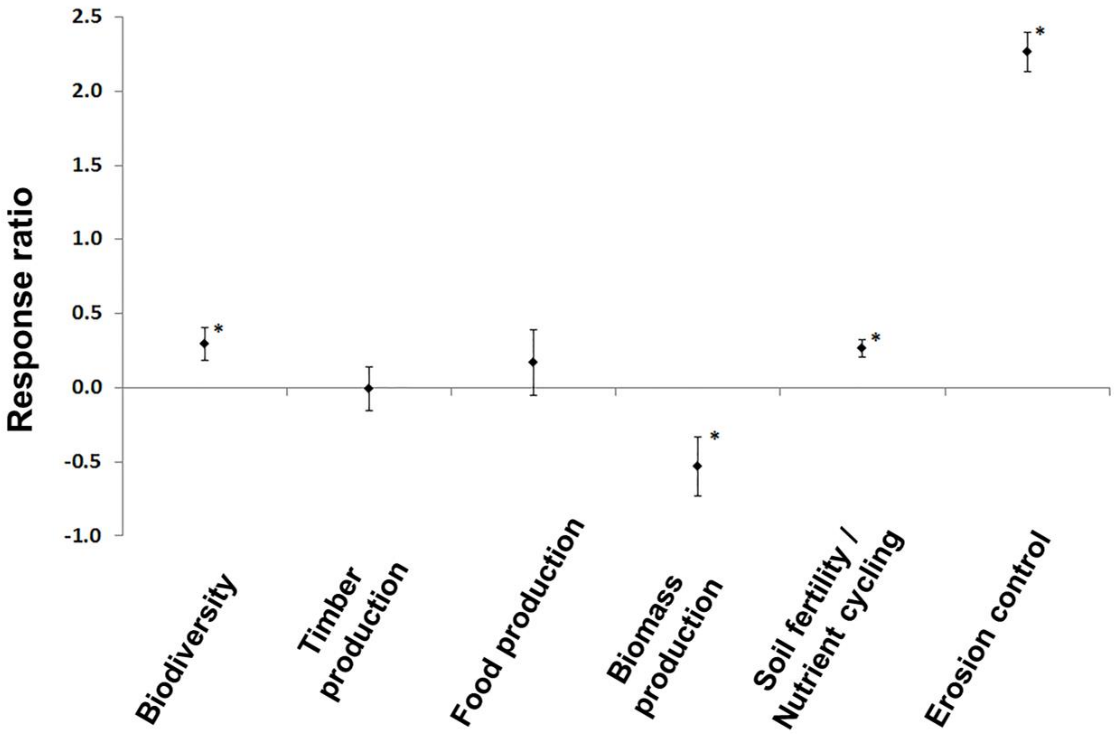

Figure 2. Mean effect size (response ratios) of agroforestry on different ecosystem service categories. *Effect sizes differed significantly from zero (p<0.05).

Among the woody species used in European agroforestry, olive trees, followed by chestnut, walnuts and cherry species had highly significant positive effects (Figure 3A; Table 4F). Conifers were the only group that displayed a strong negative effect, whilst species such as poplar, willow, and ash showed negative but non-significant effects. We found strong increases in ecosystem service provision in studies that were performed at landscape (1-1000 km²) and regional (>1000 km²) scales (Figure 3B; Table 4E).

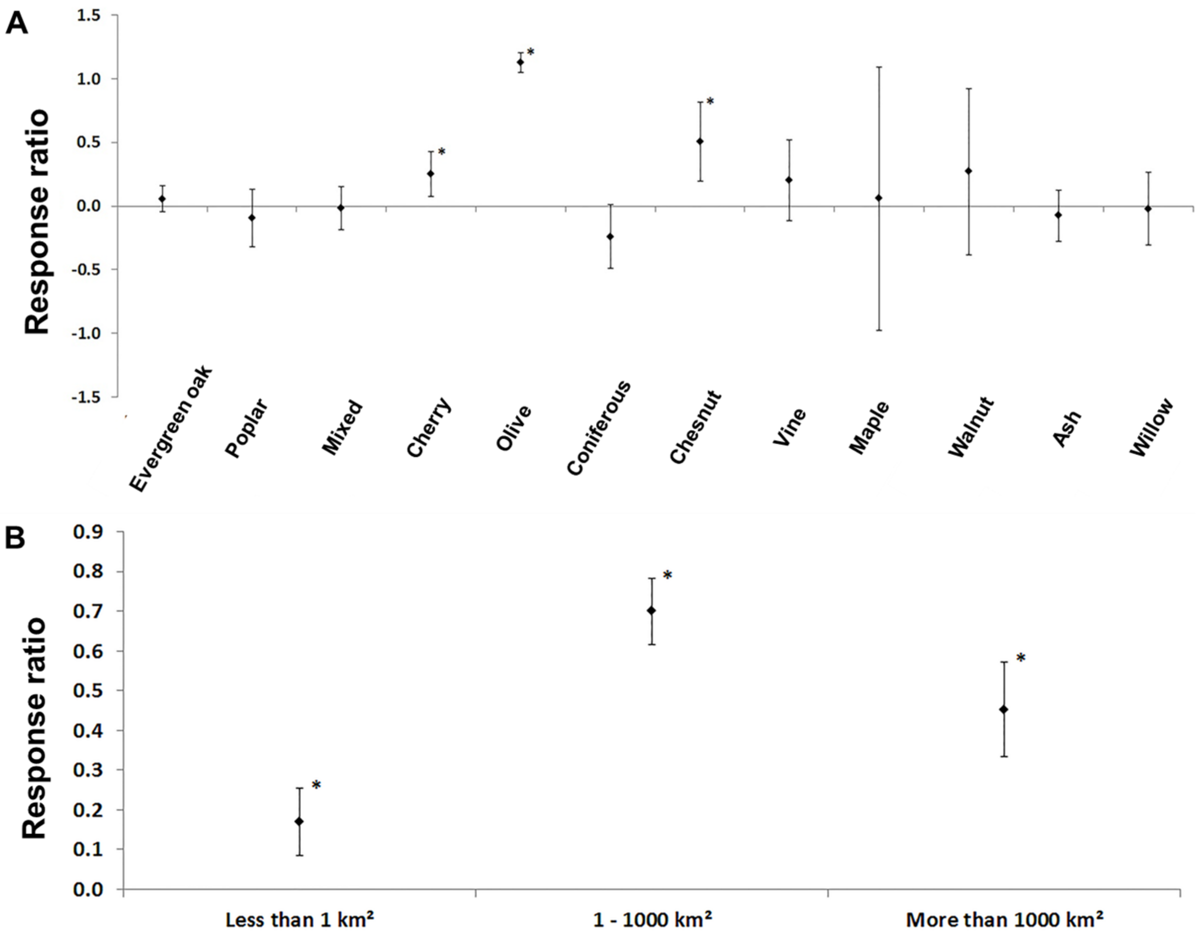

Figure 3. Mean effect size (response ratios) of agroforestry depending on: A. Main woody species. B. Study scale. * Effect sizes differed significantly from zero (p<0.05).

Both silvopasture and silvoarable systems had significant positive effects on erosion control and soil fertility but only silvopasture systems had a significant positive effect on biodiversity and a significant negative effect on biomass production (Figure 4A; Table 4B). For mixed systems, the analysis did not show clear positive or negative outcomes. In terms of the different comparators, agroforestry showed significant benefits in erosion control, biodiversity and soil fertility relative to forestry, and significant reductions in biomass production relative to both forestry and pasture. The responses of other ecosystem services were not significantly different from zero (Figure 4B; Table 4C).

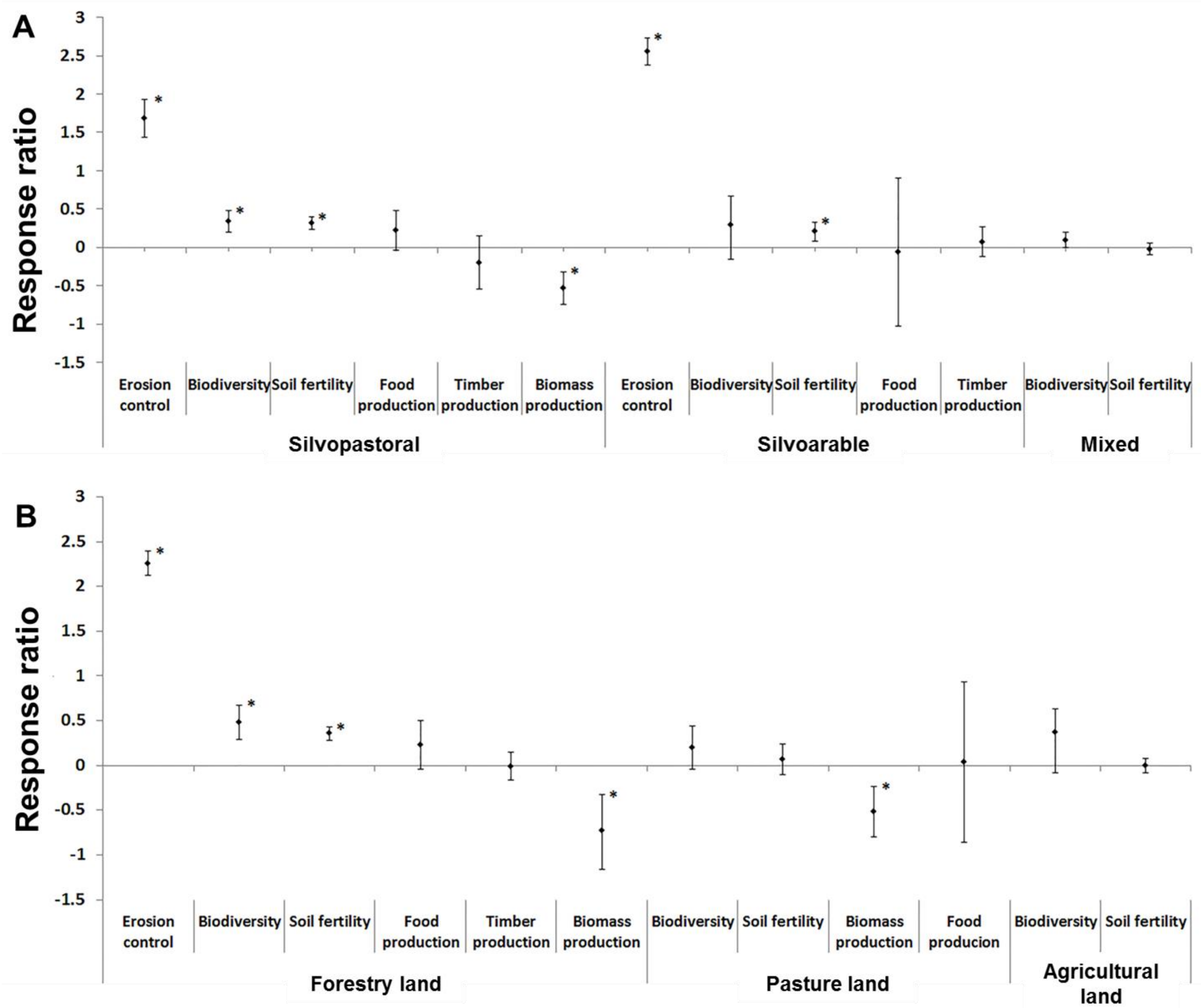

Figure 4. Mean effect size (response ratios) of agroforestry on different ecosystem services, differentiated according to: A. broad types of agroforestry, and B. comparator systems used. Here, positive effects refer to positive effect of agroforestry when compared to alternative land-use system. * Effect sizes differed significantly from zero ($p<0.05$).

Overall, significantly positive effects of agroforestry on biodiversity and ecosystem services were observed for the Mediterranean and Pannonian biogeographical regions; the effects of agroforestry in the Continental, Alpine and Boreal regions were not significant (Figure 5A; Table 4G). In line with this, there was a trend that the ecosystem service benefit of agroforestry tended to decrease with precipitation (slope = -0.001 mm-1; Figure 5B; Table 4I) and increase with temperature (slope=0.164 °C-1; Figure 5C; Table 4H), but the effects were not clear enough to infer an influence.

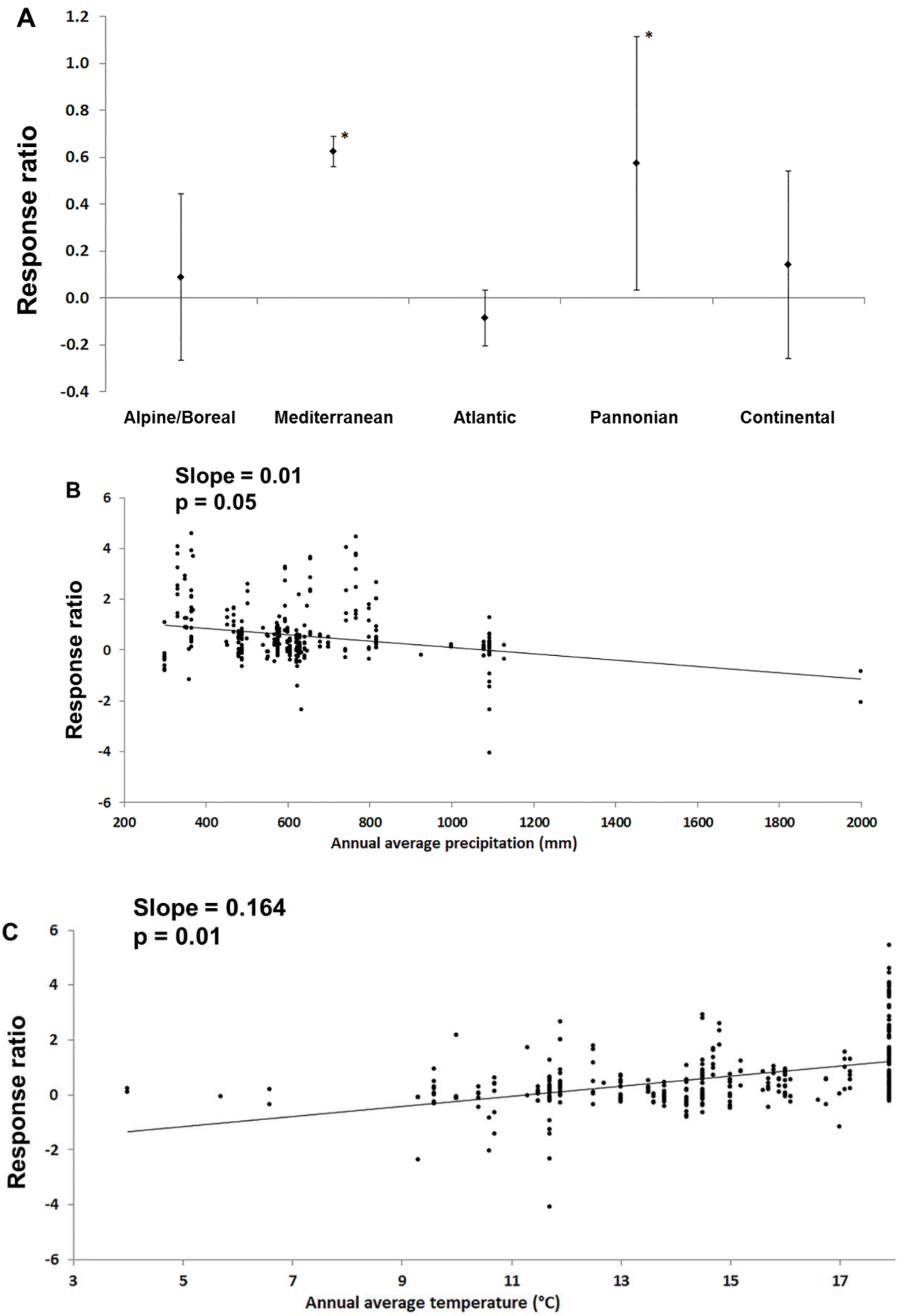

Figure 5. A. Mean effect size (response ratios) of agroforestry depending on the biogeographic region. B. Linear relationship between the annual average precipitation (mm) and the effect size of ecosystem service provision. C. Linear relationship between the annual average temperature (ºC) and the effect size of ecosystem service provision. * Effect sizes differed significantly from zero.

The specific subgroup meta-analysis for biodiversity using the Hedges' g as effect size index showed a significant positive effect of agroforestry systems on biodiversity (Figure 2), meaning that species richness and abundance were higher in agroforestry systems than in specialized agricultural and forestry systems (Table 4J; g = 0.874; 95% confidence interval = 0.532 to 1.215). In this case, heterogeneity values revealed again large variation in the study outcomes (Z = 139; p<0.01) but less heterogeneity than the rest of the explanatory variables analyzed. This smaller value in heterogeneity is in part explained by the effect size index employed and in part because of the relatively homogeneity in the indicators used to assess biodiversity in the literature. The funnel plot showed no big asymmetries (Annex B) and the fail safe number analysis showed no publication bias (fail safe number = 2484.6). The random-effect models revealed a positive trend of agroforestry in all the taxa, but the effect was only significant for birds (Figure 6; Table 4J).

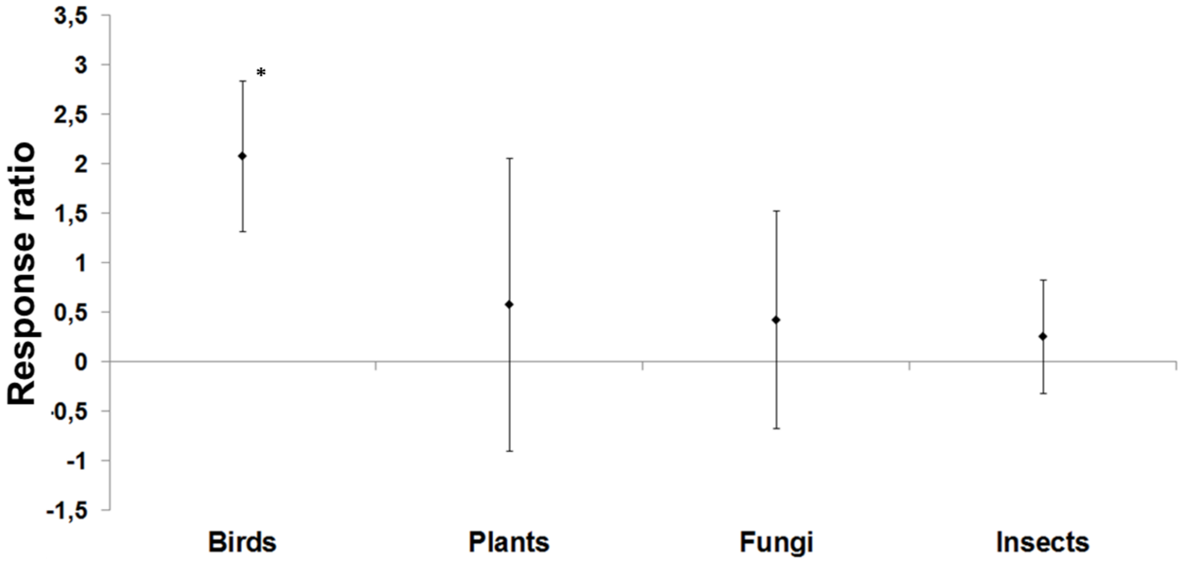

Fig. 6. Mean effect size (response ratios) of agroforestry on biodiversity depending on the taxon studied. * Effect sizes differed significantly from zero.

Table 4. Summary results of the meta-analysis. Effect size significantly different from zero (p<0.01) is highlighted

Moderator (Q;P)	Effect size	Standard error	Z	95% CI Lower	95% CI Upper	N
A **Overall analysis**	**0.454**	**0.115**	**1070**	**0.393**	**0.516**	**360**
B **Ecosystem service (951.54; 0.01)**	**0.426**	**0.144**	**1975**	**0.382**	**0.470**	**360**
Timber production	-0.009	0.088		-0.158	0.142	28
Food production	0.173	0.016		-0.049	0.395	19
Biomass production	**-0.532**	**0.111**		**-0.729**	**-0.334**	**20**
Soil fertility / Nutrient cycling	**0.261**	**0.108**		**0.200**	**0.322**	**171**
Erosion control	**2.234**	**1.552**		**2.104**	**2.364**	**57**
Biodiversity	**0.297**	**0.152**		**0.187**	**0.407**	**65**
C **Agroforestry system (61.66; 0.001)**	**0.449**	**0.115**	**1214**	**0.391**	**0.506**	**360**
Silvoarable	**0.772**	**0.764**		**0.670**	**0.875**	**122**
Silvopastoral	**0.324**	**0.329**		**0.251**	**0.397**	**218**
Mixed	0.061	0.014		-0.180	0.302	20
D **Comparator (123.77; 0.001)**	**0.439**	**0.116**	**1478**	**0.387**	**0.490**	**358**
Agricultural land	0.097	0.020		-0.094	0.288	27
Pasture land	-0.015	0.271		-0.122	0.092	82
Forestry land	**0.636**	**0.292**		**0.574**	**0.699**	**249**
E **Study scale (54.14; 0.01)**	**0.181**	**0.099**	**924**	**0.141**	**0.221**	**303**
F **Woody element (224.12; 0.001)**	**0.176**	**0.100**	**1318**	**0.143**	**0.209**	**302**
G **Biogeographic region (62.17; 0.02)**	**0.181**	**0.099**	**937**	**0.141**	**0.221**	**303**
H **Temperature Intercept (-1.810)**	**0.164**	**0.184**	**879**	**0.463**	**0.602**	**314**
I **Precipitation Itercept (1.176)**	**-0.001**	**0.124**	**879**	**0.463**	**0.602**	**314**
J **Biodiversity (Hedges'g)**	**0.874**	**0.282**	**139**	**0.532**	**1.215**	**65**
Fungi	0.422	1.115		-0.675	1.520	9
Arthropods	0.539	2.04		-0.321	0.823	25
Plants	0.575	10.72		-0.904	2.054	6
Birds	**2.068**	**2.04**		**1.309**	**2.828**	**16**

4.4 Discussion

Most attempts to summarize the effects of agroforestry have focused on tropical and subtropical ecosystems (Kwesiga et al., 2003; Schroth, 2004; Tscharntke et al., 2011), on specific agroforestry practices (De Beenhouwer et al., 2013; Riiser and Hansen, 2014; Tsonkova et al., 2012), or on individual ecosystem services (Lorenz and Lal, 2014; Poch and Simonetti, 2013; Rivest et al., 2013; Pumariño et al., 2015). This study is the first attempt to analyze the effect of agroforestry practices on a broad set of ecosystem services and taxonomic groups in Europe. It covers varied agro-climatic regions and a high variety of agroforestry, agricultural and forestry practices, addressed largely by the CAP.

Our meta-analysis shows an overall positive effect of agroforestry on biodiversity and ecosystem service provision. Hence our findings demonstrate that, when compared to conventional land uses such as grassland, arable land, or forests, agroforestry supports higher levels of biodiversity and ecosystem goods and services. This analysis confirms the basic premise of agroforestry science that land-use systems that are structurally and functionally more complex than either crop- or tree-based systems result in a greater structural diversity that entails a tighter coupling of nutrient cycles, soil retention, and increased biodiversity, not necessarily compromising productivity (Cannell et al., 1996; Lefroy et al., 1999; Nair, 2007). However, the variation within the results was high, especially regarding provisioning services, showing that the benefits of agroforestry are context related. This is, in part, a result of the methodology which included publications with different indicators and research designs in a single statistical analysis (cf. Rey Benayas et al., 2009). Variation can also arise because the benefits provided by agroforestry are dependent on the context and the choice of land use selected for the comparison.

4.4.1 Effects on ecosystem services

Our meta-analysis revealed that most of the ecosystem services included were positively influenced by agroforestry (Figure 2). Agroforestry seems particularly useful in controlling soil erosion, significantly reducing the surface-runoff of soil (Francia et al., 2006; Gómez et al., 2009; García-Ruiz et al., 2010). This is especially relevant in the vineyards and olive trees plantations found on drought-stressed sloping land in the Mediterranean Basin (Durán Zuazo and Pleguezuelo, 2008). Agroforestry also enhanced soil fertility and nutrient cycling. While the capability of agroforestry to improve soil fertility has been documented for the tropics (Pinho et al., 2012; Zake et al., 2015), our meta-analysis demonstrates similar effects of increased soil organic matter content and nutrient concentration levels in European agroforestry.

As expected, the effects of agroforestry on the supply of provisioning services (food, timber, and biomass production) are mixed, depending to a large degree on the specific parameters that are compared. Here, it is important to keep in mind that the studies included in our meta-analysis compared only individual provisioning service elements (e.g., woody biomass production or grass production), not the full amount of food, timber, or biomass produced. A key hypothesis in agroforestry is that productivity is higher than in other systems due to the complementary use of resources that allow the provision of more than one product (Carnell et al., 1996). Field experiments and modelling exercises that were performed in three European countries showed that agroforestry can increase overall yields by up to 40% relative to monoculture arable and woodland systems (Graves et al., 2007). In general, our meta-analysis shows that agroforestry can provide similar levels of timber as forestry, and similar levels of food production as pasture land. One reason why this is possible is that the different components of an agroforestry can be partly complementary in their use of solar radiation and water (Smith et al. 2012). Surprisingly our meta-analysis suggests that agroforestry reduced biomass production in relation to forestry and pasture (Figure 4). These results suggest that the competition for resources result in a reduction of biomass production. However, biomass results should be taken with caution as some of the authors that found such effects (López-Díaz et al., 2011; Pereira et al., 2002) acknowledge the difficulty to assess productivity in agroforestry systems as the biomass usually considers only the woody or the non-woody elements of the system, but not both together, giving a partial assessment of the biomass production in the system.

Although the aim of this meta-analysis was to assess a wider range of ecosystem services provided by agroforestry, many ecosystem service categories could not be included in the analysis. The absence of cultural ecosystem services particularly stands out, probably due to the difficulties to measure them quantitatively (Hernández-Morcillo et al., 2013; Milcu et al., 2013). Similar difficulties with including cultural ecosystem services were found in previous meta-analyses that addressed ecosystem services (Rey Benayas et al., 2009; De Beenhouwer et al., 2013; Howe et al., 2014; Meli et al., 2014; Barral et al., 2015).

4.4.2 Effects on biodiversity

Our analysis shows a strong positive effect of agroforestry on biodiversity (Figure 2), which is in line with findings from other parts of the world (Schroth, 2004; Felton et al., 2010; De Beenhouwer et al., 2013). The capacity of agroforestry to provide food, shelter, habitat, and other resources for multiple species has been documented (McAdam and McEnvoy, 2009; Jose, 2009) and is one of the main reasons why many agroforestry areas are protected under the Natura 2000 Directive (European Union, 1992) and are frequently recorded as High Nature Value farmlands (Paracchini et al., 2008). Plieninger et al. (2015) documented that almost a quarter of the natural habitat types listed in the Annex I of the Directive (European Union, 1992) refer to some extent to silvopastures.

However, the benefits of agroforestry differ among the studied taxa (Figure 6). We found a strongly positive effect for bird communities. This is in line with findings from Fischer et al. (2010) though in contrast to the findings from De Beenhouwer et al. (2013). The difference is probably a result of Beenhouwer et al. (2013) comparing agroforestry to natural forests and plantations in the tropics, while the comparison in our meta-analysis included tree-less grasslands and croplands which generally have lower structural and functional diversity than “natural” systems.

4.4.3 Variation related to context factors

The outcomes of the comparative analysis between agroforestry system types and between comparators showed a clear positive effect for both silvoarable and silvopastoral systems, though the effect size is stronger for silvoarable systems (Figure 4A). This illustrates the importance of the comparator systems: silvopastoral systems was particularly rich in biodiversity and ecosystem services (Plieninger et al., 2015), but many tree-less grassland have a high nature value as well (Veen et al., 2009). Silvoarable systems may provide these benefits to a lesser degree, but here the contrast (and by this the potential for improvements in biodiversity and ecosystem services) to monocultural cropping systems is particularly strong (de Klein and Eckard, 2008).

The comparator system was an important category as well, with a significant positive effect size for comparisons of agroforestry systems against pure forest systems (Figure 4B). Surprisingly, the effect of agroforestry is not so clear in comparisons to agricultural and pasture land, indicating that the benefits of incorporating agroforestry into a land-use system is context-related and might depend on the different elements combined in the system.

Our meta-analysis suggests that the benefits of agroforestry were most apparent with deciduous and/or hardwood species such as olives, walnut, chestnut, and cherry species (Figure 3A; Table 4F). This is in line with other studies (e.g., Verhulst et al., 2004; Martins et al., 2010; Chiti et al., 2011; Zuazo et al., 2014), and is probably linked to the opportunity for complementary resource use being greatest for deciduous species, or species that are traditionally planted at a wide spacing. In contrast, fast-growing conifer species typically devoted to timber or biomass production showed a negative effect size for agroforestry. However, many of the studies on conifer systems only assessed indicators for provisioning services (Gul and Avciouglu, 2004; Silva-Pando, 2002).

Our analysis also points to geographic differences, as effect sizes were highest in the Mediterranean and Pannonian regions of Europe (Figure 5A). Also, the bioclimatic conditions analysis followed the same pattern, with increased ecosystem service supply in areas where temperature is higher and precipitation is lower (Figure 5 B and C). The increased ecosystem service provision in warmer and drier regions is consequence of the strong positive impact in the meta-analysis of results in publications assessing erosion control and nutrient cycling, extensively studied in the South of Europe. This result indicates that existing research highlights the benefits of agroforestry to moderate the effects of high temperatures and drought stress.

The study also shows that the positive effects of agroforestry on ecosystem services were more apparent at a landscape and regional-scale than at a farm-scale (Figure 3B). This has potentially important policy implications as it suggests that landscape- and regional-scale responses are more than just the sum of farm-scale responses. This is particularly relevant in the European context, where agri-environment interventions are often addressed at a farm-, rather than at a catchment or landscape-scale (Concepción et al., 2012; Plieninger et al., 2012).

4.4.4 Limitations of the meta-analysis

Some considerations need to be taken into account when interpreting the results and conclusions of this study. The systematic literature search and the selected inclusion criteria might have not captured all relevant publications addressing the research question of the meta-analysis. The search terms might have missed important information in grey literature especially in non-English publications, and the requirement that the publication provided means, standard deviations and population numbers forced us to disregard many publications. Many publications that reported ecosystem service assessments could not be included as they were assessing a single land use and lacked any comparison. Finally, although key agroforestry practices and each European biogeographic region were represented, there is a geographic bias in our pool of primary studies. In the Mediterranean area, concerns related with desertification encourage research on soil erosion while in more temperate climates interest in timber production may be higher. When analyzing the overall results, this fragmented structure of the primary data should be taken into account, especially when focusing on trade-offs between ecosystem services.

4.5 Conclusions and policy implications

Our analysis demonstrates that agroforestry generally enhances biodiversity and ecosystem service provision relative to conventional agriculture and forestry in Europe. However, the substantial variation in results also highlights that the responses are dependent on biophysical and land-use conditions. In Atlantic and Continental Europe, intercropping in chestnut and walnut systems, or integrating trees in arable systems can increase soil fertility and enhance biodiversity whilst maintaining agricultural productivity. In Mediterranean Europe, the studied publications indicate, that integrating cover crops and/or grazed legumes in vineyards and olive monoculture plantations generally increases soil fertility and nutrient retention whilst reducing soil loss. At the same time, existing silvopastoral systems such as the French pré-verger and the Central European Streuobst (Eichhorn et al., 2006) should not be neglected. The meta-analysis also stresses the importance of promoting features and practices that act at a landscape scale, as in the case of hedgerows, which play an important role in landscape-scale biodiversity conservation (Aviron et al., 2005; Michel et al., 2007; Rollin et al., 2013) as well as in creating barriers for wind erosion, creating a favorable microclimate (Smith et al., 2012), increasing soil fertility (Chifflot et al., 2005) and controlling pests and diseases (Pumariño et al., 2015).

The CAP does provide options for national governments to support the establishment of new agroforestry systems. However national governments have been reluctant to take up this opportunity, and often the level and duration of funding is less than for afforestation projects. Our results suggest that policy measures to support European agroforestry could be particularly effective in addressing biodiversity and ecosystem services such as soil erosion and runoff control, and nutrient retention at a landscape level. Hence, land managers and national and regional policy makers should be aware of this response diversity when prioritizing measures to promote European agroforestry.

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ANNEX A for Torralba et al (2016): Review Protocol - Do European agroforestry systems provide more ES than other European agricultural or forestry practices?

Objective

The main objective is to determine, based on the published scientific literature, to what degree agroforestry systems increase the provision of ecosystem services in Europe compared to other agriculture and forestry systems (Population, Intervention, Comparator and Outcome are highlighted in **Table 1)**. Specifically we raise the following research questions:

1. Does European agroforestry support higher levels of biodiversity and ecosystem services than monoculture agriculture or forestry?
2. What category/ies of ecosystem services and what species groups are most supported by agroforestry?
3. What differences arise between different kinds of agroforestry (e.g. silvoarable systems, silvopastoral agroforestry, agro-silvopastoral systems, buffer strips, and multipurpose trees systems)?
4. Are there physical and biological driven-forces for inter-sites differences?

Table 1. Population, Intervention, Comparator and Outcome

Population	Intervention	Comparator	Outcome
European forestry, agricultural and livestock land-use systems	European agroforestry systems	Non Agroforestry systems: forestry, agricultural or livestock systems	ES provision (↑ or ↓)

The aim of the search is to find all available studies containing data from field experiments assessing ES provision on European agroforestry systems. The main approach will be to conduct electronic searches in scientific databases. The systematic mapping will follow established guidelines (Pullin and Stewart 2006; Pullin and Knight 2009; Collaboration for Environmental Evidence 2013; Billota *et al*., 2014) and will be oriented by previous meta-analyses (Felton *et al*., 2010; Paillet *et al*., 2010; Batary *et al*., 2011; Meli *et al*., 2014; Plieninger *et al*., 2014)

Search terms and strings: scope will be performed by searching keywords that include aspects of the population, intervention and the outcome.

Scoping exercise revealed a weak power of general terms related with ecosystem services when looking for publications. Thus, search terms related with the population and intervention will stay always the same; while terms related with the outcome will change in the different steps depending on which ecosystem service we are scoping.

To refine the scoping results related with the intervention all European countries will be included in the search string with the following terms:

Europe OR EU OR Albania OR Andorra OR Armenia OR Austria OR Azerbaijan OR Belarus OR Belgium OR "Bosnia and Herzegovina" OR Bulgaria OR Croatia OR Cyprus OR Czech* OR Denmark OR Estonia OR Finland OR France OR Georgia OR Germany OR Greece OR Hungary OR Iceland OR Ireland OR Italy OR Kazakhstan OR Latvia OR Liechtenstein OR Lithuania OR Luxembourg OR Malta OR Moldova OR Monaco OR Montenegro OR Netherlands OR Norway OR Poland OR Portugal OR Romania OR Russia OR "San Marino" OR Serbia OR Slovak* OR Slovenia OR Spain OR Sweden OR Switzerland OR Macedonia OR Turkey OR Ukraine OR "United Kingdom" OR England OR Wales OR Scotland*

To address agroforestry systems, terms used to describe different agroforestry systems across Europe where included.
agroforestry OR silvoarable OR silvopastoral OR agrosilvopastoral OR “farm woodland” OR “forest farming*” OR “forest grazing” OR “grazed forest*” OR “isolated trees” OR “scattered tree*” OR “tree outside forest*” OR “farm tree*” OR woodlot* OR “timber tree system” OR dehesa OR montado OR “oak tree*” OR “olive tree*” OR “fruit tree*” OR pré-verger OR Streuobst OR pomarada* OR Hauberg OR Joualle OR “orchard system” OR “orchard intercropping” OR parkland* OR “alley cropping” OR “wooded pasture*” OR “wood pasture*” OR pollarding OR “fodder tree*” OR pannage OR hedgerow* OR windbreak* OR “riparian woodland*” OR “riparian buffer strip*“ OR “buffer strip*” OR “riparian buffer*” OR “shelter belt*”*

To address the different ecosystem services, preliminary scoping exercises were performed to find out which ES have enough published literature to perform a meta-analysis. Only ES which were able to contribute with at least 7-10 publications were included in the final scoping exercise. This process revealed that the ecosystem services able to be included in the meta-analysis were those related with food and timber provision, ES related with soil formation, nutrient retention and erosion control, and biodiversity (**Table 2**).

Related with Provisioning services:
Product OR Provision**

Related with Soil services:
“Soil formation” OR “soil organic carbon” OR “soil carbon” OR “soil C” OR “soil organic C” OR SOC OR “carbon pool” OR “carbon stock” OR “carbon storage” OR “soil organic matter” OR SOM, “carbon sequestrat” OR “C sequestrat*” OR “Nutrient cycling” OR “Nutrient retention” OR “soil services” OR Nitrogen OR Phosphorus OR Erosion OR “soil loss”.*

Related with water quality ES:
"water quality" OR "water regulation" OR "water purification" OR "hydrological regulation"

Related with biodiversity:
Biodiversity OR richness OR “species abundance” OR “species composition” OR “biological diversity”

Electronic academic databases included in the search for relevant items include:
- ISI Web of Science.
- Scopus.
- Biosis.
- Cab Abstracts
- Google scholar (100 first results).

Table 2. Preliminary scoping exercise performed in July 2014

	Food and timber provision	Soil fertility/nutrient cycling	Erosion control	Biodiversity
Hits (search in ISI Web of knowledge 7/2014)	2483	570	240	1813
Title and keywords riddle	129	186	43	218

The numbers of articles retrieved, accepted and rejected will be noted down. Titles and abstracts will be stored in an Endnote database and duplicates will be removed.

Study inclusion and exclusion criteria

Inclusion criteria will be first applied to the publication title and key words; after this filtering process the abstract will be addressed and finally the remaining publications will be filtered revising the whole document. Every time one case arise doubts about its inclusion, it will be included to the next stage for further evaluation (Pullin & Stewart 2006)

To check for data quality and consistency of application of the inclusion criteria, another reviewer will go through the scoping exercise of the 10% of the references (Pullin & Stewart 2006). The inclusion criteria will be performed by a stepwise process by applying the procedure describe in the **table 3.**

Table 3. Inclusion criteria

1. Agroforestry systems	Every kind of agroforestry system that follows the definition: Agroforestry is the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal production systems to benefit from the resulting ecological and economic interactions. This means that the following systems will be included: silvoarable systems, silvopastoral agroforestry, agro-silvopastoral systems, buffer strips and multipurpose trees systems.
Types of comparable land use	The compared system must be a farmland or a forestry system with low cover of agroforestry within the same region.
Geographical scope	Farmland and forest systems in Europe. The study areas were limited to Europe in a geographical context (e.g. including Switzerland and European parts of Russia and Turkey)
Methodological Approach	Only studies that perform quantitative ecosystem service assessment based in primary data.

Data extraction strategy

In order to perform a meta-analysis, available quantitative data related with each ES assessment will be extracted from every publication and those will be the response variables. For the dependent variables, a dataset will be performed with information about the ecosystem service studied and the indicator used to measure it. Observations of multiple ecosystem services and/or different study sites within one study will be included separately in the dataset and considered independently. For each observation, means, standard deviation and sample sizes will be extracted. If the data from the publications is valid, but summary statistics is not available in the text, it will be extracted from tables and graphs, or calculated from available raw data. If none of them are available, authors will be contacted and asked for the information.

As Independent variables, information about the study conditions will be extracted from each publication: kind of agroforestry system, kind of system compared and extent of the study area. Climatic and biogeographic information, which might not be included in the study region, will be taken from other data sources (WorldClim, and Google Earth) (**Table 4**).

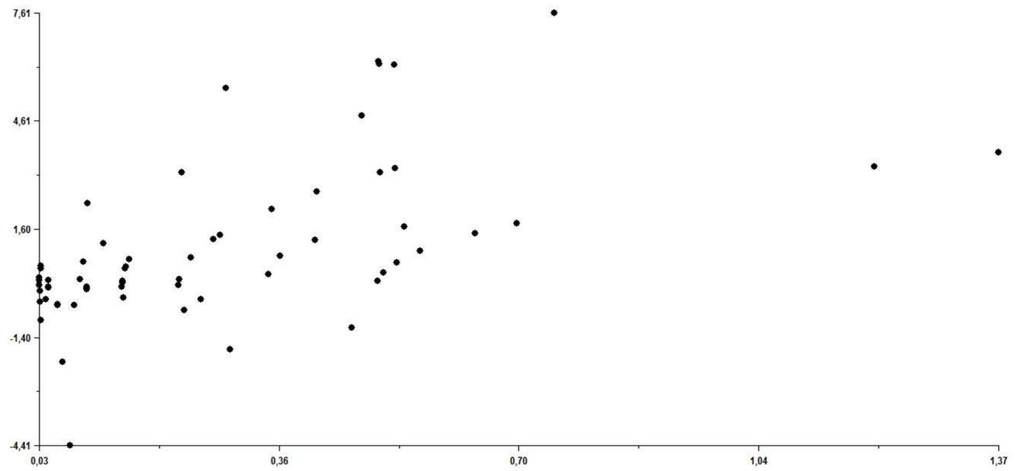
Table 4. Explanatory variables provided by primary studies and additional data sources that were included in the meta-analysis

Explanatory variable	Description	Source
Agroforestry system	Agroforestry system on which the study was conducted: silvoarable systems, silvopastoral systems, and mixed systems	Primary studies
Comparator	Specialised land-use system that the publication uses to compare the agroforestry system against. The three categories employed were: agricultural land, pasture land, and forestry land	Primary studies
Scale of the study	Surface extent of the study area (km^2)	Primary studies/Google Earth
Main woody element	Main woody species of the agroforestry system	Primary studies
Taxa studied[a]	Taxa studied (Plants/arthropods/fungi/birds/worms)	Primary studies
Biogeographic region	Biogeographic region in which the study was conducted: Boreal/Continental/Atlantic/Pannonian/Mediterranean/Alpine	Primary studies
Ecosystem service category	Ecosystem service category assessed according to the Millennium Ecosystem Assessment (2005) framework	Primary studies
Temperature	Mean annual temperature (°C)	WorldClim/Primary studies
Precipitation	Mean annual precipitation (mm)	World clim/Primary studies

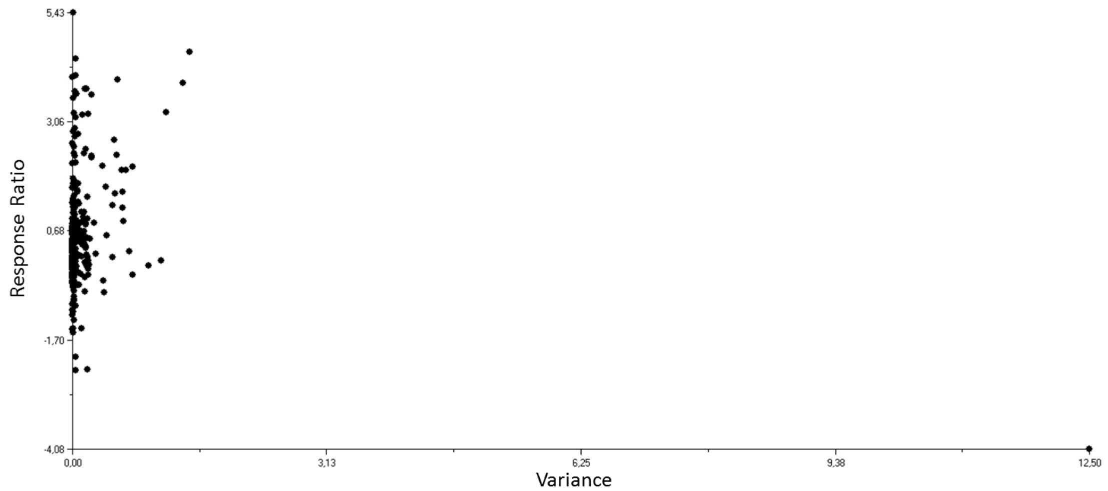
[a] Studies in which biodiversity is assessed.

ANNEX B for Torralba et al (2016)

Funnel plot of effect sizes between the variance and the Hedge's g of biodiversity levels between agroforestry and non-agroforestry systems



Funnel plot of effect sizes between the variance and the response ratios of ecosystem services between agroforestry and non-agroforestry systems



ANNEX C for Torralba et al (2016): List of publications

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5 Paper 3: Wood-pastures of Europe: Geographic coverage, social-ecological values, conservation management, and policy implications

This is a pre-print version of the following paper:

Plieninger, T., Hartel, T., Martín-López, B., Beaufoy, G., Bergmeier, E., Kirby, K., Montero, M.J., Moreno, G., Oteros-Rozas, E., Van Uytvanck, J. (2015). Wood-pastures of Europe: Geographic coverage, social-ecological values, conservation management, and policy implications. Biological Conservation 190: 70-79. http://dx.doi.org/10.1016/j.biocon.2015.05.014

Abstract

Wood-pastures are archetypes of high nature value farmlands in Europe and hold exceptional ecological, social, and cultural values. Yet, wood-pastures have been through a sharp decline all over Europe, mainly due to processes of agricultural intensification and abandonment. Recently, wood-pastures have found increasing attention from conservation science and policy across Europe. In this paper we (i) perform the first pan-European assessment of wood-pastures, considering individual countries and biogeographic regions, (ii) present the ecological and social-cultural values of a wide diversity of wood-pasture systems in Europe, (iii) outline management challenges around wood-pastures, and (iv) provide insights for the policy agenda targeting wood-pastures in Europe. We estimate that wood-pastures cover an area of approximately 203 000 km² in the European Union (EU). They are distributed across all biogeographical regions, but more abundantly in the Mediterranean and Eastern European countries. Substantial ecological values are revealed in terms of landscape level biodiversity, ecosystem dynamics, and genetic resources. Social-cultural values are related to aesthetic values, cultural heritage, and rich traditional ecological knowledge. We discuss the anthropogenic character of wood-pastures, requiring multifunctional land management, which is a major conservation challenge. Despite increasing societal appreciation of wood-pastures, their integration into effective agricultural and conservation policies has proved to be complicated, because institutional structures are traditionally organized within mono-functional sectors. We offer suggestions as to how these shortcomings might be overcome in the Common Agricultural Policy, including Rural Development policy, and the Habitats Directive of the EU. We conclude that research should be guided by a holistic vision of wood-pastures, which integrates information about ecology, societal values, and institutional arrangements.

Keywords: Agro-forestry, Habitats Directive, High Nature Value farmland, Land-use change, Silvo-pastoralism, Social-ecological research

5.1 Introduction

Protected areas may soon cover 17% of the global land surface (Watson et al. 2014), but there is wide recognition that segregated conservation strategies must be complemented by integrative approaches, especially in landscapes shaped by agriculture and forestry (Fischer et al. 2006). Efforts to realign biodiversity conservation with agricultural production have recently gained momentum, as growing competition for land (Smith et al. 2010), urban land expansion (Seto et al. 2011), and land degradation (Plieninger and Gaertner 2011) make it increasingly difficult to set aside large areas exclusively for biodiversity conservation. One prominent integrative strategy is High Nature Value (HNV) farming, a conservation approach that links ecology, land use, and public policies and expands conservation from traditional site protection to the scale of managed landscapes (Oppermann et al. 2012). The HNV approach was developed in acknowledgement of the crucial importance of low intensity farming for many elements of biodiversity (Halada et al. 2011).

Wood-pastures – landscapes in which livestock grazing co-occurs with scattered trees and shrubs – are archetypes of High Nature Value farmland and excellent model systems to explore how such farmlands could be incorporated into conservation strategies (Bergmeier et al. 2010). They represent an important part of the European cultural and natural heritage, but are also mirrors of dramatic changes in the relationship between people and their natural environment (Rotherham 2013). Scientific interest in wood-pastures has recently grown across Europe (e.g., Garbarino et al. 2011; Hartel et al. 2013; Horák and Rébl 2013; Plieninger 2012, 2015; Vojta and Drhovská 2012). Studies of wood-pastures have been performed at plot or local scales, often generating insight for wood-pasture conservation at large. However, to inform conservation policy, such local research needs to be complemented by studies acting across regions and continents (Schimel 2011). Therefore, our paper aims to provide the first European synthesis of the available knowledge about wood-pastures. In particular, we (i) evaluate the extent of wood-pastures in Europe by country and biogeographic region, (ii) present the ecological and social-cultural values of the variety of wood-pasture systems in Europe, (iii) outline the management challenges around wood-pastures, and (iv) suggest relevant insights for the policy agenda in Europe.

5.2 Extent of wood-pastures in Europe

For the quantification of wood-pastures, we used information from the LUCAS project of the EU, a geo-referenced database of 270 277 points that provides harmonized and comparable statistics on land use and land cover across the whole of the EU's territory in 2012 (EUROSTAT 2015). The database covers 27 European countries (EU-27 hereafter), and consists of a systematic sample with points spaced 2 km apart (around 1 100 000 points). Each point of the first phase sample was photo-interpreted and assigned to one of the following seven pre-defined land cover strata: arable land, permanent crops, grassland, wooded areas and shrubland, bareland, artificial land, and water. In a second stage, a quarter of the points were visited and interpreted at ground level in 2012. This second stratified sample (with >270 000 points; located every 4 km x4 km, on average) was selected according to the proportion of each of the seven main land uses in every European region (NUTS2 level). A scheme maximizing the distance of the points, both in the same and in different strata (region x land use), was designed as a sample selection method, producing a quasi-regular grid of points (Martino et al. 2009). Nevertheless, for logistic limitations, points above 1500 metres of altitude and those far from the road network were considered inaccessible and excluded (Eurostat 2015). The presence of trees in the observational point was assessed considering a 20 m radius. On the basis of the LUCAS data, we defined wood-pastures as those sampled points that show a combination of a tree cover (density of tree-crown >5%) with a pasture cover (grassland communities with clear evidences of grazing, coded as land use U111 in the LUCAS database). We mapped three categories of wood-pastures: (1) pastures in open woodlands, including those points with woodland (density of tree-crown >10%) as the primary land cover (coded as C10 to C33), and with grassland as the secondary land cover (coded as E10 and E30); (2) pastures with sparse trees (density of tree-crown between 5% and 10%), directly defined in the LUCAS database as a specific land cover class (coded as E10); and (3) pastures with cultivated trees (coded as B71 to B81) with recorded grazing land use, i.e., excluding points that are ungrazed permanent croplands rather than fully-fledged wood-pastures (see Fig. 1 for examples). As a result, we found that the LUCAS database contains 12 772 points that we considered wood-pastures. Given the comprehensive sampling grid that was included in LUCAS, the set of points can be viewed as representative of the land cover at EU but for the larger countries also at national scales (Table 1). Hence, in order to estimate the extent of wood-pastures, we multiplied the proportion of points defined as wood-pasture in each country by the surface of the country divided by the overall number of LUCAS points in this country. As sample density varied between 3 and 12 points per 100 km², an alternative approach based on Thiessen proximal polygons was generated for every sample point (i.e. the lower the sample density is, the bigger are the polygons), which produced very similar results (data not shown).

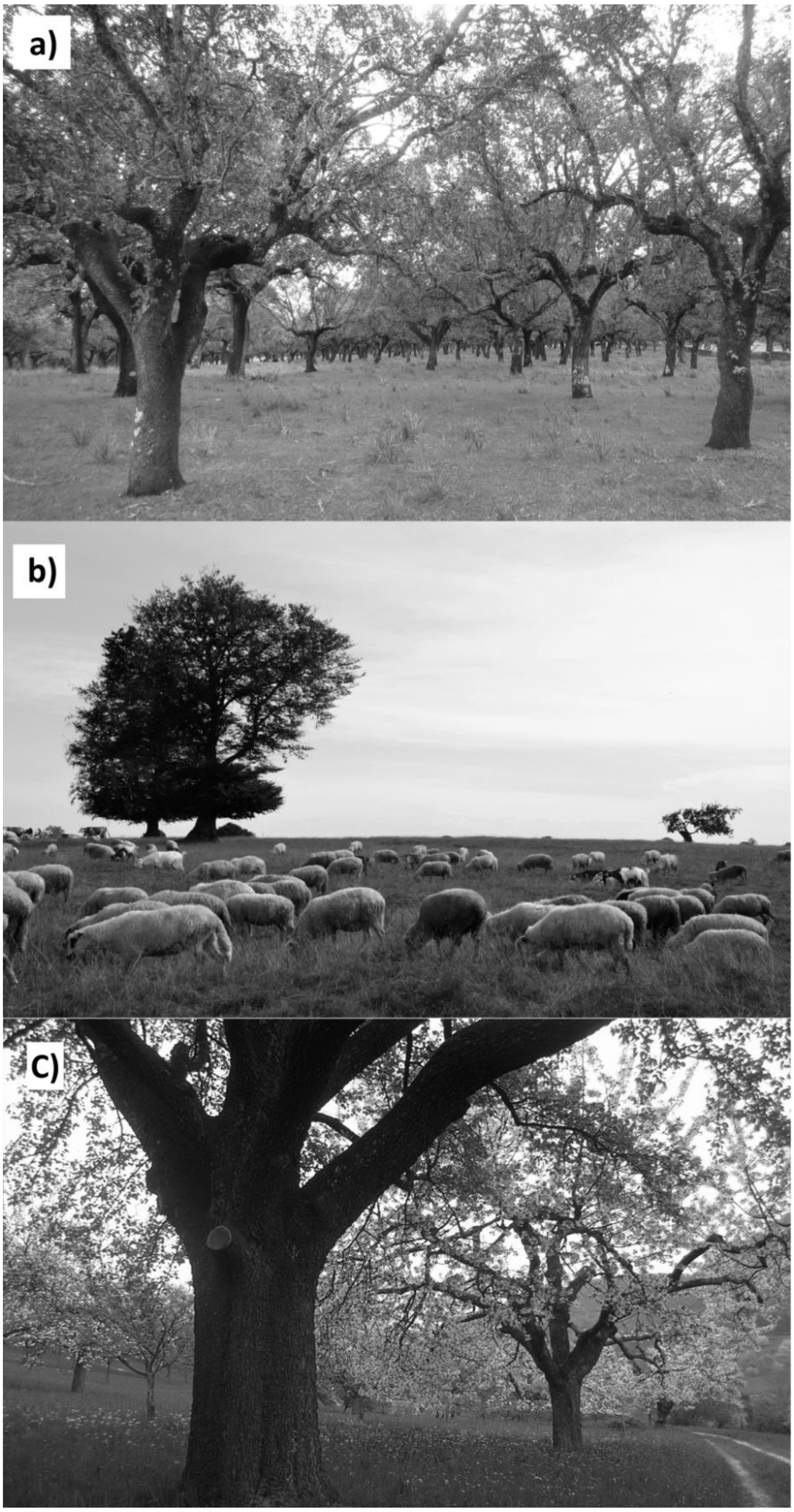

Fig. 1. Examples (from top to bottom) of (a) pastures in open woodlands (Dehesa with *Quercus ilex* in Torrecillas de la Tiesa, Spain), (b) pastures with sparse trees (pasture with scattered *Fagus sylvatica* trees in Eastern Transylvania, Romania), and (c) pastures with cultivated trees (orchard meadow in Lenningen, Germany).

Table 1. Extent of three categories of wood-pastures in the 27 EU member states derived from the LUCAS database. See text for further details.

Country	**Pastures in open woodlands (km²)**	**Pastures with sparse trees (km²)**	**Pastures with cultivated trees (km²)**	**Wood-pasture total (km²)**	**Proportion of territory covered by wood-pasture**
Austria	364	766	221	1 350	1.6%
Belgium	150	501	25	676	2.2%
Bulgaria	969	10 278	201	11 448	10.3%
Cyprus	16	47	35	99	1.7%
Czech Rep.	314	457	86	857	1.1%
Denmark	524	112	0	636	1.5%
Estonia	21	960	0	981	2.1%
Finland	274	598	0	872	0.3%
France	6 644	13 861	544	21 049	3.7%
Germany	2 494	2 752	344	5 591	1.6%
Greece	4 200	8 007	1 246	13 454	10.1%
Hungary	180	1 985	0	2 166	2.3%
Ireland	1 540	1 981	0	3 521	5.1%
Italy	3 610	10 477	1 059	15 145	5.3%
Latvia	102	848	0	950	1.5%
Lithuania	84	2 124	67	2 275	3.5%
Luxemburg	24	60	24	108	4.2%
Malta	0	0	0	0	0.0%
Netherlands	128	112	32	271	0.8%
Poland	1 058	3 573	114	4 746	1.5%
Portugal	10 724	2 693	1 135	14 553	16.4%
Romania	981	15 278	731	16 990	7.2%
Slovakia	140	718	0	857	1.8%
Slovenia	139	919	38	1 095	5.4%
Spain	36 771	19 407	1 917	58 096	11.7%
Sweden	2 150	3 086	20	5 256	1.2%
UK	3 448	4 410	140	7 998	3.3%
EU-27	**85 219**	**109 247**	**8 901**	**203 367**	**4.7%**

We estimate that wood-pastures cover a total of approximately 203 000 km² in the EU27 (4.7%, Fig. 2), with roughly 109 000 km² being pastures with sparse trees, 85 000 km² pastures in open woodlands, and 9 000 km² pastures with cultivated trees (mainly grazed olive groves and fruit trees). Out of 1 053 000 km² of grasslands in the EU, 19.3% are represented by wood-pastures. The largest extent of wood-pastures is found in Spain, France, and Romania (Table 1). Pastures with sparse trees have their largest surface in the Mediterranean (Spain, France, Italy) and Eastern European countries (Romania, Bulgaria). Pastures in open woodlands are particularly concentrated in Spain and Portugal, where they occur mainly as holm oak (*Quercus ilex*) and cork oak (*Quercus suber*) wood-pastures (called *dehesas* and *montados*). Grazed pastures with cultivated trees are found across the Mediterranean countries, with the highest extent being found in Spain, Greece, Portugal, and Italy. Wood-pastures cover 10.8% of the Mediterranean biogeographical region, 5.6% of the Black Sea region, and 4.7% of the Alpine region as defined by the European Environment Agency. Wood-pastures cover less than 4.0% in the Continental, Boreal, Atlantic, Pannonian and Steppic regions. Since we did not include shrublands (even if grazed and with presence of sparse trees) and grazed forests without pasture understory in our definition of wood-pastures, the numbers of the extent of wood-pastures in the EU-27 are conservative estimates. The figures should also be treated with caution as there are many interpretation issues and other variables at play. For example, mountainous and other remote areas may be underrepresented in the LUCAS survey, and information concerning management and tenure of wood pastures is very poor (e.g., simultaneous presence of tree and grass cover may be integrated in the same parcel or management unit or in adjacent ones).

5.3 Ecological values of European wood-pastures

The exceptional ecological values of wood-pastures are a result of their contribution to landscape level biodiversity, their dynamic character, and their role as a repository of genetic resources.

5.3.1 Contribution to landscape level biodiversity

Spatial heterogeneity in wood-pastures operates at multiple scales. Canopy-caused resource gradients (e.g., light conditions, wind, temperature, soil fertility) determine a ubiquitous fine-scale heterogeneity at the plot scale. Wood-pastures are often more heterogeneous environments than other managed ecosystems in the same biogeographical region such as closed forests or open, treeless farmlands. This is caused by the wide cover of native vegetation in wood-pastures, their structures and succession stages as well as the density and age structure of the tree communities. Structural heterogeneity creates ecological niches for a wide range of organisms. In particular, large, old trees are more common in wood-pastures than in other managed ecosystems, including forests (Hartel et al. 2013). These trees are known to act as ecological keystone structures (Manning et al. 2006). Wood-pastures in Romania have distinctive passerine bird communities, with more functional groups and higher absolute species richness than closed forests and treeless pastures (Hartel et al. 2014b). Similarly, oak wood-pastures in Spain have carabid assemblages that are distinct from those of closed forests (Taboada et al. 2011), and plant, bees, spiders and earthworms assemblages distinct to adjacent open pastures (Moreno et al., personal communication), thus contributing to landscape scale biodiversity. Richer saproxylic beetle communities were reported with increasing openness around old, hollowing trees from the Czech republic (Horák and Rébl 2013 for click beetles) and Sweden (Koch Widerberg et al. 2012 for other beetle species), suggesting that there are significant differences in the species communities of these organisms between wood-pasture and closed forests. Ancient trees in wood-pastures also contain significantly more lichen species than those being surrounded by secondary woodland as a result of grazing abandonment (Paltto et al. 2011). There is a considerable number of saprotrophic fungi and mycorrhizal fungi which are more common in wood-pasture type of landscapes (Diamandis and Perlerou 2008; Reyna-Domenech and García-Barreda 2009).

Management practices contribute to the biodiversity value of the wood-pastures. For example, extensive grazing with buffalo and cattle contributes to the maintenance of ponds, which are of crucial importance for the protected yellow bellied toad (*Bombina variegata*) (Hartel and von Wehrden 2013), while pollarding can promote hollowing in certain tree species, making the trees attractive for saproxylic biodiversity (Sebek et al. 2013). Multifunctionality and multiple management practices have been identified as main drivers of high biodiversity of Iberian dehesas (Díaz et al. 2013). Some species may be regionally restricted to wood-pasture landscapes, for example shade-tolerant unpalatable geophytes such as peonies (*Paeonia* spp.) and hellebores (*Helleborus* spp.) in southern Europe (Chaideftou et al. 2009). Wood-pastures often cover large contiguous areas, providing part of the home ranges of some large carnivores, such as the brown bear (*Ursus arctos*), or threatened species, such as Iberian lynx (*Lynx pardinus*) or Spanish imperial eagle (*Aquila adalberti*), which find important food resources in wood-pastures (Bergmeier et al. 2010; Roellig et al. 2014). Thus, wood-pastures can be considered umbrella ecosystems providing habitats for many species of conservation interest (Bergmeier et al. 2010).

5.3.2 Dynamic character

Current ancient wood-pasture systems may be the closest analogues to the pre-human, semi-open, and dynamic landscapes of parts of lowland Europe (Pokorný et al. 2015; Sandom et al. 2014). The temporal variation of natural forces such as mega-herbivores, climatic events, pests, and predators could have resulted in a fluid and dynamic landscape (sensu Manning et al. 2009) where pulses of tree and shrub regeneration were followed by opening of the woodlands. Dynamic human land-use through shifting rotation management systems, extensive livestock grazing, shrub clearing, or hay making, together with the high regenerative potential of the trees and shrubs creates a constantly changing landscape mosaic (Chételat et al. 2013). For example, the regeneration of trees in a Spanish wood-pasture is higher in areas with transhumant grazing (which represented a seasonal impact of livestock on the vegetation) than in areas with permanent grazing (Carmona et al. 2013). Thus, multifunctional management of wood-pastures may resemble or mimic the natural drivers of pre-human ecosystems, which are thought to function as dynamic mosaics. These are driven by an alternation of plant facilitation and competition, phases of grazing and regeneration. Spatial asynchronization of this cyclic mechanism causes shifting mosaics with patches of all structural vegetation types involved (Olff et al. 1999). This intrinsic dynamic mechanism is nowadays widely talked about – and sometime applied - in conservation management in Western Europe, aiming to restore wood-pasture landscapes.

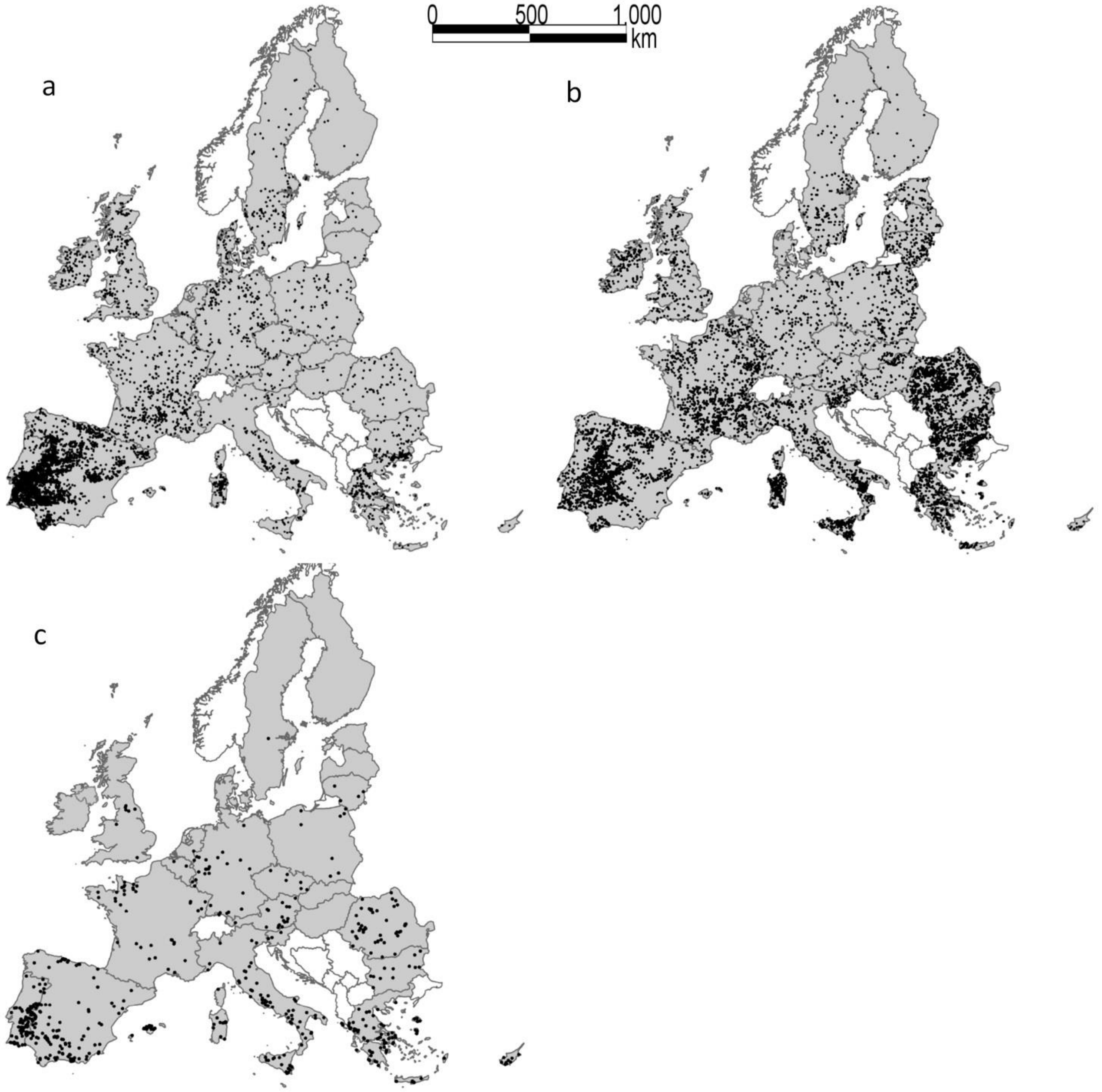

Fig. 2. Distribution of wood-pastures in Europe ((a) pastures in open woodland, (b) pastures with sparse trees, and (c) pastures with cultivated trees). Grey background indicates the surveyed area, while areas in white remained unconsidered. Note that points represent the location but not the extent of wood-pastures as they are not at scale.

5.3.3 Genetic resources

Trees in wood-pastures have often been planted or selected by humans over centuries. Wood-pastures therefore harbour a large part of the European trees species, and potentially high genetic diversity (Bergmeier et al. 2010). Oaks, beech, and other tree species from the Fagaceae family were maintained for their mast, which was an important food for pigs and sheep for centuries. Wild fruit trees such as pears, cherries, plums, and apples (*Pyrus* spp., *Prunus* spp., *Malus* spp.) were also spared from cutting and wood clearing because of their fruits. Though not abundant these trees are much more frequent in wood-pastures than in closed (semi-natural and natural) forests. Among the rare, locally distributed or threatened tree species occurring in wood-pastures and their margins are for example *Malus sylvestris* (Central and South Europe), *M. dasyphylla* (Southeast Central Europe, Balkans), *Mespilus germanica* (Southeast Balkans and Southwest Asia, naturalized in parts of Central and South Europe), *Prunus cocomilia* (East Mediterranean), *Pyrus pyraster* (Central, East and South Europe), and *Sorbus domestica* (South and Central Europe) (Garbarino and Bergmeier 2014). Many of these, particularly in wood-pastures of South-East Europe, represent wild fruit tree relatives. For example, wild species of *Pyrus* and *Prunus* have been used for grafting domestic pears, plums, cherries, and almonds. As a consequence of century-long breeding in other populations, many wood-pastures and semi-wild orchards have become important reservoirs of old landraces and cultivars (Paprštein et al. 2015).

5.4 Social-cultural values of European wood-pastures

While social-cultural values are much less researched than ecological values, some studies are available on the aesthetic and cultural heritage values, and on the traditional practices able to maintain them. Some of these social-cultural values of wood-pastures are related to the gathering of wild products, for example mushrooms and asparagus, and hunting practices (Oteros-Rozas et al. 2014).

5.4.1 Aesthetic and recreational values

Humans have been fascinated by the beauty of wood-pastures for a long time (Woodcock 1984). Moreover, recreation and nature tourism activities often depend on the aesthetic value attached to them. The mosaic land cover, the presence of livestock, or the presence of scattered, old trees all contribute to their aesthetic values (López-Santiago et al. 2014). A particularly high aesthetic value was attributed to the extensive oak wood-pastures of Spain (*dehesas*) (García-Llorente et al. 2012) and Portugal (*montados*) (Barroso et al. 2012). Different stakeholders may put different weight on the aesthetic value of wood-pastures, based also on other values and benefits. For example, farmers tend to value open wood-pastures managed for livestock highly, while nature tourists and hunters prefer wood-pastures with higher density of shrubs and environmental managers those with higher density of trees (Barroso et al. 2012; Pinto-Correia et al. 2011). These differences are driven by diverse motivations behind landscape preferences (Barroso et al. 2012) which embrace aspects of tradition, knowledge types, cultural identity, or associated recreational activities (Hartel et al. 2014a; García-Llorente et al. 2012). In spite of such differences regarding the structural details, all stakeholder groups preferred landscape configurations which are similar to wood-pastures (Surová et al. 2014).

5.4.2 Cultural heritage

Many wood-pastures have had continuity since pre-modern times (AD 500-1700) and are therefore important from a cultural and historical point of view (Jørgensen and Quelch 2014), though their cultural heritage values have been rarely investigated. Many wood-pastures bear legacies from historical land uses. For example, Mediterranean wood-pastures host terraces, stone walls, threshing floors, and other infrastructural elements that give evidence of past land-use practices (Plieninger et al. 2011). Further, coppicing and pollarding have been ancient practices across European wood-pastures that nowadays represent cultural legacies from the past (Jørgensen and Quelch 2014; Kirby et al. 1995). The ancient borders between wood-pastures and forests also bear a rich cultural heritage (Szabó 2010). The combination of soil productivity, economic demands, land ownership, and other factors often led to locally specific land management practices, which created today's cultural heritage values (Szabó and Hédl 2013). Many of these practices, for example those related to seasonal livestock movements (transhumance) (Oteros-Rozas et al. 2014), can be considered cultural heritage values by themselves.

5.4.3 Traditional knowledge

The strong reliance of local communities on the provisioning services of wood-pastures resulted in the development of profound ecological knowledge, for example, about the location and the spatial and temporal availability of natural resources (e.g. water availability, primary productivity, medicinal plants), about the effects of livestock on trees and shrubs, and about responses to disturbances such as diseases (Otero-Rozas et al. 2013). Therefore, traditional and local ecological knowledge is considered a valuable complement to scientific studies for improving understanding and stewardship of wood-pastures (Bürgi et al. 2013; Varga and Molnár 2014). The acknowledgement of traditional knowledge around wood-pastures is also essential to ensure the provision of multiple ecosystem services, including food, genetic resources, soil fertility, habitat for species, nature tourism and cultural identity (Calvet-Mir et al. 2012; Lamarque et al. 2011). Recognition of wood-pasture related traditional knowledge can be used, together with the wood-pasture itself, as a contribution toward rural development because it promotes environmental awareness, ecotourism and recreation, the creation of localized food brands, income generation outside agricultural production, social support for traditional management practices, and the transmission of this knowledge to new generations (Bieling and Konold 2014).

5.5 Management challenges

A major challenge for the conservation of current wood-pastures is their anthropogenic origin and thus the need of constant and specific management. Livestock grazing is the most influential and dominant management intervention which drives the structure and dynamics of wood-pastures. Grazing is complemented by forestry practices (such as logging, coppicing, or pollarding), shrub clearing, mowing tall herb vegetation, or using controlled fire (Van Uytvanck 2009). Multiple management practices are, therefore, indispensable for the long-term preservation of wood-pastures in Europe.

5.5.1 Important components of wood-pasture management: livestock grazing

Among the components of wood-pasture management, limiting the grazing pressure, choosing the grazing regime, and allowing for time and space gaps between grazing activities are relevant practices for ensuring tree regeneration while halting the encroachment of dense shrub cover. A grazing pressure threshold is usually expressed as the number of grazing animals per hectare per year (animal units, AU ha^{-1} y^{-1}). Thresholds that prevent or enable woody species regeneration differ depending on tree species, livestock, regions, wood-pasture types, and management phases. For the main regeneration phases in the New Forest (UK), maximum grazing pressure thresholds amount to 0.3 AU ha^{-1} y^{-1} for cattle, 0.15 AU ha^{-1} y^{-1} for ponies, and 0.45 AU ha^{-1} y^{-1} for deer (Mountford and Peterken 2003). Former pastures and arable fields in Belgium have similar thresholds of 0.35 and 0.50 AU ha^{-1} y^{-1} that allow tree regeneration in the developing mosaic vegetation during the first 5-10 years after the cessation of agricultural use (Van Uytvanck 2009). One rarely explored advantage of wood-pastures is the reduction of fodder needs of livestock thanks to tree shelter under unfavourable climatic conditions (Higgins and Dodd 1989). Concerning the grazing regime, in some locations studies have found that a year round ‘natural grazing’ by mixed, free-ranging feral herbivores, with populations limited by late winter conditions is preferable from a conservation point of view to seasonal grazing limited by summer fodder (Mountford and Peterken 2003). In practice, it is desirable that managers have knowledge about the grazing capacity of a site in wintertime, allowing them to choose an appropriate grazing density, prevent mortality, and meet EU legislation that obliges the removal of livestock carcases. The former requires lower stocking rates, supports greater habitat diversity, and allows trees to regenerate in open areas (Helmer 2002). Browsing intensity on saplings is much greater in spring and summer, when saplings have nutritious buds and green leaves, than in spring or winter (Van Uytvanck 2009). Therefore, woodland regeneration is not prevented by winter-grazing or year-round grazing by domestic herbivores (e.g., cattle, sheep). However, there are differences in browsing response according to tree or shrub species, plant size at the moment of browsing, local site conditions, frequency of browsing, amount and type of tissue eaten, and competition with ground vegetation (Hester et al. 2006). For a large variety of trees, short time gaps in grazing (2-3 years) facilitate regeneration in grassland vegetation and, equally important, allow growth beyond the browseline of large herbivores. Longer grazing exclusion is particularly needed for Mediterranean wood-pastures (Smit et al. 2008). Thus, appropriate variation of time gaps in space and time allows regeneration of woody species and conservation of grassland values at the same time (Uytvanck et al. 2008).

5.5.2 Important components of wood-pasture management: forestry practices

To maintain wood-pastures and their values, particular forest management practices are needed as well, often to be considered on a tree-by-tree basis (Fay 2004). The standard forestry practices aim to enhance growth of the main tree stems as these are the valued end-product. In wood-pastures the objectives of forestry practices are different, aiming to produce branches for fodder, firewood, and poles that are cut on relatively short cycles (Read 2006). Trees valued for their shade or for their fruit, including acorns for pannage (Jørgensen 2013), might be left with well-developed crowns. Particular management efforts are needed to maintain the old trees for as long as possible to allow for any species living in or on them to transfer to the new generation when it becomes suitable. This may involve reducing ground compaction around roots and impeding bark damage by livestock, as well as removing the branches that have become too large, endangering tree stability (Lonsdale 2013).

Restoration of pollarding, where this was once carried out, has been tried successfully in some sites on old trees even after several decades without cutting, but is likely to be less successful the longer the period since the trees were last cut (Read et al. 2010). Where encroachment of young saplings around veteran trees has occurred, an additional management priority is to reduce tree competition by removing young trees surrounding veteran ones – a practice known as 'haloing' (Alexander et al. 2010). More general thinning out of the young growth may be required to create gaps to improve herbage production, leaving a low density of stems that can develop large crowns under free growth conditions or might be turned into new pollards. The net effects of trees on pasture production are strongly context-dependent, but they are overall neutral to positive for deciduous tree species, and neutral to negative for evergreen ones, as revealed by a recent meta-analysis (Rivest et al. 2013) and several empirical studies (e.g. Gea-Izquierdo et al. 2009; Rozados-Lorenzo 2007; Sigurdsson et al 2005; Teklehaimanot et al 2002). Positive effects are mainly due to shelter and improved soil fertility, negative impacts due to competition for light, water and nutrients (Moreno et al. 2013). Further studies are needed to understand under which ecological conditions and plants traits the tree effects change from net competitive to net facilitative (Blaser et al 2013). The number of young trees to be encouraged in open ground or left after thinning in-filled wood-pasture must allow for mortality (Lonsdale 2013): not all the young trees will survive more than the approximately 150 years needed before they start to develop hollows and other veteran tree characteristics. However the more that are left the greater the overall canopy cover will be, leading to increased competition for the existing veteran trees and greater reduction of herbage production because of shading. The density and number of veteran trees needed to support key invertebrate species (Bergman et al. 2012) must also influence the replacement rate. How the young trees are then managed depends on local circumstances and objectives. Some may be pollarded to maintain the traditional practice and products from the wood-pasture and to speed-up the creation of hollows and other features associated with high value for saproxylic invertebrate and bats (Sebek et al. 2013).

5.5.3 Facing land-use changes: abandonment vs intensification

Wood-pastures are nowadays facing the effect of two contrasting land-use changes, namely abandonment and intensification, together with conversion into other landcover types (Bugalho et al. 2011; Plieninger 2012). A frequent driver of the abandonment of wood-pastures has been rural marginalization and decline of livestock farming (Plieninger and Bieling 2013) and the introduction of organized forestry in areas previously managed as pastoral systems. Reduction or exclusion of livestock grazing in wooded pastures favours the encroachment of trees and shrubs. This in turn leads to a decline of landscape heterogeneity, with a subsequent erosion of the ecological and social-cultural values of wood-pastures. In contrast, overgrazing and wood overexploitation are probably the most important drivers of wood-pasture loss in the southernmost parts of Europe. A decline in palatable perennial herbaceous species and lacking tree regeneration is sometimes followed by a complete disappearance of vegetation and subsequent soil erosion (Chaideftou et al. 2011; Moreno and Pulido 2009). In many oak dominated wood-pastures, increased grazing pressure is often associated with a reduction in old-growth tree density, regeneration failure, and tree ageing (Bergmeier et al. 2010).

5.6 Policy implications: beyond conservation legislation

Integrating wood-pastures into new agricultural and conservation policies has proved to be complicated, as institutional structures are traditionally organized within mono-functional sectors, with different bodies at different administrative levels often dealing with agriculture, forestry, environment etc. These challenges and possible ways to overcome them are exemplified in the way wood-pastures are treated in the Common Agricultural Policy, including Rural Development policy, and the Habitats Directive of the EU.

5.6.1 Common Agricultural Policy

The Common Agricultural Policy (CAP) provides essential economic support to farmers managing wood-pastures in the form of direct payments that are intended for all active farmers in the EU. These payments are especially needed by low-intensity livestock farmers, as their income from sales is often insufficient to cover costs, and they are particularly justified because the market generally does not reward the great variety of ecosystem services they provide (Plieninger and Bieling 2013).

The CAP applies rules that determine whether land (arable, permanent crops, permanent grasslands) is eligible for direct payments, which has important implications for wood-pasture conservation. Permanent grasslands are described as land used to grow grasses or other herbaceous forage. In the

2013 CAP reform, it has been added that permanent grasslands "may include other species such as shrubs and/or trees which can be grazed provided that the grasses and other herbaceous forage remain predominant as well as, where Member States so decide, land which can be grazed and which forms part of established local practices where grasses and other herbaceous forage are traditionally not predominant in grazing areas" (European Union 2013c: 619). Under this rule, Member States are given the option of applying a maximum allowable tree density on pastures (increased from 50 trees ha^{-1} under the old CAP to 100 trees from 2014), or a system of pro-rata reductions in eligibility, in proportion to the coverage of trees or other landscape elements seen as not productive. In principle, there is no limit to the number or coverage of trees that are used for grazing, but these must be distinguished from trees that are not grazed (European Commission 2014). The result of the reformed CAP is a system of rules and exceptions that potentially allows Member States to implement a well-adapted approach to pastures with trees and landscape features if they choose to and if they make extra administrative efforts. However after the heavy fines imposed by the European Commission on Member States for being too lax, authorities may prefer the simpler option of excluding any land that could raise the suspicions of EU auditors, while farmers may find it easier to remove trees and other features to avoid losing payments (Beaufoy 2014).

Policy options for a clearer recognition of wood-pastures through the direct payment system of the CAP have been suggested (Beaufoy 2014). Rather than defining the maximum number of trees or percentage of crown cover permitted on pastures, EU rules could allow for trees as long as they are part of a functioning pastoral system, as defined in terms of livestock density or grazing days. Additional eligibility criteria could be designed at national or regional levels. Also, the term 'wood-pasture' could be introduced as an explicit category of 'pasture' in the policies supporting farming. In this way, specific rules could be applied allowing for a proportion of the wood-pasture area to be eligible for payment as regeneration areas without the clearance and grazing activities that characterize actively used non-wooded pastures.

5.6.2 EU Rural Development Policy

Through its Rural Development Policy, the EU provides schemes to support specific rural development activities (inside and beyond the farming sector) (European Union 2013a). Among these, agri-environment schemes are potentially very useful for wood-pastures, as, for example, they can help to encourage appropriate grazing patterns and to manage tree regeneration. They are intended to provide payments for farmers who take on environmental commitments above and beyond those established under the rules on Good Agricultural and Environmental Condition (GAEC) of the CAP. According to the current regulation Member States are meant to "make [agri-environment] support available throughout their territories, in accordance with their national, regional or local specific needs and priorities" and "the additional needs of farming systems that are of high nature value should be given specific attention" (European Union 2013a: 491). However, only a very small minority of wood-pastures in the EU has been engaged in such schemes so far (though precise data are lacking). There is also a specific scheme in the Rural Development regulation for the establishment of agro-forestry systems on agricultural land, but this intended for tree copping as an adjunct to arable systems as much as for establishing silvo-pastoral systems until now.

Available policy options to support active farming and positive management of wood-pastures could be harnessed much more intensively by national and regional authorities, using the various measures available under the Rural Development Policy. Agri-environment is the most important of these, but there are other complementary measures such as aid for investments and for management plans.

5.6.3 EU Habitats Directive

The Habitats Directive is the major EU legislative instrument for wildlife and nature conservation. Adopted in 1992, the aims of the Directive are to maintain and restore favourable conservation status of natural habitats and of wild fauna and flora of Community interest (European Union 1992). Natura 2000, a pan-European network of protected areas, is at the core of the Directive.

Among the 233 European natural habitat types listed in Annex I of the Directive (European Union 1992), 65 are to some extent related to wood-pasture (European Commission 2013). However, only four habitat types are explicitly recognized as grazed woody formations (i.e. *Juniperus communis* formations on heaths or calcareous grasslands, Arborescent matorral with juniper, Dehesas with evergreen oaks, and Fennoscandian wooded pastures). Our analysis of LUCAS data reveals that 27.6% of the wood-pastures in the EU-27 are included in the Natura 2000 network (17.7%, 31.2%, and 25.6% of wood-pastures with cultivated trees, in open woodlands and with sparse trees, respectively). Although 27.6% is above of the proportion of the area covered by Natura 2000 in the EU-27 territory (17.5%), wood-pastures are still underrepresented in many countries (Fig. 3).

Many Annex I habitat types related to wood-pasture refer actually to forest habitats but managing these as, or restoring them towards, forests as demanded by the definition given in the Interpretation Manual, would endanger many of the specified ecological and social-cultural values of wood-pastures. If criteria and definitions of forest habitats were strictly applied (which they are frequently not), wood-pastures would have to be assessed as in unfavourable conservation status (Bergmeier et al. 2010). Adequate forest management, as defined in the management plans of many Natura 2000 sites, focusses on natural processes and aims to maintain or restore ungrazed, dense, and tall forest. In this way, restoration would lead to natural old-growth forest rather than safeguarding open wood-pasture. In current practice, however, sustainable livestock grazing in forests of Natura 2000 sites is frequently tolerated, at least in South and Southeast Europe and UK.

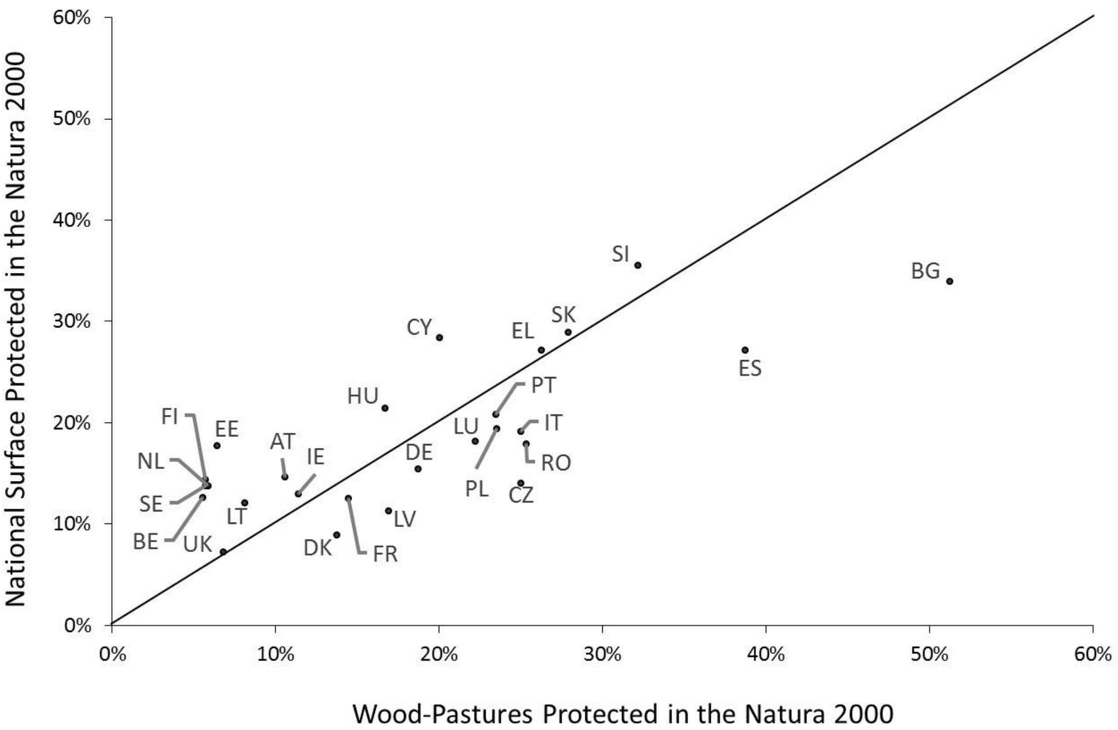

Fig. 3. Proportion of wood-pastures protected by the Natura 2000 network in 27 European countries, compared to the proportion of the countries' territory that is covered by the network (source: European Environment Agency).

The resulting uncertainty in Natura 2000 sites of what should be managed as forest, pasture, or wood-pasture calls for clarification. Some wood-pastures are seen as forest while others are recognized as pastures, neither providing optimal management prescriptions for wood-pastures (Bergmeier 2008). Conservation of many outstanding wood-pastures that are not included under the Natura 2000 network due to their – presumably – poor conservation status (judged from the perspective of natural forest) could be fostered through introducing a new habitat group into the Habitats Directive – wood-pasture – that would acknowledge the particular conservation values of wood-pastures.

5.7 Conclusion

Given that the High Nature Value of wood-pastures is the result of a long-lasting and complex interaction between humans and nature, a narrow disciplinary research agenda has limited capacity to provide solutions for the sustainable conservation of wood-pastures. Therefore, research should ideally be guided by a holistic vision which integrates information about ecology, societal values, and governance. Ecological research would provide information on biodiversity, patterns in species distribution and abundance, and the ecological processes underlying these patterns, the keystone structures for biodiversity, and the status of and main threats to wood-pastures. In many European countries there is little large-scale spatial and process-based monitoring of wood-pastures. Data are lacking on surface area, species composition, animal density and herding seasonality, tree age structure and rejuvenation, tenure, and current and past land use. This is the evidence needed to develop policies to protect and maintain wood-pastures. A second research dimension would identify the societal value of the wood-pastures, including their ecological and social-cultural values. The knowledge generated by ecosystem service research can be a powerful tool in developing contextual policies for wood-pastures, because it gives insights into the societal relevance of these landscapes under various bioclimatic, social-cultural and economic settings. A third research dimension would address the institutional arrangements which govern wood-pastures. Wood-pastures by definition are heterogeneous landscapes with elements of woody vegetation and open areas, and a varied institutional framework to match. The future of wood-pastures depends on the ability of these various institutional arrangements to form a common vision and to show the flexibility to implement such a vision. Research could support such visioning by facilitating an understanding of the nature of these potential institutional barriers and of the kinds of innovative changes that could be adopted in order to maintain the ecological and social-cultural values of wood-pastures.

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