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Mixtures of forest and agroforestry alleviate trade-offs between ecosystem services in European rural landscapes

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Abstract

Rural Europe encompasses a variety of landscapes with differing levels of forest, agriculture, and agroforestry that can deliver multiple ecosystem services (ES). Whilst provisioning and regulating ES associated with individual land covers are comparatively well studied, less is known about the associated cultural ES. Only seldom are provisioning, regulating, and cultural ES investigated together to evaluate how they contribute to multifunctionality. In this study we combined biophysical and sociocultural approaches to assess how different landscapes (dominated by forest, agriculture or agroforestry) and landscape characteristics (i.e. remoteness and landscape diversity) drive spatial associations of ES (i.e. synergies, trade-offs and bundles). We analysed data of: i) seven provisioning and regulating ES (spatially modelled), and; ii) six cultural ES (derived from participatory mapping data) in 12 study sites across four different biogeographical regions of Europe. Our results showed highly differentiated ES profiles for landscapes associated to a specific land cover, with agroforestry generally providing higher cultural ES than forest and agriculture. We found a positive relationship between the proportion of forest in a landscape and provisioning and regulating ES, whilst agriculture showed negative relationships. We found four distinct bundles of ES. Three of them were directly related to a dominant land cover and the fourth to a mixture of forest and agroforestry that was associated with high social value. The latter bundle was related to zones close to urban areas and roads and medium to high landscape diversity. These findings suggest that agroforestry should be prioritised over other land covers in such areas as it delivers a suite of multiple ES, provided it is close to urban areas or roads. Our results also illustrate the importance and application of including people's perception in the assessment of ES associations and highlight the relevance of developing integrated analyses of ES to inform landscape management decisions.

Keywords: multifunctionality; perceived landscape values; agroforestry systems; ecosystem services bundles; public participatory GIS

1. Introduction

Across Europe, land managers face the challenge of delivering multiple ecosystem services (ES) that provide short- and long-term benefits to society from a constrained area of land (MEA, 2005). Achieving high levels of all ES simultaneously is difficult, particularly in farming landscapes where negative associations between provisioning and cultural ES are common (Howe et al., 2014). Understanding how to guide management of rural landscapes in order to enhance the delivery of various ES simultaneously, while reducing undesired tradeoffs, is a long-standing challenge of ES research (Carpenter et al., 2009). Hence, much effort has been placed on evaluating the interconnections between ES for specific land covers. The assumption is that evaluating ES synergies and trade-offs, and how they consistently group across space or time in ES bundles, can help to predict the implications of management and environmental policy decisions (Spake et al., 2017).

Previous studies on the relationships among ES in landscapes where various land covers are intermingled, such as farming landscapes, have mainly focused on single ES values (Fagerholm et al., 2016b). In other words, many ES studies investigate either the biophysical or sociocultural dimensions (e.g. Kay et al., 2018; Plieninger et al., 2019). Such approaches have been criticized for being biased or too simplistic (Boerema et al., 2017). Biophysical studies have generally focussed on the maximum potential of ecosystem structure and functioning to provide ES, with independence if ES are used, recognised and valued for humans (Tallis et al., 2012). These studies have grown substantially in number over the last two decades (Ochoa and Urbina-Cardona, 2017). One positive point of this approach is that they often develop spatially explicit models of a wide range of provisioning and regulating ES that provide an improved understanding of spatial relationships between ES, including synergies and trade-offs (Nelson et al., 2009, Kay et al., 2018a). This approach has allowed, for example, the comparison of different land use scenarios at landscape scale (Kay et al., 2018), the development of high resolution models of ES and their relationships (Nguyen et al., 2018), and the integration of a wide range of spatial scales. However, the use of high-spatial resolution or spatially-accurate models does not mean that they can be directly used for landscape management and decision support if they are not useful nor user friendly to allow stakeholder engagement (Zulian et al., 2018). For this reason, and in order to include the human dimension of social-ecological systems, the use of sociocultural approaches for ES assessment has increased in recent years (Scholte et al., 2015).

Sociocultural landscape studies typically adopt the perspective of the beneficiary. They often investigate how society uses and/or perceives the services provided by nature or landscapes. Sociocultural preferences can help to identify which ES are important for human well-being, why this is, and which ES bundles and trade-offs are commonly found (Martín-López et al., 2012). Various approaches to sociocultural research allow for the collection of comparable data and have an easily reproducible structure (Fagerholm et al., 2016a; Garcia-Martin et al., 2017; Schmidt et al., 2017). Among them, spatially explicit techniques are particularly compatible with biophysical data (Hernández-Morcillo et al., 2013). Public Participation Geographic Information Systems (PPGIS) where *"participants identify spatially explicit direct and indirect benefits from ecosystems that contribute to human well-being and may also include an assessment of the relative importance of the services provided"* is one example of how the integration of biophysical and sociocultural dimensions can be achieved (Brown and Fagerholm, 2015, p. 120).

The few existing integrative approaches, that spatially analyse the relationships between biophysical and sociocultural values, have provided important insights (Wei et al., 2017). For instance, Castro et al., (2014) reported spatial mismatches among biophysical, sociocultural and economic values of multiple landscape units in southern Spain. Similarly, integrative spatial analysis has helped to highlight potential conflicts among stakeholders (Zoderer et al., 2019). Such integration can inform the management and governance of European farming landscapes, where there is an urgent need to tackle challenges associated with land abandonment or land use intensification (Benayas et al., 2007; Rolo et al., 2020; van der Zanden et al., 2017).

Agroforestry, defined as the "*deliberate integration of woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions*" (Burgess and Rosati 2018, p. 803), is a significant land use in Europe (den Herder et al., 2017), and its wider adoption could foster multifunctionality in European rural landscapes (Kay et al., 2019; Moreno et al., 2018). Agroforestry systems can provide high sociocultural benefits, such as cultural heritage or spiritual benefits (Fagerholm et al., 2016b; Oteros-Rozas et al., 2018). Many authors have also emphasized the role of agroforestry for biodiversity (Manning et al., 2006; Moreno and Rolo 2019; Torralba et al., 2016) and for ES provision, such as climate regulation, control of soil erosion and nutrient leaching, and provision of raw materials (Torralba et al., 2016; Kay et al., 2018a, 2018b, Crous-Duran et al. 2018, 2020). Developing approaches that quantify and integrate the biophysical and sociocultural values of agroforestry could enable more holistic and comprehensive landscape management strategies in European farming landscapes (Garcia-Martin et al., 2017).

In this study, our aim was to assess ES synergies, trade-offs and bundles in 12 rural areas across Europe to understand how the spatial association of forest, agriculture and agroforestry shape their multifunctionality. We combined biophysical and sociocultural approaches (for convenience and simplicity, both approaches will be called ES hereafter) and undertook a spatially-explicit analysis to assess the distribution of ES and their potential overlaps and mismatches in space. We mapped three provisioning and four regulating ES with a modelling approach and six cultural ES with participatory mapping methods, and examined if land cover and other landscape characteristics such as distance to urban areas and roads and diversity (i.e. proportion of different land cover types) drive ES delivery. Our specific objectives were: i) to assess the spatial overlap between biophysical and sociocultural dimensions and, thereby, the potential synergies and trade-offs among different ES; ii) to identify potential bundles of ES, and; iii) to study the effect of land cover (and specifically agroforestry) and landscape characteristics on the presence of ES bundles in European rural areas.

2. Materials and methods

2.1. Study sites

The study considered 12 rural study sites across nine European countries (Fig.1). The study sites spanned four different biogeographical regions (Mediterranean, Atlantic, Boreal and Continental), were representative of the major types of rural areas in Europe and spread across a large gradient of land covers (Kay et al., 2017). Study sites were embedded within a larger rural area with similar socio-economic characteristics and share of land covers. Agriculture, forest and agroforestry were the dominant land covers, ranging between 63 and 93 % of the total study site area (Table 1). Agroforestry land cover included either the integration of trees in arable systems, trees in livestock systems, or livestock in tree-based systems (den Herder et al., 2017). Agriculture land cover consisted of farmland without the tree component but with cropping or pasture activities, whilst forest land cover consisted of forest areas with little agricultural activity. The Mediterranean sites include “dehesa” and “montado” systems where woodlands of *Quercus ilex* and *Quercus suber* are grazed, or the combination of olive trees (*Olea europea*) with arable crops, fields of cereal crops and oaks and pine forests. Study sites located in the Atlantic region included multiple broadleaved (e.g. *Castanea sativa*) and coniferous tree species, hedgerows in areas for grazing and for arable crops, grasslands and crops and vegetables fields. Continental sites from Central and Eastern Europe included coniferous (e.g. *Picea abies*) and broadleaved (e.g. *Quercus robur*, *Prunus* sp.) trees and woody elements in a wide range of agricultural uses (e.g. livestock, crops or horticulture). The study site located in the Boreal region was characterized by areas for animal grazing mixed with large oak trees (*Quercus robur*) and coniferous forests (Table 1).

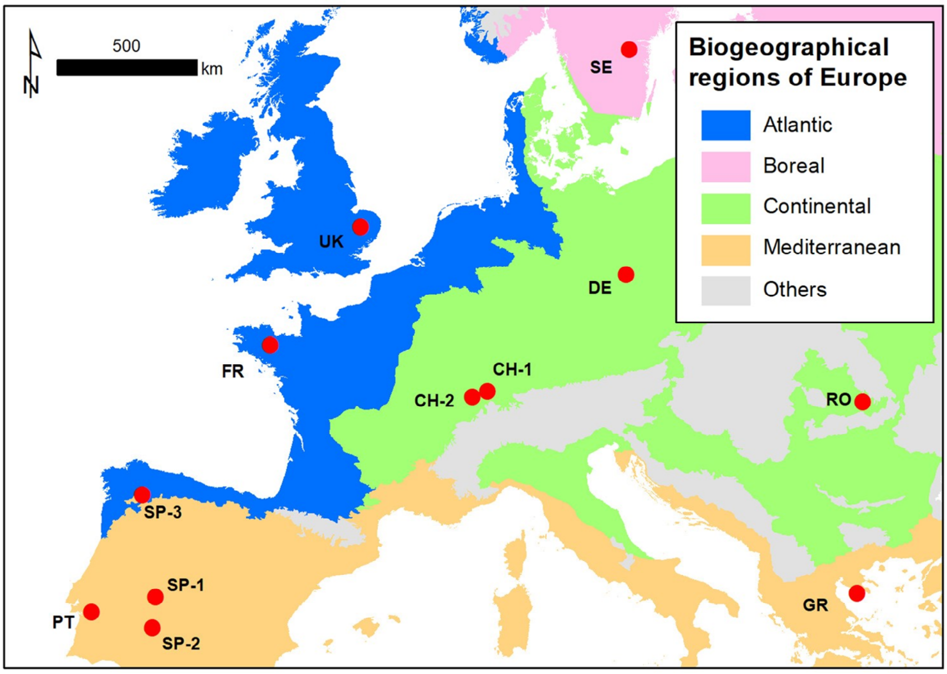

Figure 1. Location of the different study sites across the biogeographical regions of Europe.

2.2. Data sources

Land cover classification

Land cover maps (cell size 100 m x 100 m; 1 ha) were based on an improved and simplified version of the CORINE 2012 land cover data (EEA, 2012) complemented with either high resolution aerial ortho-images (0.25-0.25 m) or Copernicus Tree Cover Density (EEA, 2016) derived from remote sensing of European forest cover. First, CORINE 2012 land cover types within each study site were grouped into five main categories. The five categories were: i) artificial (CORINE codes 111 to 142: e.g. urban, fabric, mining, and roads); ii) agriculture involving arable land (codes 211 to 213), permanent crops (codes 221 to 223) and pasture (codes 231 and 321: managed pastures and natural grasslands); iii) heterogeneous agricultural areas (codes 241 to 244), defined here as agroforestry systems because agroforestry was an important land cover in most study sites (Table 1); iv) forest and semi-natural areas (codes 311 to 335, except 321); and finally v) water and wetlands (codes 411 to 523). CORINE Land Cover provides relevant information at large spatial scales, and it is available for the whole European Union. However, the methodology of CORINE to map agroforestry land cover is not consistent among countries, agroforestry *sensu strictus* is recorded by CORINE only in countries where it is the prevailing land use (Portugal, Spain and Italy, and small patches in France and Austria), while agroforestry combinations are present in many other regions of Europe (den Herder et al 2017). In order to refine the CORINE land cover categories, we either used high-resolution aerial ortho-images (0.25-0.25 m) or Copernicus Tree Cover Density (EEA, 2016).

In seven study sites, where high-resolution images were available (three case studies in Spain, two in Switzerland, one in France and one in the UK), images were decomposed in red, green and blue raster layers. Each layer was averaged (±SD) for every 1 ha of land (100 m x 100 m cell size). The six vector layers (3 bands x 2 values, the mean and the SD) were plotted separately for each of the land cover categories that appears in CORINE. The 1-ha cells that deviated beyond the 25-75 quartiles in any of the six vector layers were visually checked and reassigned to another category where it was necessary. For instance, low mean values were very useful to detect additional forest areas, high mean values to detect additional urban areas, and high SD to detect agroforestry areas. Overall, between 10% (Spain, SP-1) and 30% (Switzerland, CH-1) of the cells were reassigned.

For the rest of study sites (Greece, Portugal, Sweden, Germany and Romania), we combined CORINE and Copernicus Tree Cover Density data (EEA, 2016) derived from remote sensing of European forest cover. More detailed criteria used for this classification are in supplementary material (Supplementary material, Table A1). By combining CORINE and Copernicus Tree Cover Density data we could identify areas with predominantly agricultural land cover but also significant tree cover (5-50%). These were the areas where agroforestry land cover located but omitted by the original CORINE Land Cover classification. Reassigned cells ranged between 10 % (Portugal) and 20 % (Germany).

Table 1. Study sites description including the share of various land cover types (F: Forest; AFS: Agroforestry; A: Arable; B: Built up areas) and the number of respondents that participated in the Public Participation Geographic Information Systems procedure (Resp. Number).

Region	Study site	Area, ha	Landscape description	Land cover (%)	Resp. Number

Atlantic	SP-3, Spain	52684	Mountainous area with forests, pastures, arable land, semi-natural traditional chestnut (*Castanaea sativa*) groves	F: 41.2 AFS: 41.7 A: 9.1 B: 7.9	171
	FR, France	73706	Arable land with mixed diary, fodder and grain production dominating, some grasslands, traditional hedgerow networks (*bocage*)	F:19.5 AFS:41.1 A: 18.2 B: 21.2	146
	UK, United Kingdom	163988	Intensive agriculture, outdoor pig production, crop and vegetable production, and plantation conifer forestry	F:30.0 AFS:21.0 A: 26.2 B: 22.8	173
Boreal	SW, Sweden	157837	Arable and urban land, some coniferous forest, open and patchy oak pastures of (*Quercus robur* and *Quercus petraea*)	F: 43.2 AFS: 11.7 A: 18.1 B: 27.0	172
Continental	CH-1, Switzerland	4989	Farmland, grasslands and traditional orchards (*Prunus avium*) with mosaic of forest patches, recreation area for nearby city	F: 28.8 AFS: 18.9 A: 15.1 B: 37.2	219
	CH-2, Switzerland	5214	Mountain forest and grasslands with trees, outdoor recreation tourism, wood pastures with free ranging horses and cattle	F: 58.8 AFS: 4.4 A: 23.8 B: 13.0	167
	DE, Germany	9276	Intensive agriculture, forests and heterogeneous agricultural land with arable crops and seminatural features (hedgerows, trees, woodlots)	F: 34.5 AFS: 10.9 A: 31.5 B: 23.1	158
	RO, Romania	23773	Traditional land use practices, pastures with scattered trees, typically oak (*Quercus robur, Quercus petraea*), forests and arable fields	F: 31.2 AFS: 13.0 A: 31.9 B: 23.9	182
Mediterranean	GR, Greece	33272	Arable land (cereals), scattered olive trees, pine forests, olive groves with understory cultivation or grazing or both, tourism main economic activity	F: 28.2 AFS: 27.6 A: 28.5 B: 15.7	168
	PT, Portugal	122851	Oak (*Quercus suber, Quercus rotundifolia*) pastures (*montado*) combined with agriculture (cereals)	F: 36.6 AFS: 33.2 A: 17.0 B: 13.2	173
	SP-1, Spain	94048	Oak (*Quercus ilex*) pastures (*dehesa*) for livestock breeding (sheep, cattle, Iberian black pigs) combined with extensive cereal crops and shrublands	F: 20.2 AFS: 48.6 A: 16.2 B: 14.9	219
	SP-2, Spain	63768	Arable lands, arable lands with scattered oaks (*dehesa*), forest and shrublands, increasing nature tourism	F: 18.4 AFS: 42.7 A: 30.1 B: 8.8	182

Ecosystem service assessment

Provisioning and regulating ES were modelled using a series of previously developed and tested ecological models for the same study sites based on detailed field, environmental and cartographic data (see Kay et al., 2018a, 2018b). Five different models were used to quantify provisioning and regulating ES. Modelled provisioning ES included biomass yield and stock and groundwater recharge, and regulating ES included carbon sequestration and stock, nutrient retention and soil preservation. The Yield-SAFE model was employed for quantifying biomass production and biomass stock of trees and crops. Yield-SAFE is a parameter sparse model that calculates daily tree and crop growth in forestry and arable production and accounts for the solar-radiation and water-based interactions of trees and crops in an agroforestry system (van der Werf et al., 2007; Palma et al 2016, Crous-Duran et al., 2019). A water balance equation was used to calculate groundwater flows and recharge rates by taking into account the amount of precipitation minus plant evapotranspiration, surface runoff and storage change in the soil (Kay et al., 2018b). The MODIFFUS 3.0 model was used for evaluating nitrate retention. MODIFFUS 3.0 calculates the load of nitrate leached from land to the environment. We calculated the inverse of the load value as a proxy of nitrate retention (Han et al., 2019). Soil preservation was based on the RUSLE equation for rating soil losses that takes into account rainfall-runoff erosivity, erodibility, slope and cover management (Renard et al., 1997). Similarly to nutrient retention, we calculated the inverse of soil losses as a proxy of soil preservation. The logic behind the transformation was to turn a disservice into a metric that could indicate the potential of risk reduction. Finally, the Yield-SAFE model and the YASSO 0.7 model were used to calculate above-ground and below-ground carbon sequestration. These models were computed, adapted and reclassified per land cover class at a spatial resolution of 100 x 100 m (c.f. Table 2 and Kay et al., 2018).

Cultural ES were assessed using a Public Participation Geographic Information Systems (PPGIS) approach. A total of 2,130 local residents across the 12 study sites (ranging from 146 respondents in France to 219 in Switzerland and Spain, Table 1) were engaged through a facilitated map-based survey to locate ES that were relevant to each individual (Fagerholm et al., 2019). We developed a typology of cultural ES that sought to capture the material and symbolic/intrinsic benefits of ES (Scholte et al., 2015). In this way, the ES mapped related to the subjective values and activities of respondents in the landscape, which are often linked to the cultural ES category (Brown and Fagerholm, 2015).

Table 2. Description of biophysical and cultural ecosystem services (ES).

ES Category	Description (units)	Symbol	Model	Reference
Provisioning	Biomass production - Annual amount of biomass harvested (t dry matter ha^{-1} yr^{-1})	Byl	Yield-SAFE	van der Werf et al., (2007); Palma et al., (2016), Crous Duran et al., (2019)

	Biomass stock - Total amount of biomass stored (t dry matter ha^{-1})	Bst	Yield-SAFE	van der Werf et al., (2007); Palma et al., (2016), Crous Duran et al., (2019)
	Groundwater recharge rate - Proportion of the precipitation which infiltrates into groundwater (%)	Rch	Water balance equation	Kay et al., 2018b
Regulating	Nutrient retention - Inverse of annual amount of nitrogen leaked to water bodies (1/kg N ha^{-1} yr^{-1})	Nrt	MODIFFUS 3.0	Hürdler et al., (2015)
	Soil preservation – Inverse of annual amount of soil sediment lost by water (1/t soil ha^{-1} yr^{-1})	Spr	RUSLE equation	Renard et al., (1997)
	Carbon sequestration - Annual amount of carbon sequestered (t C ha^{-1} yr^{-1})	Csq	Yield-SAFE Yasso07	Crous-Duran et al., (2019) (2020) Liski et al., (2005)
	Carbon stock - Total amount of carbon stored (t C ha^{-1})	Cst	Yield-SAFE Yasso07	Crous-Duran et al., (2019) (2020) Liski et al., (2005)
Cultural	Outdoor activities - Sports, walking, hiking, biking, dog walking	Out	PPGIS	Fagerholm et al., (2019)
	Social interactions - Spending time together with other people	Soc		
	Aesthetic values - Enjoy seeing a beautiful landscape or landmark	Aest		
	Cultural diversity/heritage - Places appreciated for the local culture, cultural heritage or history	Cult		
	Inspiration value - Inspiration by feelings, new thoughts, religious or spiritual meanings	Ins		
	Existence value - Places appreciated as such, independent of any benefit to humans	Exs		

A common interview guide was developed, which was applied in all study regions, and interviewers were trained to follow a common protocol, that was also adapted to local customs. Respondents were addressed in key public spaces such as markets, cafés, schools or health care centers. The survey started by locating the respondents' home and afterwards each respondent located ES benefits as points in the map. The ES mapping was operationalized using ES benefit statements such as "*I appreciate, enjoy or get inspired here*". The full set of statements used for each ES benefit is included in the Supplementary material Table A2. The same set of statements was used in each study site. In each study site, local residents were recruited through purposive stratified sampling based on gender and age (three groups: 15-29, 30-59 and ≥ 60 years) in proportion to local census data. The survey was translated into local languages and data collection was carried out between May 2015 and August 2016 using a web-based survey tool during face-to-face interviews. The background map was a Bing satellite image overlain with Open Street Map objects. A minimum zoom level of 1:25,000 was enforced to ensure spatial scale coherence in mapping.

Statistical methods

To enable cross-site and ES comparisons, we standardized ES values between 0 and 1 (i.e. subtracting the minimum value and dividing by the range) for each study site. For provisioning and regulating ES, values lower or higher than the 5th or 95th percentile were assigned the 5th or 95th value respectively to minimise potentially erroneous transformations due to the presence of outliers. We followed the approach previously developed by the group to transform PPGIS point data into density maps (Plieninger et al., 2019) and to bring all data sources to a comparable spatial scale (Fig. 2). Each study site was divided into a grid of 400 m cell size. Then, cultural ES elicited through PPGIS were transformed into density by counting the number of responses (i.e. mapped points) that fall within a grid cell. Grid cells that did not contain any response were discarded. Provisioning and regulating ES values were extracted for each PPGIS point and the median was computed at the grid cell level. Similarly, land cover type (i.e. forest, agroforestry and agriculture) was extracted for each point and the proportion of each land cover was calculated at the grid cell level. For simplicity we name grid cells as landscape unit (LU). We follow the terminology proposed by Termorshuizen and Opdam (2009) who defined landscape as a spatial social-ecological area where multiple ES are delivered to society. Figure 2 depicts the data management process.

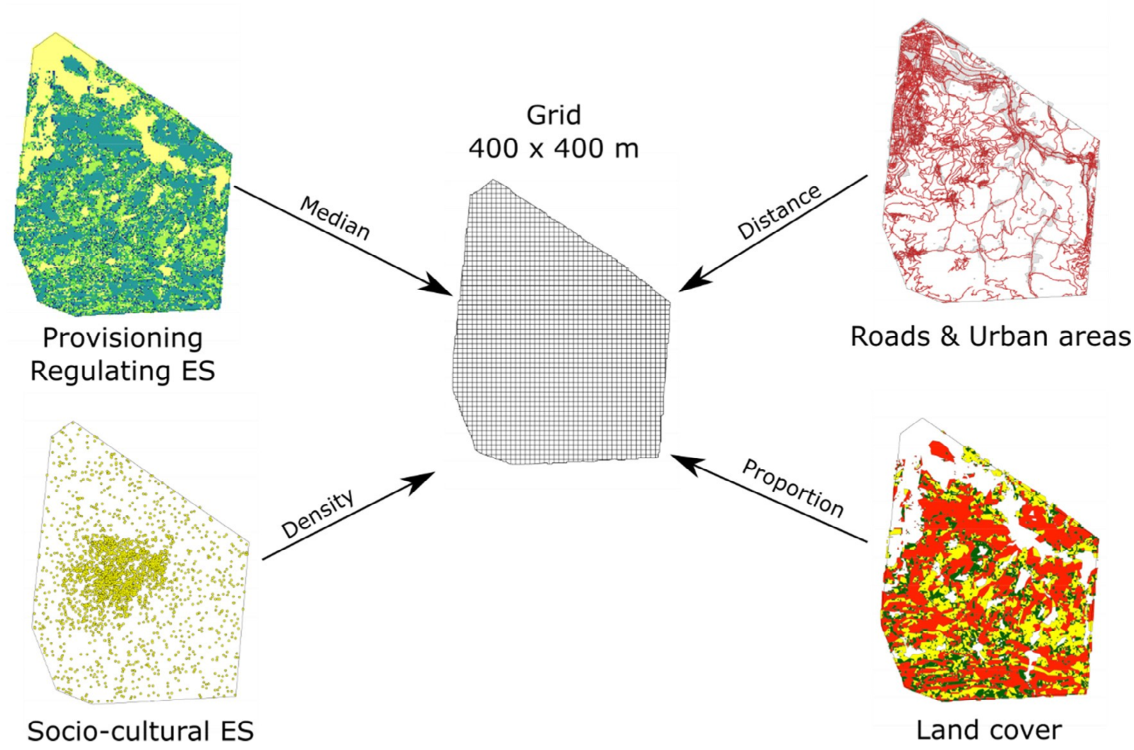

Figure 2. Example of the CH-1 study site depicting the data management process. All data were referred to a grid cell of 400 x 400 m. In each cell, provisioning and regulating ES were summarized by taking the median. The density of points was computed for cultural ES. For each land cover, the proportion was calculated. Finally, a remoteness metric was assessed for each grid cell by taking into account the distance from roads and urban areas. For simplicity we name in the text grid cells as landscape unit (LU).

To assess spatial overlaps among ES and their relation to land cover, we ran bivariate Spearman's rank correlations among ES and land cover proportion. Spatial agreement between ES indicates synergies, whereas discordant relationships infer trade-offs. We also ran a principal coordinate analysis (PCA) to assess the multivariate association of ES and their relation to land cover. PCA were run using the full dataset of ES and separately for each ES category (provisioning, regulating and cultural). We subsequently extracted the scores for each grid cell of the axis of the PCA that used the full dataset with eigenvalues higher than one. We used this dataset to compute a hierarchical cluster analysis using Euclidean distance and Ward's technique. We then used the Calinski–Harabasz stopping criterion in order to identify the optimal number of bundles among ES (Caliński and Harabasz, 1974). This allowed us to define ES groups based on the spatial association of the various ES and land cover types. Following the clustering, we rendered ES associations by using star diagrams and evaluated how bundle frequencies differed among land cover types, we computed mean values and bootstrapped 95% confidence intervals of each land cover for each bundle group.

Given the dependency of cultural ES on the proximity to urban areas (Fagerholm et al., 2019) and dependence of ES delivery on the presence of people in a landscape (Peña et al., 2015), we assessed the influence of remoteness in driving the presence of each bundle. We calculated a proxy for remoteness (i.e. potential to reach places to benefit from ES) for each grid cell per study site based on the distance from the nearest urban area and from roads (Paracchini et al., 2014). The remoteness for each grid cell was calculated by summing standardized values (ranging between 0 and 1) of both distances, so that the metric ranged between 0 (low remoteness) and 2 (high remoteness). The distribution of remoteness values showed a three modal tendency (Fig. A1), thus we categorized it into low (< 0.4), medium (0.4 < remoteness < 1.2) and high (≥ 1.2) remoteness. Land cover diversity was assessed by computing Shannon diversity for each grid cell based on the proportion of each land cover type. As for remoteness, the distribution of diversity values showed a three-modal tendency (Fig. A1), thus we categorized this into low ($h = 0$), medium ($0 < h < 1$) and high ($h \geq 1$) land cover diversity. We ran generalized linear models with a Poisson distribution, using frequency of the corresponding contingency table as a response variable, and bundle, remoteness, landscape diversity and their interactions as predictors. The significance of each variable was tested by likelihood ratio tests.

All these analyses were conducted in R v3.5.3 (R Core Team, 2019).

3. Results

3.1. Distribution of Ecosystem Services values

Our results showed different ES profiles depending on the dominant land cover at the landscape unit level (LU, i.e. at 400 x 400 m grid cell) (Fig. 3). Forest LU (i.e. a LU where forest occupied > 50 %) showed higher values of biomass stock, carbon stock and carbon sequestration across study sites than the rest of LUs dominated by other land covers. Agriculture LUs showed the highest values for groundwater recharge, and the lowest values for nutrient retention and soil preservation across study sites as compared with forest and agroforestry LUs. In agroforestry LUs, provisioning and regulating ES values were between forest and agriculture LUs (e.g. it had higher values of carbon sequestration than agriculture LUs but lower values than forest LUs), but showed systematically higher values for cultural ES than the other two. This pattern was consistent across study sites and biogeographical regions. There was substantially less variation in the ES provided by agroforestry LUs within each study site as compared to forest or agriculture LUs which exhibited, on average, more than a two-fold increase in the coefficient of variation. This pattern was particularly evident in the DE study site, that had the largest differences in terms of variation of ES values, with agroforestry LUs showing a coefficient of variation across ES of 40.2 % while forest and agriculture LUs had coefficients of variation of 100.3 % and 176.9 %, respectively. On average, taking together all study sites, the coefficient of variation across ES was 51.4 ± 2.5 % for agroforestry, was 91.9 ± 2.4 % for forest, and 131.0 ± 7.7 % for agriculture LUs.

3.2. Spatial associations among provisioning, regulating and cultural ES

Bivariate and multivariate analysis showed consistent associations between ES (Fig. 4 and Fig. A2). Associations between pairs of ES tended to cluster into three groups where ES shared strong positive correlations but that had no or negative correlations with the rest of the ES (Fig. 4). Biomass stock, carbon sequestration and carbon stock, the proportion of forest cover in a LU and to a lesser extent nutrient retention and soil preservation formed a cluster of positive associations. The proportion of agriculture and recharge rate showed a positive association and both of them were strongly and negatively related to carbon stocks and nutrient retention. Indeed, agriculture cover showed negative or no associations with most regulating and provisioning ES except for recharge rate. Principal component analysis confirmed the negative correlations between the cluster composed by biomass yield together with recharge rate and carbon sequestration and carbon stock, biomass stock, nutrient retention and soil preservation. Both groups were split along the first PCA component that explained about 30% of the variability. In total, the first two components of the PCA explained about 45% of the variability (Fig. A2A). The proportion of agroforestry in a LU showed weaker relations than forest and agriculture cover, only showing a negative association with biomass and carbon stocks, and a positive association with soil preservation. To a lesser extent, cultural ES comprised a third cluster of associations, but with weaker associations among its components than found in the other two groups. Within the cultural ES group, cultural heritage, existence, aesthetic and inspirational values showed higher levels of association with each other than to outdoor activities, or social interaction. For instance, social interaction was only correlated to outdoor activities and aesthetic values. In general, cultural ES were not correlated with any of the three land cover types, except for inspirational values and forest cover.

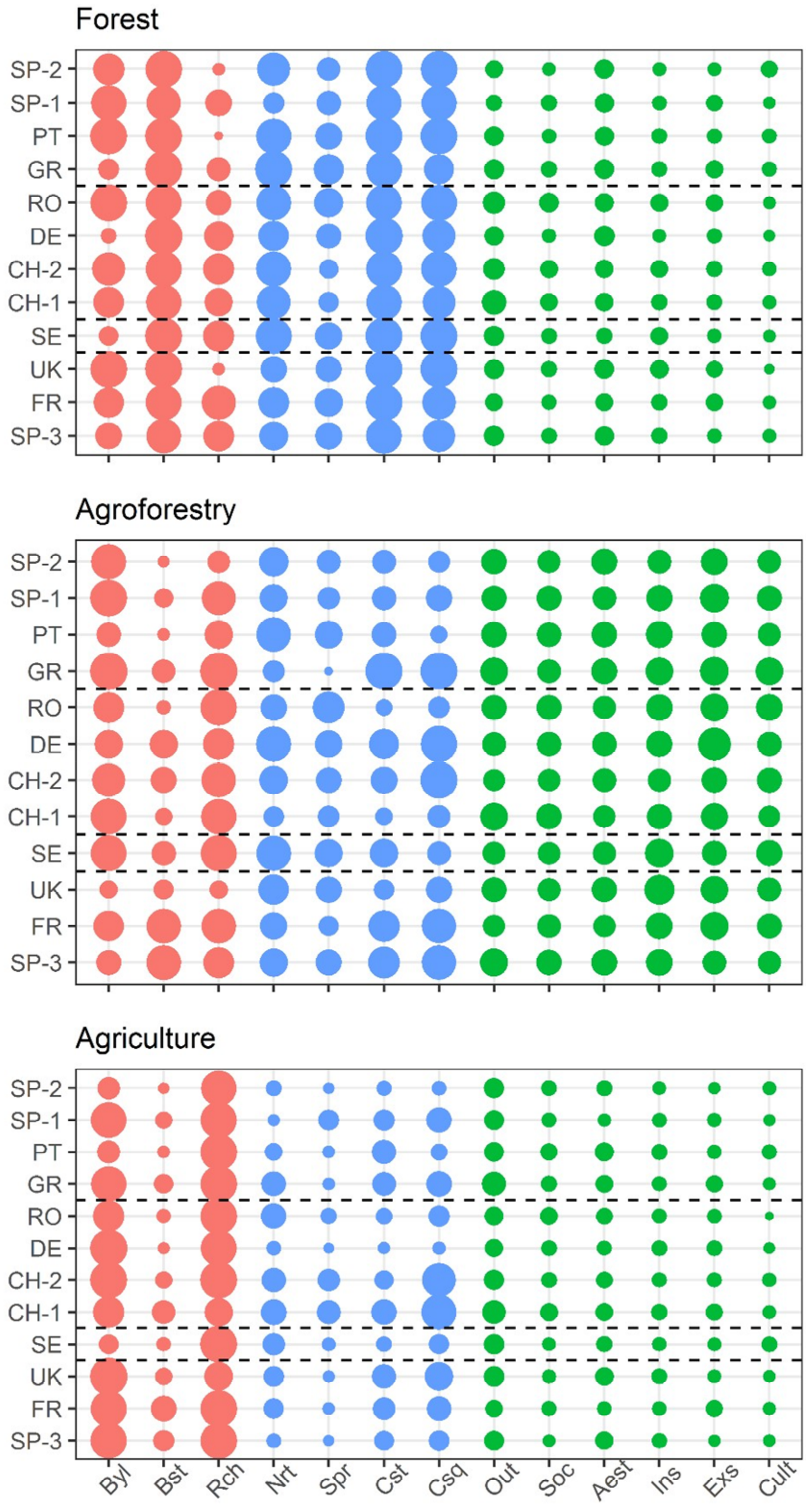

Figure 3. Standardized ES values of landscape units where forest, agroforestry and agriculture land covers were dominant (> 50 %) for each study site. Point size varies according to ES values. Provisioning, regulating and cultural ES are depicted in red, blue and green, respectively. See Table 2 for ES abbreviations. Dashed horizontal lines separates biogeographical regions (Mediterranean, Continental, Boreal and Atlantic, from top to bottom).

Bivariate analysis showed a higher number of significant associations between cultural ES and provisioning or regulating ES than multivariate analysis. PCA results showed that cultural ES did not correlate with provisioning or regulating ES, being negatively related to the second component that explained about 13% of the variability and to the proportion of agroforestry in a LU (Fig. A2A). By contrast, bivariate analysis showed a number of associations. For instance, recharge rate was negatively associated to outdoor activities and aesthetics but positively related to cultural heritage and existence values. Inspirational values showed the highest number of linkages, being positively related to carbon and biomass stocks and carbon sequestration and negatively related to biomass yield.

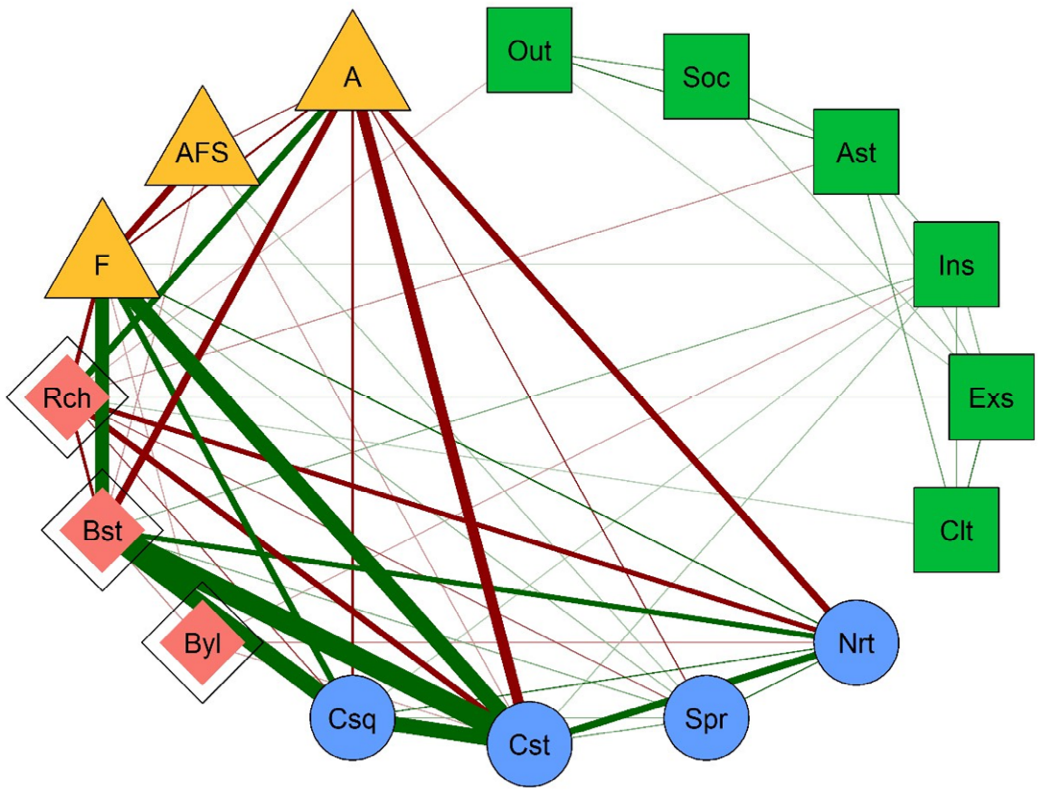

Figure 4. Spearman bivariate correlation amongst provisioning (red diamonds), regulating (blue circles), cultural ES values (green squares) and forest (F), agroforest (AFS) and agriculture (A) land cover proportion (orange triangles). Only significant correlation and with a value of $r_s >$ 0.2 are shown. Green and red lines depict positive and negative correlation, respectively. The width of the line is proportional to the strength of the correlation. ES abbreviations are explained in Table 2.

Separate analysis of each ES category resulted in the same division among individual ES. The first two components of the PCA of provisioning and regulating ES explained 71% and 75% of the variability, respectively (Fig. A2B and A2C). Variability explained by the PCA of cultural ES was about 37% (Fig. A1D). This analysis confirmed a strong negative association of cultural ES and agriculture and no association with forest or agroforestry. This result contrasts when taking all the dataset together where cultural ES were positively related to agroforestry land cover (Fig. A1A).

3.3 Spatial bundles of provisioning, regulating and cultural ES

The ES values were clustered into four well-defined bundles by using the Calinski and Harabasz criterion of the hierarchical cluster analysis (Fig. A2). The first and third groups were similar to the two cluster groups identified using bivariate correlations and PCA analysis.

Bundle A (n = 1488) was characterized by places with high biomass and carbon stocks, high rates of carbon sequestration and high cover of forest (hereafter called forest dominated for convenience), whereas bundle B (n = 1058), where agriculture was dominant (hereafter agriculture dominated), was located in places where biomass yield and groundwater recharge had high values (Fig. 5). In both groups, the perceived values of cultural ES were generally low. For bundle C (n = 1524), where agroforestry land cover was dominant (hereafter agroforestry dominated), cultural ES were valued slightly higher than for bundle A or B; groundwater recharge and biomass yield values were greater than the forest-dominated cluster A, but less than in the agriculture cluster B. In bundle D (n = 505), forest and agroforestry were the dominant land cover types (hereafter forest- agroforestry mixture). This bundle comprised places where cultural ES ranked highest and had a balanced representation of provisioning and regulating ES. Thus, bundle D could be considered a win-win situation, where cultural, provisioning and regulating ES are balanced.

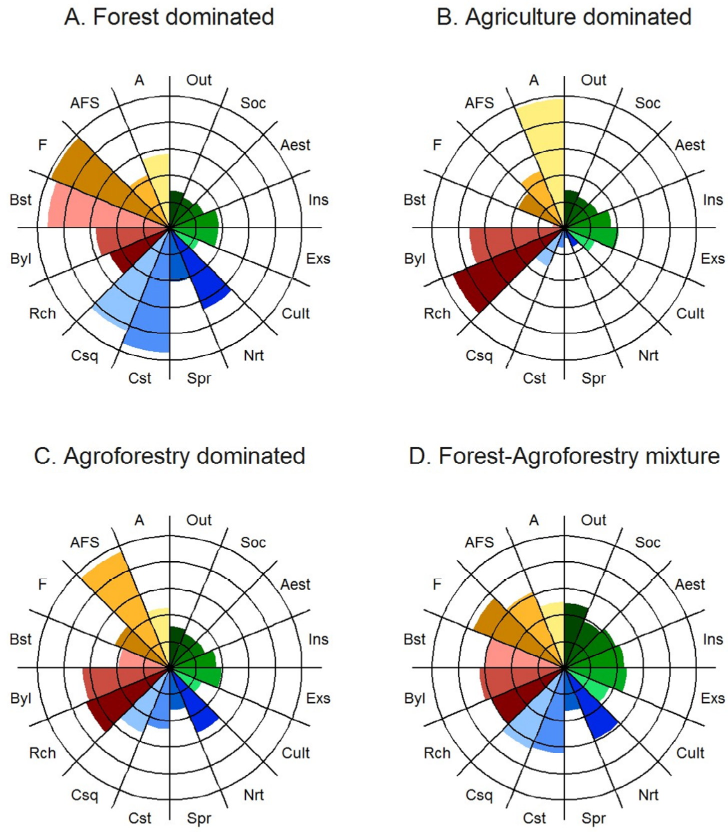

Figure 5. Polar diagrams depicting average values of provisioning (red), regulating (blue), cultural (green) ecosystem services (ES) and forest (F), agroforest (AFS) and agriculture (A) proportion at the landscape unit level (orange) for each bundle. ES abbreviations are explained in Table 2.

3.4. Associations among bundles and landscape characteristics

Bundles A, B and C were unequivocally associated with places where forest, agriculture and agroforestry were the dominant land cover, respectively (Fig. 5). Bundles A and B showed the most distinct separation because each excluded the other land cover (Fig. 6). In other words, agriculture was almost non-existent in bundle A and forest was almost non-existent in bundle B. Bundle C, where agroforestry was dominant, had similar areas of forest and agriculture land cover (~15%). Bundle D was located in places with a high share of forest (~60%) and a substantial representation of agroforestry (~30%) whilst the rest was composed of agriculture land (~10%).

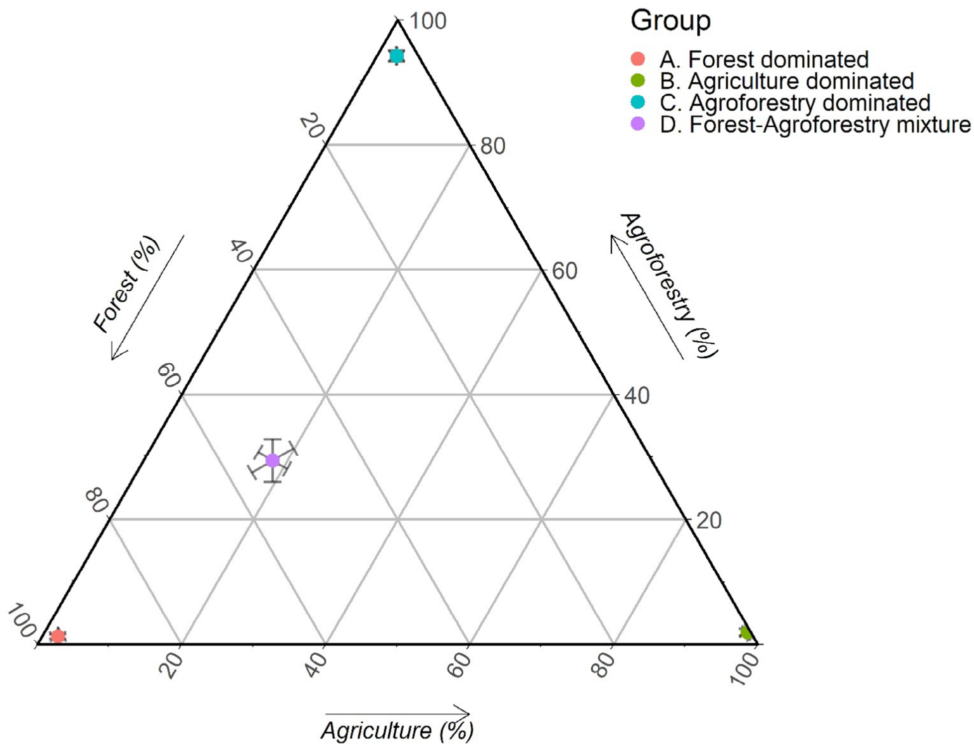

Figure 6. Ternary plot depicting average values of forest, agroforestry and agricultural land cover for each bundle.

The number of cases of each bundle class was significantly different between remoteness areas ($P < 0.001$) and landscape diversity ($P < 0.001$) (Table 3). The forest dominated bundle (A) showed a significantly higher frequency of cases in low diversity and remote areas. The agriculture dominated bundle (B) showed a different pattern, with higher frequency of cases in low landscape diversity and medium to low remoteness. Both bundles had lower frequency in intermediate or high landscape diversity than expected at random. The agroforestry bundle (C) was similar to the forest bundle with a significantly higher frequency of cases in low diversity and remote areas. By contrast, forest-agroforestry mixed bundles (D) showed the opposite pattern with significantly lower frequencies in places with remote and low diversity and significantly higher frequency than expected at random in places with medium to high landscape diversity.

Table 3. Contingency table of observed frequency for each bundle category in places of low (L), medium (M) and high (H) distance to urban areas and roads (remoteness), and low (L) medium (M) and high (H) landscape diversity. Red and blue tiles depict significant negative and positive deviations respectively from the expected frequencies under the null model assuming independence of the variables.

		Bundle											
		A. Forest (1488)			B. Agriculture (1058)			C. Agroforestry (1524)			D. Mixture (505)		
Land cover diversity	L	971	383	48	562	371	70	915	371	69	152	97	17
	M	46	32	4	36	15	3	86	62	11	96	98	14
	H	1	2	-	-	1	-	3	4	3	9	13	9
		H	M	L	H	M	L	H	M	L	H	M	L
		Remoteness											

Standardized residuals	<-4	-2	-2:0	0: 2	2	>4

4. Discussion

4.1 Characterising the ES profiles of different land covers

Our study combined a series of spatially explicit models and participatory mapping data to identify synergies, trade-offs and bundles among ES and their associations with landscape characteristics (i.e. land cover type, remoteness and landscape diversity) in 12 study sites across four biogeographical regions of Europe, comprising various types of rural landscapes. The combination of two robust datasets (Fagerholm et al., 2019; Kay et al., 2018a) allowed an integrated assessment that linked biophysical and sociocultural values, which can be used to advance our understanding of how the share of different land covers can drive ES interrelationships in European farming landscapes. Landscapes had a distinctive ES profile depending on the dominant land cover that - roughly - corresponded to regulating ES for forest, provisioning ES for agriculture and cultural ES for agroforestry. The delivery of multiple ES could, therefore, be theoretically derived from the spatial combination of various land covers. This is in accordance with findings that suggest that spatial association of different land covers can improve synergies among ES while alleviating trade-offs (Verhagen et al., 2018). For example, it is common practice to locate agricultural production to the most fertile land, and to locate forest on more marginal areas within a given landscape. However, these considerations would need to be context specific, particularly for agroforestry. In fact, European rural landscapes have a high diversity of agroforestry systems which highly vary in the delivery of multiple ES (Moreno et al., 2018). In this line and despite the multiple benefits of agroforestry in the delivery of ES (Fagerholm et al., 2016b; Torralba et al., 2016), its particular advantages will vary with the particular agroforestry system and its context.

4.2 Synergies and trade-offs in ES between land cover types

Our results confirm that trade-offs between provisioning and regulating ES are commonly found in arable land (Maes et al., 2012; Nelson et al., 2009). We also found evidence for tradeoffs between cultural and provisioning ES. Negative associations between cultural and provisioning ES have previously been reported for agricultural landscapes (Howe et al., 2014; Martín-López et al., 2012). We found that inspirational and aesthetic values were negatively related to biomass yield and groundwater recharge. This suggests a generally negative perception of agricultural activities within farmed landscapes, in agreement with previous findings in woodland pastures where negative associations were found between cereal production and cultural ES (Torralba et al., 2018). We also observed a positive association between cultural heritage and groundwater recharge. This may be because European farming landscapes include large areas of high nature value where agricultural production is associated with natural and cultural heritage values (Lomba et al., 2020). Similarly, we observed a number of positive associations between cultural ES and biomass stock, carbon sequestration and carbon stock. Forests had the highest values of these biophysical ES. As a result, our findings support the generally accepted multifunctional role of forests for ES provision at landscape level (e.g. Roces-Díaz et al., 2018), and the interpretation of forest patches as bundles of "forest ES" (Queiroz et al., 2015). Despite the various associations between cultural and regulating or provisioning ES, most of them were positive correlated, indicating that rural residents generally perceive cultural ES to be synergistic, in part because local residents in farming landscapes potentially have a higher human-nature connection (Plieninger et al., 2019).

4.3 The relationship between land cover and bundles of ES

The most abundant land cover in a landscape often drives ES associations (Palacios-Agundez et al., 2015). Accordingly, we found four distinctive bundles of ES that can be related to the proportion of forest, agroforestry and agricultural land cover. Bundle A was mainly linked to forest areas. Forest dominated landscapes were related to the supply of provisioning (as biomass stock) and regulating (as carbon sequestration) ES and showed intermediate associations with cultural ES such as inspirational and existence values (EEA, 2016). Interestingly, forests were not connected to recreational ES, such as outdoor activities, suggesting that other factors, such as remoteness, could be more important (Paracchini et al., 2014). Despite not showing the highest values for cultural ES, forest patches had a positive impact on the relationships between biophysical and cultural ES. Forests had the highest number of positive interactions between these two groups of ES, identifying potential synergies for ES provision (Roces-Diaz et al. 2018) which is a key challenge for managing multifunctional landscapes (Mouchet et al., 2017). Success in managing multifunctional landscapes can be eased where the main stakeholders (e.g. owner, the public, local authorities) have a similar perception of what they derive from a particular land use (Agbenyega et al., 2009).

Agroforestry and agricultural systems can have similar production aims, but they can vary in their structure and functional characteristics. For instance, our results show that both land covers had similar profiles for provisioning ES but opposing profiles for regulating ES. Whereas agriculture showed low values for nutrient retention and soil preservation, agroforestry showed higher values for carbon stock and sequestration, in line with forest land cover. Landscapes dominated by agroforestry and agriculture were associated with similar cultural ES, which were mainly negatively related to provisioning and regulating ES. This is in contrast to previous research that has found higher levels of associations between agroforestry and cultural ES such as social interaction or inspirational values (Moreno et al., 2018; Oteros-Rozas et al., 2018). Moreover, although a high aesthetic value is generally attributed to agroforestry (e.g. Herzog, 1998; Pinto-Correia et al., 2011), our results did not show any relationship. This may be due to the negative perception that farmers have of trees in agricultural land (e.g. Blanco et al. 2020). In addition, identifying clear distinctions between agriculture and agroforestry land in our case study sites was very challenging. In this respect, the use of alternative approaches for assessing ES, such as socially perceived demand (see Fagerholm et al. 2016a) could help to identify ES differences between agroforestry and agriculture.

It has been suggested that in agricultural systems, it is difficult to simultaneously deliver high levels of provisioning, regulating and cultural ES (Howe et al., 2014). One way of obtaining high levels of all three categories of services was observed in bundle D, which mainly comprised forest cover, with a substantial proportion of agroforestry, and low proportion of agriculture. In bundle D, there was a slight decrease in most provisioning and regulating ES, with the exception of biomass yield, and a substantial increase in cultural ES values. This result suggests that by mixing forest and agroforestry land covers, a relatively equitable and high level of ES can be achieved. Bundle D may also encompass places where agroforestry systems have a high proportion of semi-natural vegetation, leading, therefore, to a soft boundary between both land covers and benefiting from the proximity of the forest. Semi-natural woody vegetation patches play a key role within agricultural landscapes, sparsely forested areas, and agroforestry areas (Decocq et al., 2016). Agri-environmental measures commonly promote the presence of semi-natural vegetation due, mainly, to their great importance for biodiversity (Concepción et al., 2020) but fail to acknowledge their sociocultural importance (Uthes and Matzdorf, 2013). Our results suggest that wide bundles of ES could be produced by including agroforestry in mixed landscapes that combine land covers. This requires greater understanding of how ES are produced and perceived under different land covers to support the delivery of more balanced ES bundles to increase overall welfare to society.

4.4 Role of remoteness and landscape diversity

In addition to land cover type, both remoteness and landscape diversity were important factors in driving the presence of ES bundles. Bundles A and B, relating to forest and agricultural areas, were mainly located in homogeneous landscapes but in high and low remoteness areas, respectively. Bundles C and D were located in heterogeneous landscapes and, mainly, in zones close to urban areas and roads. This confirms remoteness as a key determinant for the enjoyment of cultural ecosystem services (Fagerholm et al., 2019), and in particular, the importance of recreational landscapes close to cities and towns (Haberman and Bennett, 2019; Martín-López et al., 2012). Moreover, our results also highlight the influence of landscape diversity for the delivery of multiple ecosystem services. High landscape diversity can enhance the multifunctionality of agricultural landscapes (Knoke et al., 2016; Giannitsopoulos et al., 2020). However, this effect may only be achieved if complementary land covers are promoted (Knoke et al., 2016). Our results suggest that the mixture of agroforestry systems with forest is a win-win solution. However, our results only show ES delivery from the current patterns of land cover, and this may not be the best option for enhancing the delivery of ES in the future. In this respect, knowledge of the trade-offs and synergies between different land cover types together with the application of participatory approaches can assist future land use, land management, and environmental policy decisions (Fagerholm et al. 2019).

4.5 Recommendations for future research

There are various ways in which this research can be taken forward. Deriving similarity in the land cover composition of our agricultural, agroforestry, and forestry sites across our European sites was challenging. Increasing this “inter-case study” similarity in the land cover composition could potentially improve the results in future research. Nevertheless, our work as shown here, has provided some answers to landscape-scale questions that cannot be adequately addressed with local studies. A further constraint was the low resolution of CORINE land cover. This could have masked fine grained patterns of ES associations and the relationship with their drivers. If possible, future research should use higher resolution land cover data. Our study only included three main land cover types, which may have led to an oversimplification of the landscape structure and the delivery of ES. Whilst agroforestry was an important part of the landscape in all the selected case studies, we were nevertheless obliged to include agricultural areas within the agroforestry land cover, which could explain some of the high variability observed in our results. Nevertheless, we thoroughly checked original maps and used additional sources to properly assign each land cover type. In doing so, we used two different datasets and procedures for mapping land cover types which could have introduced further errors. However, we think that the use of the best available information for each site helped to improve the delineation of heterogeneous landscape areas, where woody and other elements are mixed. Within the CORINE classification, agroforestry is defined in a narrow sense, mostly as dehesa and montado systems in Spain and Portugal, and grazed wood-pastures in Italy. By contrast den Herder et al. (2017) use a broader definition, which encompasses all land use systems where woody perennials are deliberately integrated with arable and/or livestock production. Future research could make use of data that more precisely defines the location of agroforestry systems, but also needs to recognise that the intended role and therefore ES benefits of agroforestry systems are likely to vary significantly from place to place.

5. Conclusions

This study provides an integrated assessment of ES for 12 different case study sites in different farming landscapes in Europe, merging biophysical and sociocultural data. This involved an extensive and coordinated research process, involving many disciplines, ranging from face-toface interviews with more than two thousand individuals across Europe to application of advanced modelling simulations and spatial analytics. This has allowed an integrated evaluation of the interactions between different ES on a scale that is rarely undertaken. Our methodological conclusion is that careful planning and interdisciplinary collaboration centred around study landscapes allows comprehensive analysis of provisioning, regulating and cultural ES.

Our findings showed a strong correlation between land cover type and landscape context characteristics, such as remoteness and land cover diversity, on ES delivery. Each land cover type was associated with a specific bundle of ES that consistently appear together, with the exception of the mixture of agroforestry systems and forest that, in addition, had the highest level of cultural ES. This bundle of ES highlights the potential flexibility of agroforestry systems for landscape management and illustrates the benefit of integrating biophysical and sociocultural approaches in the ES assessments.

Increasing agroforestry systems in landscapes where they are scarce could increase provisioning, regulating, and cultural ES to a greater extent than increasing agroforestry in landscapes where it is already dominant. However, this also depends on contextual factors such as distance to urban areas and presence of roads, which will determine whether certain ES, particularly cultural ES, are consumed and therefore valued by people. Areas with large populations, such as urban settlements, are often hotspots of ES demand. Our analysis has highlighted how ES benefit flows to society can be augmented by integrating agroforestry systems in the landscapes and this needs to be promoted through appropriate policy measures to improve the wellbeing of European citizens.

Author contributions

V.R, J.V.RD., S.K., A.G., J.H.N.P., F.H., T.P. and G.M. conceived the original idea. V.R, J.V.RD. and M.T. wrote the first draft. V.R performed the statistical analysis and led the writing. S.K. computed the biophysical models. J.V.R.D and G.M. created land cover layers. N.F., T.P. and M.T. planned the PPGIS data collection protocol. N.F., S.A., J.CD., N. FD., T.H., K.M., M.R.ML., P.B., A.S., E.S. V.V and T.P. collected and provided data. P.B. and A.G. proofread the manuscript. All authors discussed the interpretation of the results and contributed to the final manuscript.

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SUPPLEMENTARY MATERIAL

Table A1. Criteria for mapping based on Corine LC + Tree Cover Density information.

Classes	Criterion		
Forest and semi-natural	Classified on CLC as: 311, 312, 313, 322, 323 OR 324	OR	TCD >= 50%
Agroforestry systems	Classified on CLC as 241, 242, 243 OR 244		
	Classified on CLC as: 211, 212, 213, 221, 222, 223, 231 OR 321	AND	TCD >= 5% and <50%
Agricultural	Classified on CLC as: 211, 212, 213, 221, 222, 223, 231 OR 321	AND	TCD < 5%
Artificial or unproductive soils	Classified on CLC as: 111, 112, 121, 122, 123, 124, 131, 132, 133, 141, 142, 331, 332, 333, 334 OR 335		
Water-dependent habitats	Classified on CLC as: 411, 412, 421, 422, 423, 511, 512, 521, 522 OR 523		

Table A2. Specific questions used for obtaining PPGIS information.

Ecosystem service (ES)	ES benefit indicator	Operational definition (related survey question: Do you find some particular place or area special in this landscape?)
Recreation	Outdoor activities	I practice outdoor sports, walking, hiking, biking, dog walking etc.
Social relations	Social interaction	I spend time together with other people
Aesthetic values	Beautiful landscape or landmark	I enjoy seeing this beautiful landscape or landmark
Cultural diversity, cultural heritage values	Appreciation of local culture, cultural heritage or history	I appreciate the local culture, cultural heritage or history
Inspiration, spiritual and religious values	Inspirational, spiritual or religious place, feeling or value	I am inspired by feelings, new thoughts, religious or spiritual meanings etc.
Existence value	Appreciation of a specific place as such, independent of any benefit to humans	I appreciate this place just for its existence regardless of benefits for me or others

Table A3. Factor loadings and axes eingenvalues of the PCA analysis based on ecosystem service (ES) values

ES category	ES name	PCA1	PCA2
Provisioning	Biomass production (Byl)	0.262	-0.018
	Biomass stock (Bst)	-0.911	-0.201
	Groundwater recharge rate (Rch)	0.609	-0.233
Regulating	Nutrient retention (Nrt)	-0.7	0.28
	Soil preservation (Spr)	-0.449	0.326
	Carbon sequestration (Csq)	-0.796	-0.154
	Carbon stock (Cst)	-0.947	-0.15
Cultural	Outdoor activities (Out)	-0.004	0.125
	Social interactions (Soc)	-0.009	0.393
	Aesthetic values (Aest)	-0.135	0.268
	Cultural diversity/heritage (Cult)	-0.029	0.285
	Inspiration value (Ins)	-0.084	0.254
	Existence value (Exs)	-0.054	0.236
Land Cover	Forest (F)	-0.838	-0.386
	Agroforestry (AFS)	0.169	0.806
	Agriculture (A)	0.749	-0.447
	Eigenvalue	4.8	1.8

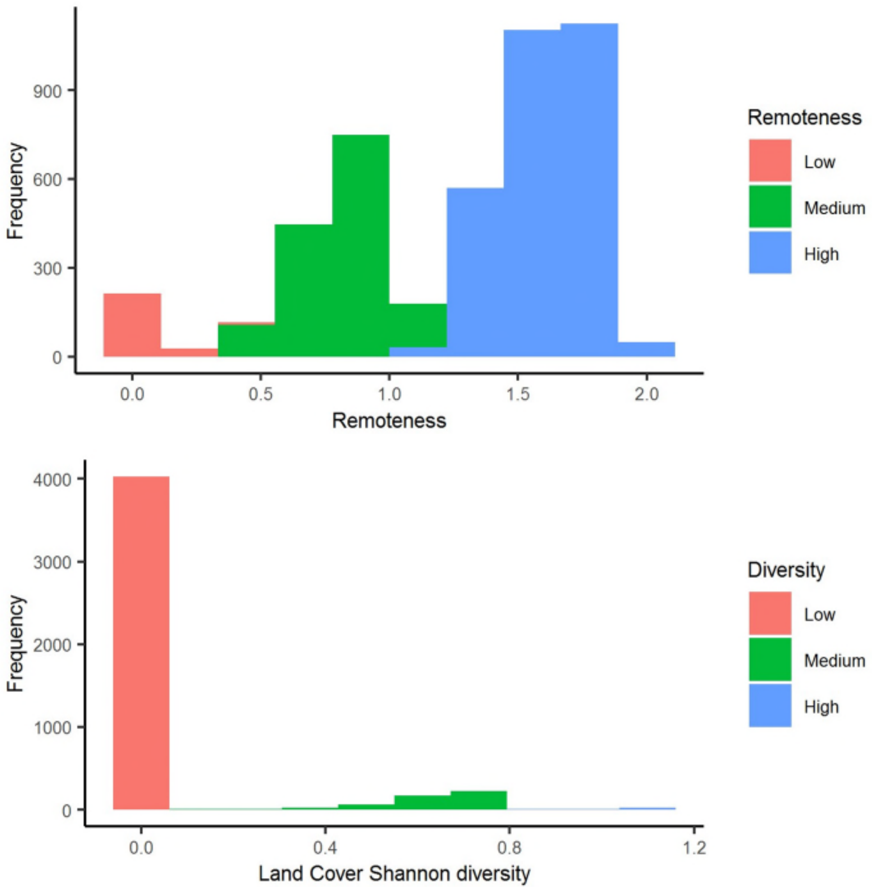

Figure A1. Distribution of remoteness (aggregation of standardized values of distance to nearest urban area and to roads) and landscape diversity (Shannon diversity values of the proportion of each land 995 cover type). Each variable has been classified into low, medium or high depending on its distribution.

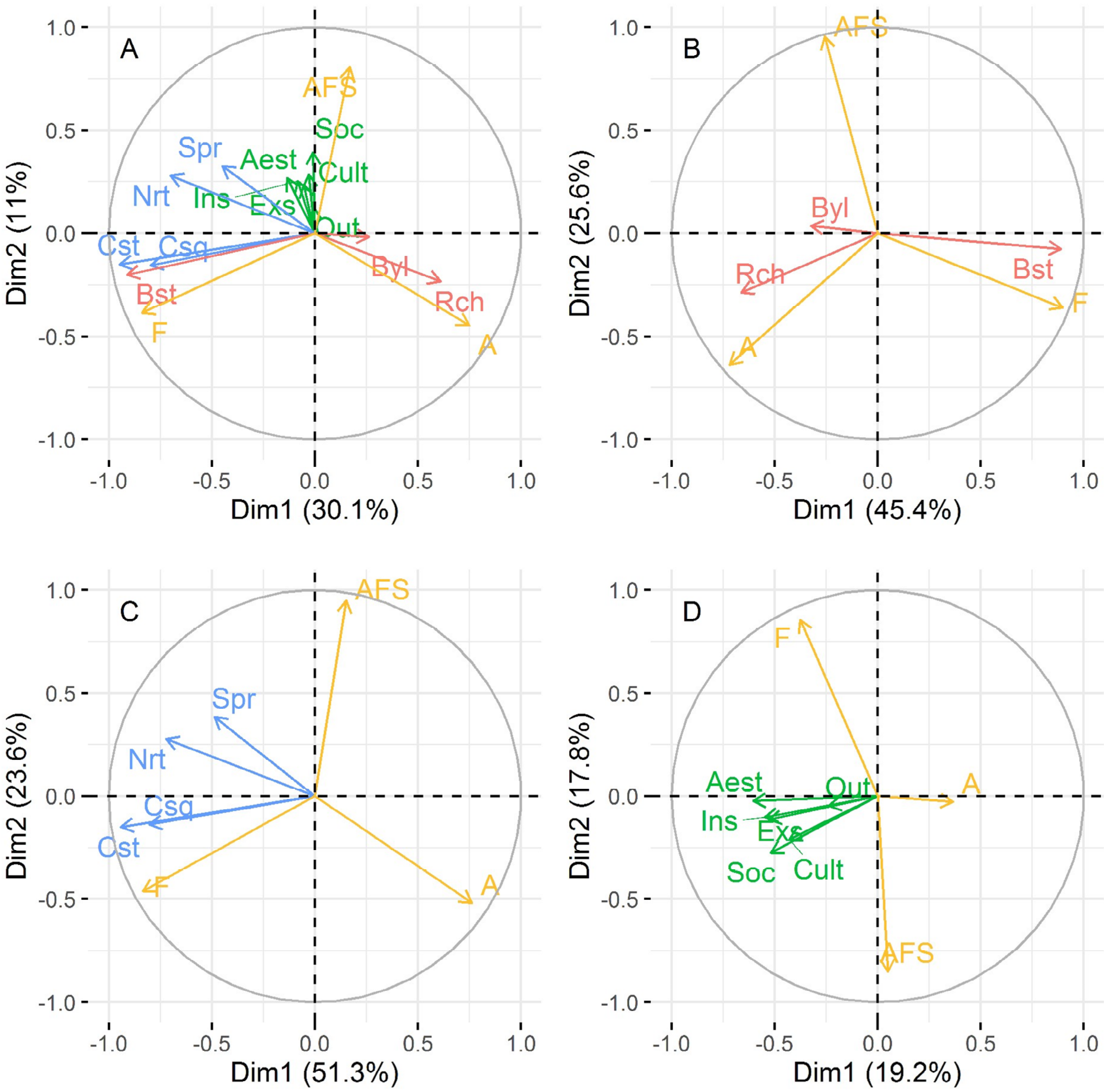

Figure A2. PCA loading plots of ecosystem service (ES) values a) and separately for each ES category b) Provisioning, c) Regulating and d) Cultural. ES abbreviations are explained in Table A3

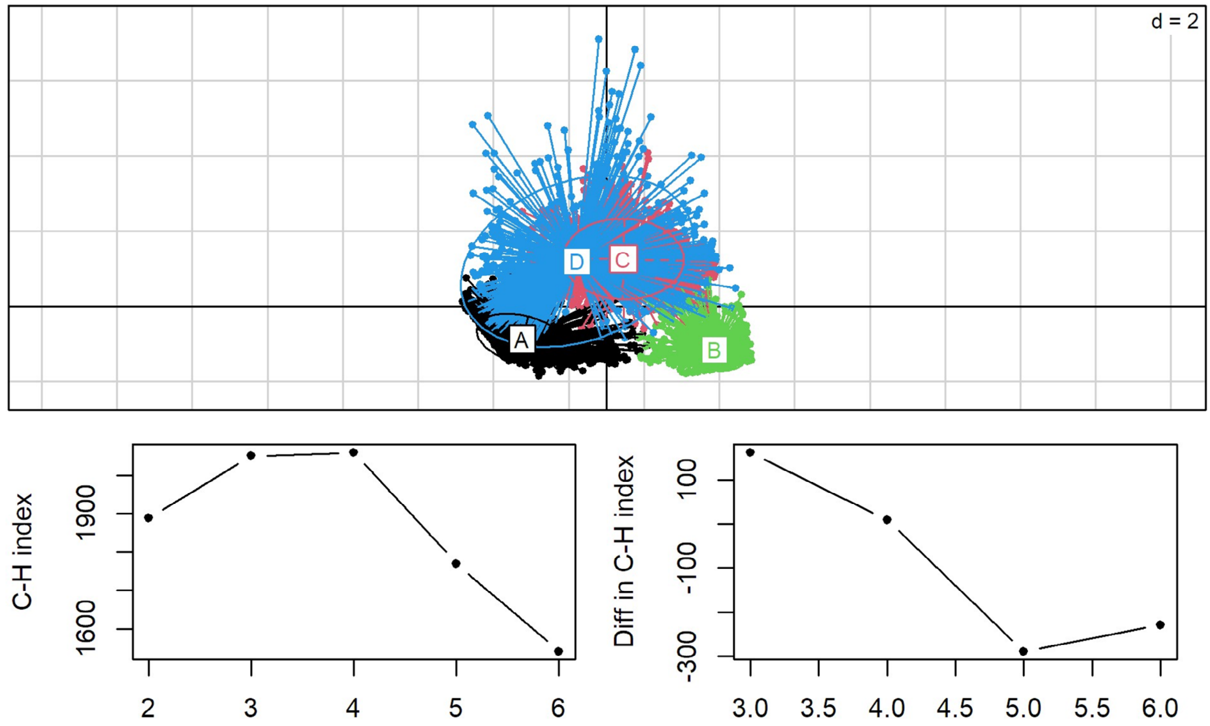

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Figure A3. Classification of the scores of a PCA of ecosystem service values and land cover by means of a hierarchical cluster analysis using Euclidean distance and Ward's technique (Top). Calinski and Harabasz criterion (left) and differences between Calinski and Harabasz criterion (right) for various cluster of difference sizes