

Economic valuation of ecosystem services in multifunctional agroforestry: implications of diversified systems for productive and resilient farming

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Abstract

Introduction

Agroforestry (AF) systems are increasingly recognised in Europe for their potential to enhance farm productivity, sustainability, and resilience. However, holistic economic assessments of their economic and environmental performance remain limited.

Objective and methods

We evaluate the annual economic value of ecosystem services (ES) in six silvoarable AF systems across Belgium, Germany, Denmark, and the UK, relative to monoculture (MC) fields. We focus on new monetary opportunities through complementary provisioning ES, and assess the indirect revenues of non-market regulating ES via their impact on management costs. Standardised field-scale samplings were conducted during 2024 to estimate three provisioning ES (crop yields, tree fruit and wood) and seven regulating ES related to soil properties in AF tree belts, AF crop alleys, and MC fields.

Results

AF tree belts generated higher economic values than AF alleys and MC fields, which showed no significant differences. Provisioning ES in tree areas averaged 1934 €/ha/yr compared with 1137 €/ha/yr in AF alleys and 1350 €/ha/yr in MC fields, due to AF tree belts leveraging a diverse array of products. Regulating ES were considerably larger, with AF tree belts (6305 €/ha/yr) outperforming AF alleys (4820 €/ha/yr) and MC fields (4769 €/ha/yr). However, high heterogeneity across sites driven by differences in system age and the extent of product diversification limits the robustness and extrapolation of the results.

Conclusion

We demonstrate that integrating trees into arable systems can increase the potential economic value when ES are fully considered. These findings underscore the multifunctional role of AF as a productive land-use supporting long-term sustainability and resilience.

1. Introduction

Modern agricultural production in Europe is largely shaped by poorly diversified monoculture (MC) landscapes that increasingly rely on high external inputs of synthetic fertilisers and pesticides (Zanten et al. 2014; Tello et al. 2023). Although such intensification boosted yields in the past, it has progressively degraded soils, reduced biodiversity, and generated numerous adverse environmental externalities (Kremen & Miles 2012). In the long term, the depletion of soil fertility and the decline in overall

ecosystem services (ES) reduce productivity, raise operational costs, and undermine the sustainability and resilience of farming systems (Woodhouse 2010).

Agroforestry (AF)—the deliberate integration of woody species (trees or shrubs) with annual arable crops (silvoarable), livestock (silvopasture), or both (agrosilvopastoral) on the same land—has re-emerged as a promising alternative (Nair 1985; Rigueiro-Rodríguez et al. 2009; Moreno et al. 2018; Pantera et al. 2018; Le et al. 2025). The presence of perennial vegetation and greater plant diversity enhances biodiversity, improves soil properties, and creates microclimatic benefits within tree belts and adjacent crop alleys, thereby enhancing ES and supporting climate resilience (Jose 2009; Hernández-Morcillo et al. 2018; Sollen-Norrin et al. 2020).

Beyond these environmental benefits, AF is increasingly recognised as a multifunctional land-use system that diversifies farm production and strengthens socio-economic resilience (Mosquera-Losada et al. 2012). In silvoarable systems, the tree component provides opportunities to obtain a diverse suite of additional outputs—both beneath and between the tree belts. In addition to tree fruit, nuts, or wood, tree belts may further contribute to total farm output through the harvesting of pruned biomass for firewood, mulch, or compost, leaves for fodder, or various understory crops, including berries, mushrooms, vegetables, medicinal and aromatic herbs, or honey (Moreno et al. 2018; Pantera et al. 2018; Le et al. 2025). Effectively utilising this diversification potential optimises the system's overall use of available resources and can increase the total value of ES delivery (Torralba et al. 2016). These expanded opportunities within AF systems support farm diversification and have the potential to enhance climate and market adaptation, and ultimately income at the farm level.

Reflecting these environmental and economic attributes, AF has attracted growing interest in Europe for its potential to deliver multiple benefits at both farm and landscape scale (den Herder et al. 2017; Santiago-Freijanes et al. 2018). However, despite this increasing attention, the transition to diversified AF practices remains significantly underutilised due to uncertainties arising from greater system complexity. On the one hand, intricate tree–crop interactions affect competition -or cooperation- for nutrients, water and light uptake, often resulting in inconsistent yields (Jose and Holzmüller 2021). These effects remain poorly understood due to their strong context dependency to pedoclimatic and system characteristics (Ivezić et al. 2021; Scordia et al. 2023; Choden et al. 2026). On the other hand, increased knowledge requirements, higher management costs associated with additional labour demands and limited availability of suitable machinery, or financial risks linked to existing socio-political agricultural frameworks—including underdeveloped supply chains, weak marketing options, and insufficient or distorted policy schemes—further undermine economic feasibility (García de Jalón et al. 2018; Rolo et al. 2020; Mosquera-Losada et al. 2023).

Economic assessments of agroforestry systems remain scarce, and traditional valuation approaches often overlook the importance of AF co-products to land managers. The financial challenges of AF may indeed be mitigated by leveraging its diversification potential and properly accounting for the added value that AF products and services may provide, both environmentally and socio-economically (Kay et

al. 2018; Alcon et al. 2024). For example, more diverse systems can be more profitable by leveraging multiple provisioning ES, such as from tree-derived products, thereby offsetting potential crop yield penalties arising from tree–crop resource competition (Smith et al. 2022; Thiesmeier & Zander 2023). In addition, greater biological diversity strengthens ecological functions and the resulting regulating ES (Zabala et al. 2023), which may improve economic performance through enhanced water and nutrient use efficiencies or better pest control, hence reducing farm management costs.

Traditional market-based approaches to valuing agricultural ecosystems focus narrowly on primary commercial outputs and fail to internalise non-marketable regulating ES (Marais et al. 2019; IPBES 2022), biasing comparisons in favour of MC systems whose negative environmental impacts are therefore overlooked. Such incomplete valuations omitting the full spectrum of AF's provisioning and regulating benefits perceived by land managers hinder wider adoption (Cai & Aguilar 2021). Comprehensive economic evaluations demonstrating the full potential of AF systems can thus play a key role in supporting farmers to make better informed decisions.

Against this context, our study aims to address these questions by focusing on three objectives.

1. Assess the extent to which silvoarable AF contributes to total provisioning ES once its diversifying potential and alternative revenue streams are accounted for. The specific focus is on whether their overall economic value can compensate for any foregone revenues relative to maximised crop yields in MC fields.
2. Quantify the potential monetary value of regulating ES derived by land managers from AF in comparison to conventional MC.
3. Ultimately, analyse how integrating regulating ES with provisioning ES alters the total economic value potentially realised by the farmer, thereby offering a comprehensive comparison of AF and MC at the farm scale.

2. Methodology

2.1. Case studies

The study is based on a network of European agroforestry (AF) sites within the REFOREST project (<https://agroreforest.eu/living-labs/>) composed of silvoarable systems with tree belts integrated into arable fields to create crop alleys. We focused on six plots in 5 different farms located in Belgium, Denmark, northern and southern regions of the United Kingdom, and Germany. These systems represent a range of local agricultural contexts and diverse environmental zones (Fig. 1), encompassing both long-established experimental trials and recently developed farms. Although most case studies operate under organic management, the study also includes conventional systems that apply chemical inputs, as detailed below. Prior to the establishment of the agroforestry systems, all fields under study were managed as the adjacent monoculture (MC) fields, which were therefore taken as the corresponding

controls. The characteristics of each site included in the study is provided in Table 1, and further details can be found in the Online Resource 1.

Table 1
Design and management characteristics of the assessed agroforestry systems.

Site	Inagro	CFE	Hof Lebensberg (Fruit/Nut)	Gibside	Wakelyns
Location	Flanders, Belgium	Taastrup, Denmark	Obermoschel, Germany	Newcastle upon Tyne, UK	Suffolk, UK
Coordinates	50°54'19.4"N 3°08'00.2"E	55°40'20"N 12°17'40"E	49°42'48.0"N 7°46'04.3"E	54°54'36.7"N 1°42'58.5"W	52°21'41.1"N 1°21'09"E
Mean annual rainfall (mm/yr)	962	717	706	994	626
Mean annual temperature (°C)	12.1	9.7	9.9	9.4	11
Establishment (year)	2023	1995	Nut: 2020/2021 Fruit: 2022/2023	2017	2001/2002
Soil type	Sandy loam	Sandy loam	Sandy loam (nuts) / Silt loam (fruits)	Loam	Sandy clay loam
Input management	Inorganic	No input*	Organic	Organic	Organic
Crop alley width (m)	24	200	Nut: 15 Fruit: 15	21	13
Tree belt width (m)	3	10.7	3	3	3
Tree density in tree belt (trees/ ha of tree area)	306	18670	Nut: 2700 Fruit: 8400	4267	127
Crop rotation and assessed species (bolt)	Winter wheat, maize, winter field beans, vegetables, clover- ryegrass ley	Winter wheat, spring barley , spring oat, clover- ryegrass ley	Nut: wheat, spelt, rye, vegetables, clover- ryegrass ley Fruit: clover- grass	Potatoes, brassicas, alliums, clover- ryegrass ley	Vegetables, cereals, pulses, clover- ryegrass-ley

Site	Inagro	CFE	Hof Lebensberg (Fruit/Nut)	Gibside	Wakelyns
Tree component and assessed species (bolt)	Walnut	Short rotation coppice (4- year cycle) with alder, willow spp., hazel	Nut: tree mix Fruit: tree mix	Hazel , willow, mix of fruit trees	Plum , walnut
Mean tree height at sampling (m)	2	7	1–2	2–3	5

*Control monoculture field under inorganic fertilisation without pesticides.

2.2. Experimental design and sampling of soil parameters

The data collection was conducted at all locations during the 2024 growing season (March–October). At each site, pairwise comparisons were conducted between AF systems' components -namely tree belt and crop alley- and adjacent conventional MC fields under equivalent conditions. Prior to the beginning of the study, a general sampling protocol for the assessment of ecosystem services (ES) was agreed upon across all sites, as shown in Fig. 2. Nevertheless, due to the considerable diversity in AF designs and contexts, the experimental setup was slightly adapted at each site. Further details of the sampling layouts followed in each site are provided in the Online Resource 1.

In the AF systems, a minimum of four sampling distances were established along the crop alley, ranging from the tree area to the alley centre. This design accounted for the presence of tree influences on yield and soil parameters within the crop alleys and ensured to obtain representative estimates at the field-scale. Further, three or four perpendicular transects (replications) were positioned at equal intervals along the alley on both sides of the tree belt, and sampling points were located at the intersection of each transect with each distance line (Fig. 2). In each counterfactual MC field, the experimental design was replicated in the centre with the same number of samplings and layout (see Online Resource 1). Due to the extended crop-alley width (200 m) in the CFE agroforestry design (Denmark), additional distances were sampled within the AF crop area. Conversely, only three samples (one distance) could be collected in the centre of the corresponding MC field in this site. Furthermore, because the trees at Inagro (Belgium) had been established only one year prior to the study, all sampling was conducted within the same field. Assuming that the minimal stature of the young trees had resulted in negligible effects on the crops and soil at the centre of the alley (12 m from the tree belt), samples taken at this furthest distance were used as the MC control.

Soil parameters to a depth of 30 cm were estimated by combining 6–8 subsamples around each sampling point using an auger. Total nitrogen and soil organic matter and carbon were analysed by Dumas dry combustion. In Denmark (CFE), fresh soil was analysed using the AgroCares near-infrared soil scanner (www.agrocares.com), as described in Kok et al. (2024). Bulk densities (BD) and soil moisture were determined using the soil-core method. Soil parameters were subsequently used to estimate the field Ecosystem Services as described in Table 2.

2.3. Quantification and economic valuation of ecosystem services

Our assessment focuses on the economic valuation of provisioning and regulating ES perceived by the land manager on an annual basis. The ES under study are displayed on Table 2, adapted from the Common International Classification of Ecosystem Services (CICES) framework (Haines-Young 2023). Accordingly, only direct benefits and costs occurring at the field scale are considered, while socio-cultural or environmental costs and benefits arising from broader farm-level externalities fall outside the scope of this assessment. Similarly, because the aim of the analysis is to compare the ES delivery between AF and MC practices, establishment and management costs specific to each system type are not included in the economic valuation.

In order to understand the yearly monetary contributions of each AF component (tree belt and crop alley) in relation to MC, all values are estimated on a differentiated area basis (AF tree, AF alley, and MC field). That is, the functional unit of the AF financial results is expressed in € per hectare of tree belt/crop alley and per year (€/ha/year). The purpose of an area-separated analysis is to distinguish the specific values originating from each AF zone (i.e., tree belt and crop alley), which gives a valuable insight of the mechanisms behind the results at the system level.

To derive the potential economic benefits realised by the farmer, the economic assessment is conducted by relating each ES to a specific marketable product. Provisioning services comprise the intended outputs of an agricultural system that meet a defined demand and can therefore be valued at current market prices. By contrast, regulating ES generally lack straightforward commercialisation (with recent carbon markets being an exception), which prevents monetary valuation through direct supply–demand mechanisms. The economic valuation was thus conducted employing so-called cost-based valuation methods (IPBES 2022), assuming each concrete agricultural input to be an approximate substitute for a regulating service. We estimate the avoided (loss) cost and replacement cost of ES degradation, which relate the delivery of ES to the farming costs. Avoided cost captures the expense that would be incurred to replace the ES through external inputs—thus constituting a benefit through the non-occurrence of the potential cost—whereas replacement cost represents the price paid to amend or substitute the degraded ES, and therefore an actual incurred cost.

ES valuation prices were selected at the European scale from market studies (Table 2). Where possible, European average prices for 2024 were used from Eurostat databases (<https://ec.europa.eu/eurostat>), complemented by UK average prices from AHDB (<https://ahdb.org.uk/>). When Eurostat values were unavailable, specific reports or scientific publications with market price standards for each category were used (see Online Resource 2). This approach ensured the use of prices representative of mean values observed by land managers in Europe.

Table 2

Ecosystem services under study and the corresponding quantification and economic valuation methods.

Ecosystem service	Biophysical indicator	Quantification method	Valuation method
Provisioning ES			
Food and fodder	Grain yield	Harvest within 0.5 m ² frames. Weighing after weed separation and threshing. Moisture adjusted to 14% following Mulvaney and Devkota (2020).	Market price: grain for human consumption. Prices adjusted to organic management
	Grass yield	Harvest within 0.5 m ² frames. Assumed 3 harvests/year (personal communication).	Market price: hay grass for fodder. Prices adjusted to organic management
	Fruits/Nuts yield	Quantities from the farm manager.	Market price: fruits/nuts
Wood biomass	Wood yield	Multiple allometric relationships used. UK sites: general Bunce equation (Bunce 1968). At Gibside, Magarik et al. (2020) method to estimate stem girth of multi-stemmed trees. CFE site: site-specific equation by (Ghaley and Porter 2014).	Market price: Woodchips
Regulating ES			
Soil erosion	Soil loss by water	Modelled with the Revised Universal Soil Loss Equation (RUSLE, Renard and Ferreira 1993). R and LS factors from Panagos et al. (2015a). K, C and P factors estimated as in Panagos et al. (2014), Panagos et al. (2015b), and Panagos et al. (2015c), respectively.	Replacement cost: agricultural topsoil
Water holding capacity	Effective precipitation	Fraction of rainfall retained in the soil after water losses through runoff and percolation (FAO 1986). Annual actual evapotranspiration values from Martinsen et al. (2022) for the period 1981–2010 attributed to baseline MC fields. AF areas adjusted according to the relative change in measured soil moisture at field capacity.	Avoided cost: water for irrigation

Ecosystem service	Biophysical indicator	Quantification method	Valuation method
Provisioning ES			
Nutrient mineralisation	Potentially mineralizable nitrogen	Fraction of easily decomposable organic nitrogen in the soil that can become available to plants (Stanford and Smith 1972). Pedo-transfer equation from Schomberg et al. (2009) based on total soil nitrogen. Values adjusted to changes in bulk density using the equivalent soil mass approach as in Fowler et al. (2023), assuming MC fields as the baselines.	Avoided cost: mean of N in several typical inorganic fertilisers
Soil formation	Net earthworm cast production	Earthworm count within a 25 cm × 25 cm × 25 cm soil volume*. Conservative net cast production value of 2.05 g DW per earthworm (Binet and Le Bayon 1998; Le Bayon et al. 2002).	Avoided cost: compost
Carbon sequestration	Carbon in SOM stocks	Values adjusted to changes in bulk density using the equivalent soil mass approach as in Fowler et al. (2023). CO₂ sequestration rates in AF estimated assuming a constant annual change since establishment relative to MC control sites, assuming these as long-term steady-state baselines**.	Market price: voluntary carbon credits
	Carbon in above- and belowground tree biomass	Estimated as 0.48 C content in dry biomass for temperate broadleaf species (IPCC 2006). Belowground C derived using a root to shoot ratio of 0.31 for temperate broadleaf tree species (IPCC 2003). CO₂ sequestration rates in AF estimated assuming a constant annual change since establishment relative to MC control sites, assuming these as long-term steady-state baselines**.	Market price: voluntary carbon credits

* 30 x 30 x 20 cm at Wakelyns (UK-South). In the CFE (Denmark), earthworms could only be collected in the middle of the crop alleys (Fig. 2, Online Resource 1), and these values were extrapolated to the entire field for this area.

**This simplified method assumes MC fields to remain in a long-term constant state, and SOC dynamics to shift at a constant rate regardless of the age or condition of the AF system. Carbon dynamics are

considerably more complex (Nair et al. 2010), particularly in recently disturbed ecosystems, and extended temporal sampling would be required for greater accuracy. Post-harvest biomass uses and soil management practices equally determine whether sequestered carbon is retained over time or re-emitted to the atmosphere. Here, soil cultivation practices are assumed to remain constant over time, and tree biomass carbon to be stored in the long term.

2.4. Statistical analysis

The data was analysed in two stages using two types of linear models to estimate the economic values of multiple ES in each area under study, namely AF belt, AF alley, and the control MC field. First, the individual data sampled within-site (collected as in Fig. 2 and shown in Fig. 3, Fig. 4) was fitted using linear regression models, with replication (transect) nested within each corresponding field (AF and MC) included as a covariate. Second, the aggregated data across sites (shown in Fig. 5) was fitted using a linear mixed-effects model with a random intercept for each replication nested within its corresponding field (AF and MC). The mixed-effects models were implemented using the *lmer* function in the *lme4* package (v. 1.1–35.5).

After fitting the models, analyses of variance (ANOVAs) and subsequent post hoc pairwise comparisons were performed on the model-predicted mean ES values for each area, in order to assess the significance of their differences. Multiple comparisons were conducted using the *emmeans* function from the *emmeans* package (v. 1.10.7), with p-values adjusted using the multivariate *t* distribution. For the linear mixed-effects models, the degrees of freedom for the calculated means during the post hoc tests were adjusted according to the Satterthwaite method. As previously described, the sampling design was adapted to the specific conditions and constraints of each site. As is typical for observational field studies, this resulted in a highly unbalanced dataset, with varying numbers of observations across sites and study areas (AF belt, AF alley, MC field). To account for this imbalance, the marginal means estimates were adjusted using weighted averages that accounted for the differing sampling frequencies. These weights were specified to the “cells” level within the *emmeans* function.

All statistical calculations were conducted using R programming v. 4.4.2 in RStudio v. 2024.09.1 + 394 (www.posit.co).

3. Results

3.1. Provisioning ecosystem services

The economic valuation of provisioning ecosystem services (ES) varied markedly amongst the network of agroforestry (AF) sites. Overall, Gibside (UK-North), Wakelyns (UK-South), and the CFE (Denmark) displayed higher average returns, closely followed by the crop areas at Inagro (Belgium), who did not perceive any revenues from the tree belt (Fig. 3). In contrast, the two German sites at Hof Lebensberg

(HLeb Fruit and Nut) displayed comparatively lower mean economic values, particularly in the crop areas.

AF tree belts recorded the overall highest revenues, particularly in Wakelyns (5208 €/ha/yr) followed by Gibside (2292 €/ha/yr). This economic advantage could be attributed to the valorisation of diverse outputs that farmers are able to monetise in a more diversified setting, both from tree products (timber, fruits or nuts) and from an understory crop (grass ley). Whereas at Gibside the trees had not yet begun fruiting, constraining the economic valuation of the nuts, in Wakelyns all considered tree products were effectively harvested. Noticeably, the largest value is derived from the tree yield (plum) due to advantageous organic premium prices, whereas the minimal tree biomass growth reflects the low tree density of the site. Conversely, a lower economic valuation was recorded at the CFE (919 €/ha/yr) where only one tree product was harvested e.g. woodchip. This lack of diversification resulted in a lower revenue than the AF alley (980 €/ha/yr), none of which could not exceed the grain revenue from the MC field (1812 €/ha/yr). Even though the tree system at the CFE is managed as short-rotation coppice (SRC) to maximise biomass productivity, it was observed that the intense harvesting regime resulted in a tree mortality of around 40% after 29 years (data not shown). Finally, the younger sites such as Inagro and HLeb did not realise any tree products yet, which hindered the valuation of the woody area and lowered the system revenues. Despite this, the two fields at HLeb displayed a surprising two-fold increase in crop yield in the AF tree areas compared to the AF alleys and MC fields, the specific reasons for which could not be investigated.

Economic values in the arable crop plots (AF alley and MC field) were only composed of one product. As in the tree areas, these displayed high variability across sites, with the highest and lowest monetary values found in the monoculture (MC) fields at Gibside (2171 €/ha/yr) and at HLeb (176 €/ha/yr), respectively. Nonetheless, within-systems comparisons showed relatively uniform values in the plots with grass, slightly favouring AF crop yields. Despite their narrow widths, AF alleys incurred only minor crop yield losses (-35 and -139 €/ha/yr at Wakelyns and Gibside, respectively) or increases (179, 200 and 223 €/ha/yr at Inagro, HLeb Fruit and HLeb Nut, respectively) compared to the MC fields (Table 1). Overall, this indicates an insignificant presence of tree-crop interactions for resources in the agroforestry alleys affecting the performance of the clover-ryegrass leys. However, these positive results in the Belgian and German systems could be due to their young age and low tree stature, as well as their southern location relative to the UK sites, resulting in minimised light competition (Eichhorn et al. 2006). This implies that crop yields may change in these younger systems as trees grow taller and resource competition intensifies. By contrast, only the CFE exhibited significantly lower yield values in the AF alley (980 €/ha/yr) relative to the MC field (1812 €/ha/yr), despite the considerably wider crop alley (200 m). This outcome is probably related to the no-input regime followed in this system compared to the inorganic fertilisation applied to the MC field, which considerably decreased the AF cereal yield and could be recovered even with a higher organic premium price.

Finally, even though the AF tree component at Inagro appeared empty of all products, it is not necessarily depleted of value. The understorey is sown with a diverse mix of perennial grasses and flowering plants

intended to play an important role in regulating ES through enhanced biodiversity, pollination and pest control. This approach indeed forgoes an additional revenue stream in market terms, but it is expected to deliver long-term returns through reduced input costs.

3.2. Regulating ecosystem services

The economic valuation of regulating ES (Fig. 4) varied relatively less amongst the sites compared to provisioning ES, with the exception of the AF tree belts at the Hof Lebensberg fields (HLeb Fruit and Nut). In general, regulating ES did not appear to be significantly influenced by any specific trend, whether by age nor input management (conventional versus organic). This suggests that the specific combination of agroforestry-related system conditions plays a more decisive role in shaping their processes.

Similarly to the provisioning ES, AF tree areas generally recorded higher revenues compared to the AF alleys and MC fields, owing to better overall compound ES levels. The highest economic values were recorded in the HLeb fields (7915 €/ha/yr HLeb Fruit and 4579 €/ha/yr HLeb Nut) associated with extraordinarily high SOC sequestration values in the tree belts relative to the AF and MC crop plots. The mature systems at the CFE (6594 €/ha/yr) and Wakelyns (5987 €/ha/yr) could similarly benefit from additional carbon sequestration returns from trees. On the contrary, AF alleys could not leverage any biomass carbon, whereas MC fields did not account for any sequestered SOC either (assumed to be in steady-state). This hindered the average total monetary values in the tree-less plots compared to the AF tree belts across the sites, yielding the lowest values (and largest differences) at HLeb Fruit (Germany), both in the AF alley (3910 €/ha/yr) and in the MC field (3910 €/ha/yr).

In general, AF and MC crop areas displayed relatively uniform revenues, with no clear pattern across sites. Noticeably, only the most mature systems in Denmark (CFE) and the UK (Wakelyns and Gibside) seemed to display some significant trend. The CFE accrued significantly higher total regulating ES in the AF crop area (5272 €/ha/yr) than in the MC field (4396 €/ha/yr), likely reflecting benefits related to the aforementioned organic management in the AF system compared with inorganic fertilisation in the MC field. Conversely, Wakelyns showed a slightly lower monetary valuation for the AF crop alley (4524 €/ha/yr) than for the control MC (4843 €/ha/yr). Surprisingly, Gibside exhibited lower SOC values in the AF system compared to the MC field 7 years after its establishment, hence incurring a significant “cost” in the monetary valuation from the assumed negative CO₂ sequestration values that decreased the accrued ES delivery (4409 €/ha/yr in AF alley versus 5212 €/ha/yr in the MC field). Finally, Inagro (Belgium) did not show any significant differences across the considered AF and MC areas, likely related to the young establishment age of the site.

The relatively higher consistency of the total regulating ES across sites and areas stemmed from a more homogeneous valuation of the considered individual ES. The total revenues were dominated by the economic valuations of the water holding capacity (related to irrigation water) and potential N mineralisation (PMN). On average slightly higher in the tree areas, these ES displayed a uniform pattern, reflecting their stability on the total revenues. In turn, only the carbon-related services -especially soil

organic carbon- showed some positive differences amongst the AF plots, even though sequestration rates were inconsistent and with greater uncertainty, which made their interpretation difficult. Ultimately, the combination of a greater number of variables contributing to the total regulating ES values (including less noticeable soil erosion and formation) added considerable redundancy to the integrated values compared to the fewer provisioning services, enhancing the resilience of the monetary revenues across areas and sites.

3.3. Aggregated total provisioning and regulating ecosystem services

Aggregating all economic valuations (Fig. 5a, b) revealed a substantial difference between provisioning and regulating ES, with the latter being more than three times as large. Consistent with the site-specific results presented above, AF tree belts outperformed the crop-based plots AF alley and MC field in both provisioning (1934 €/ha/yr compared to 1137 €/ha/yr and 1350 €/ha/yr, respectively) and, especially, regulating ES (6305 €/ha/yr compared to 4820 €/ha/yr and 4769 €/ha/yr, respectively). The robust improvement in the economic performance of the tree belts aligns with the overall patterns described above, in which the tree belts improved overall ES outcomes especially by leveraging a more diverse array of products. By contrast, AF alleys displayed monetary values similar to the MC, reflecting the inconsistent trends across the individual systems (Figs. 3 and 4). Reflecting this, the accrued contribution of all the quantified ES (Fig. 5c) resulted in significantly higher total revenues in the AF tree areas (8240 €/ha/yr) compared to the crop areas, where the AF alley and the MC field showed again minor differences (5958 €/ha/yr in the AF alley and 6119 €/ha/yr in the MC field).

The added complexity of integrating trees both from an economic and an ecological perspective was reflected throughout the results in strong context-specific dependencies across the sites. This becomes apparent when aggregating the full set of observations, yielding wider value distributions particularly within the AF tree areas. This is especially noticeable in the case of the provisioning ES (Fig. 5a), where the large variability within our dataset made the results vulnerable to the presence of each specific system, compromising the robustness of the aggregated results.

4. Discussion

The aggregated economic results across the studied agroforestry systems indicate that greater biological diversification in agroforestry (AF) enhances monetary returns through improved provisioning and regulating ecosystem services (ES), relative to monoculture (MC) fields. These increases originated primarily from the tree components, whereas the AF alleys showed no significant positive or negative effects (Fig. 5).

Regarding provisioning ES, we found that crop yields decreased by an average of 15.8% (Fig. 5a), although this reduction showed inconsistent patterns due to the large variability among sites. This outcome was primarily driven by the cereal yield gap observed at the CFE, whereas the grass-based plots

exhibited minimal differences relative to their MC counterparts (Fig. 3). Given this irregular pattern, the final effect on provisioning ES will depend on the particular characteristics of each AF system in terms of design and developmental stage. Studies investigating agronomic yields in AF systems generally show similar highly variable outcomes, but long-term evidence indicates the likely presence of yield penalties in crop alleys due to tree–crop competition (Pardon et al. 2018; Ivezić et al. 2021; Scordia et al. 2023; Choden et al. 2026). Nevertheless, agroforestry practices have been shown to improve crop yields under adverse conditions, including climate stress and financial risk scenarios (Cary and Frey 2020; Quandt et al. 2023; Rolo et al. 2023; Thiesmeier and Zander 2023). Our results are based on one-year data collected under regular growing conditions and did not incorporate any climate- and market-resilience benefits from diversification. Further assessments investigating the full economic potential of AF should include longer term periods that are able to capture the different economic and ecological circumstances that farmers face throughout the entire rotation. In turn, the tree areas outperformed MC economic returns by an average of 43.2% (Fig. 5a). Figure 3 shows that this positive result is mainly a consequence of Wakelyns and Hof Lebensberg (HLeb Fruit and Nut) and was considerably constrained in other systems by the limited valorisation of tree products—largely a consequence of their early developmental stage. Overall, our study underscores the need to expand the scope of diversification for traditional economic valuation approaches, highlighting the importance of incorporating potential co-products into more comprehensive economic assessments (Smith et al. 2022; Thiesmeier & Zander 2023).

Regarding regulating ES (Fig. 5b), we found 31% higher economic returns in AF tree belts compared to crop-only plots (i.e., AF alley and MC field), mainly observed in Wakelyns, CFE, and the fields at Hos Lebensberg (Fig. 4). Widely recognised in the literature, this increase is likely driven by the environmental benefits associated with more diverse and perennial vegetation (Sollen-Norrlin et al. 2020), as well as reduced disturbances linked to long-term tree management (Kuyah et al. 2017). Moreover, regulating ES achieved substantially higher overall values than provisioning ES, underscoring the importance of their inclusion in economic assessments. The relevance of regulating ES in enhancing the profitability of agroforestry systems is well documented in the literature, with their benefits often capable of more than compensating for yield gaps, or even increased management costs, when environmental effects are properly accounted for (Kay et al. 2018; Thiesmeier and Zander 2023). In this respect, Alcon et al. (2024) further emphasise that the economic internalisation of regulating ES is particularly crucial in recently established systems, where the diversification benefits from provisioning ES have not yet materialised. Our results confirm this conclusion and indicate that even in the earliest stages of an AF system the regulating ES are capable of providing value to the farmer.

Finally, integrating marketable provisioning and non-marketable regulating ES further strengthened the value of the tree component in AF systems (Fig. 5c). Our study found that combining these two types of services results in 34.7% higher revenues from AF tree areas compared with MC fields. Crucially, because AF crop alleys did not show significant differences relative to MC plots, the additional benefits from the tree belts translated into an overall net monetary gain for AF systems. Furthermore, when considering the cumulative effect of all ES, it is essential to acknowledge the substantial presence of immature agroforestry systems across our study sites. The aggregated results presented here are hence

likely conservative, as a more developed utilisation of the diversification potential within the AF tree belts would probably yield higher economic valuations. The inclusion of these younger systems therefore likely led to understated economic estimates, as they may not yet have reached full productive or ecological maturity.

These positive results from the total economic valuation of ES in AF are consistent with previous findings in European contexts and are often strengthened by assessments that incorporate broader environmental externalities and socio-cultural benefits of AF (Kay et al. 2018; Kay et al. 2019; Alcon et al. 2024). However, heterogeneity in both the estimation and monetary valuation of ES is widely acknowledged in the literature (Torralba et al. 2016; Thiesmeier & Zander 2023; Zabala et al. 2023), reflecting the inherent complexity of AF practices and agricultural systems more broadly. As highlighted throughout the results, this issue was also evident across our study sites and constitutes an important shortcoming to consider. Indeed, the aggregation of the overall revenues in Fig. 5 clearly illustrates the strong dependency of the resulting values on the specific context of each AF system, particularly regarding their developmental stage and the subsequent extent to which tree-derived products are able to be diversified and valorised. This heterogeneity in our dataset reduces the robustness of our conclusions and limits their interpretation under other system configurations or regions. Such challenges significantly constrain comparability across case studies and must be carefully considered when extrapolating results.

4.1. Opportunities and challenges of agroforestry diversification

Among our set of case studies, the well-established Wakelyns farm in the UK delivered considerably higher overall economic values from its combined delivery of ES, in line with previous findings at the site (Smith & Westaway 2020). Beyond its efficient diversification of multiple tree-derived products, it is noteworthy that its provisioning success is strongly driven by the optimal valuation of fruit yields (Fig. 3e). This substantial contribution from tree produce is supported by the farm's organic management, which enables it to benefit from price premiums associated with high-quality production.

This price advantage is indeed characteristic of the so-called high-value AF systems—traditional extensive farms widely recognised in Europe for their capacity to enhance profitability while providing environmental and, crucially, cultural benefits to the surrounding landscape (Moreno et al. 2018; Pantera et al. 2018; Le et al. 2025). The distinctive mix of products generated within these agroecological systems, embedded in high-nature environments, strengthens their connection with local communities and supports a broad range of environmental and socio-cultural values (Rigueiro-Rodríguez et al. 2008). Such systems can successfully leverage direct markets that recognise and reward the added value of their products (Matthews 2022), a key condition for the long-term profitability of agroforestry systems (Hernández-Morcillo et al. 2018; Thiesmeier & Zander 2023). Furthermore, these well-diversified systems generate additional value from wood produced through periodic pruning and from wood harvested at the end of the tree's life cycle which, although not contributing substantially to its annual revenue, may

constitute a valuable long-term capital return when accrued (Smith et al. 2012). Such dual diversification, across space and through time, can provide a continuous additional income stream for farmers, serving as an effective risk management strategy by reducing revenue uncertainty (Sollen-Norrin et al. 2020; Zabala et al. 2023).

In contrast, the short-rotation coppice (SRC) approach at the CFE in Denmark, designed for the efficient production of bioenergy to displace fossil fuels (Kuemmel et al. 1998), relies on economies of scale and large machinery for its economic feasibility. This constrains the cultivation of understorey crops within the tree areas, limiting alternative commercial uses and generating a substantial opportunity cost (Fig. 3f). Nonetheless, this dilemma illustrates the challenges and trade-offs associated with the broader cost-related factors that farmers must consider when designing financially feasible agricultural systems—factors that remain essential for understanding the full economic implications of AF adoption (García de Jalón et al. 2018; Pantera et al. 2018; Sollen-Norrin et al. 2020). Although extensive fruit and nut systems across our AF sites appear optimal due to their enhanced diversification opportunities, it is important to recognise that such systems often require higher labour inputs and are less compatible with mechanisation (Hernández-Morcillo et al. 2018), which limits economies of scale. In European contexts, where labour is costly and value chains are geared towards short-term cost-efficiency, these constraints hinder competitiveness and pose significant barriers to the adoption and upscaling of AF systems (Low et al. 2023). The economic performance of diversified AF systems depends not only on their inherent production potential but also on access to suitable markets for their often smaller and more heterogeneous product volumes. In practice, many agroforestry fruit producers encounter difficulties marketing diverse outputs through conventional supply chains, which can limit the realisation of their full diversification benefits.

These limitations were evident when contrasting the CFE and Wakelyns and explain the reliance on an intensified SRC approach in the former even at the expense of lower value-addition. It is therefore important to stress that revenue increases as quantified in our study will not automatically translate into a transition towards AF. As Rolo et al. (2020) highlight, AF managers face numerous hidden costs, both tangible and intangible, that are often difficult to anticipate. These costs were not accounted for in our study, but remain essential for understanding the full range of perceived risks faced by farmers and for informing the development of more effective policy schemes that support AF adoption (Mosquera-Losada et al. 2023).

4.2. The increasing relevance of internalising regulating services for productive and resilient agricultural systems

Finally, our economic assessment demonstrated the key importance of regulating ES for land managers in terms of financial and ecological sustainability (Fig. 4), a positive effect especially relevant in young AF systems still lacking short-term provisioning revenues from the tree belts. Moreover, our results show that, unlike market-based provisioning ES often prone to fluctuations, the greater redundancy of more

diverse regulating services leads to more uniform revenue streams across different areas and time periods, therefore providing increased stability and economic resilience for farmers (Rolo et al. 2023).

In modern industrialised farming systems, regulating ES have often been overlooked due to the abundant availability of soil resources and the relatively inexpensive external inputs derived from fossil fuels, intended to substitute ecological processes—such as pesticides for pest control, synthetic fertilisers for nutrient cycling, and tillage for soil structure (Woodhouse 2010; Tello et al. 2023). However, regulating ES are poised to assume an even greater role in the future, given their central contribution to ecosystem resilience. As non-renewable resources become scarcer and the effects of climate change intensify, the cost of maintaining monoculture systems is likely to rise (Crews et al. 2018), a trend further amplified by the widespread degradation of agricultural ecosystems (Právělie et al. 2024). Soils with greater water holding capacity, nutrient mineralisation potential, and enhanced soil-forming dynamics are therefore expected to become increasingly valuable. Our study demonstrates that multifunctional AF practices are well positioned to gain ecological and economic importance as the costs of replacing regulating ES—or the benefits of avoiding their loss—become more apparent.

5. Conclusion

The results of our study across multiple European silvoarable systems underscore the multifunctional capacity of agroforestry (AF) to deliver greater economic and environmental benefits to farmers compared with crop-only monoculture (MC) systems when ecosystem services (ES) are comprehensively assessed. Integrating trees into arable land enhances provisioning ES, critically through increased diversified productions that generates multiple complementary revenue streams. The consistently higher levels of regulating ES observed in AF systems, particularly in the tree areas, further highlight their importance when estimating the total value of agricultural systems. Nevertheless, multiple challenges remain to overcome the risks associated with AF adoption, as illustrated across our set of case studies.

By integrating biophysical and economic dimensions, we provide evidence of the opportunities offered by AF systems as productive land-use strategies that simultaneously deliver critical ecological services underpinning long-term sustainability and resilience. In doing so, our study supports improved decision-making and reduces adoption risks for land managers, thereby facilitating a transition towards sustainable, climate-resilient agricultural landscapes in Europe.

Declarations

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8. Supplementary Materials

Online Resource 1. Description of study sites and sampling designs

Online Resource 2. ES valuation methods and data

9. Data availability statement

The data will be available after the research project REFOREST is completed and the material is published in a scientific journal. The dataset will be accessible in the REFOREST repository (<https://zenodo.org/communities/reforest/>).

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Figures

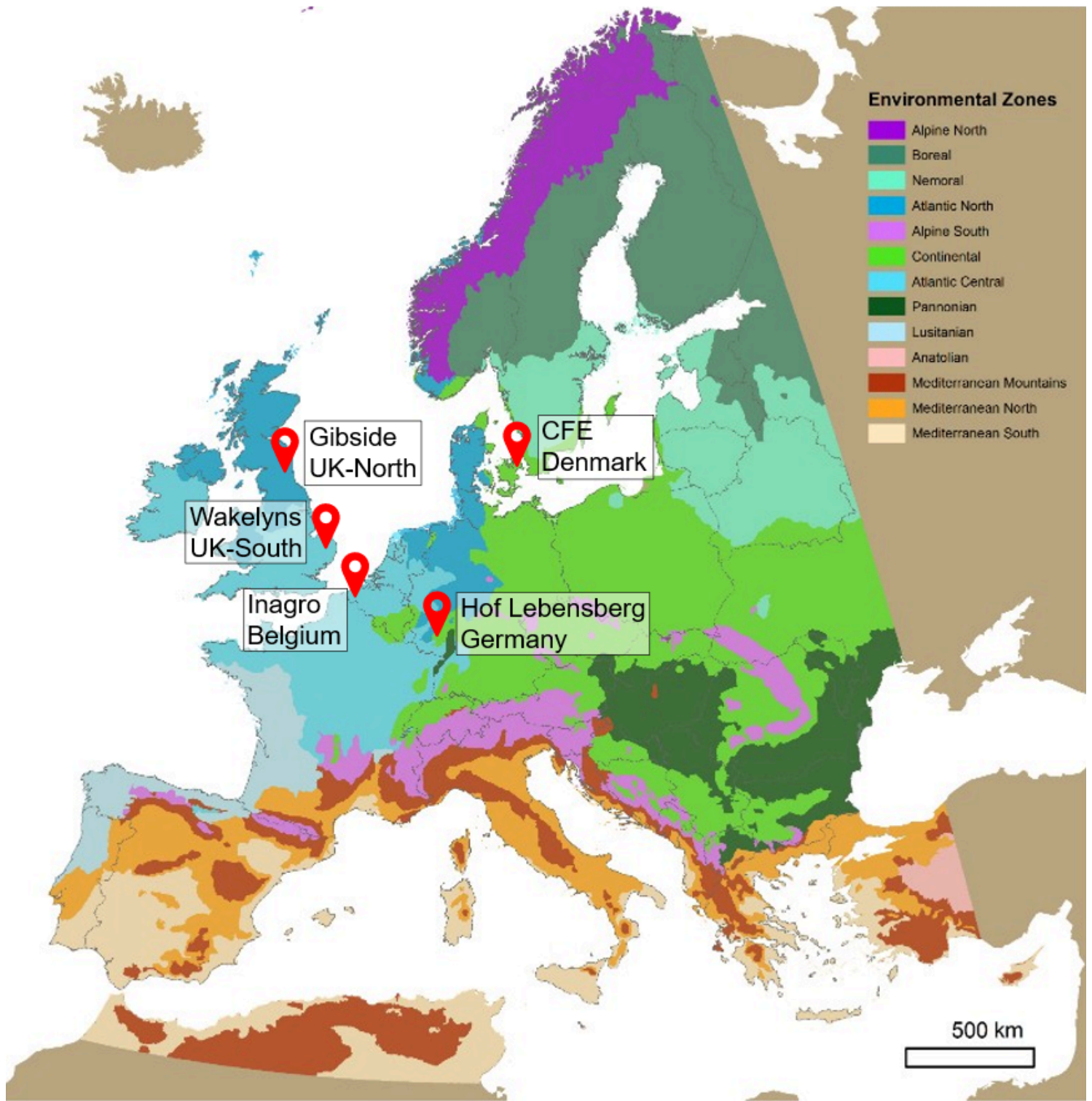


Figure 1

Agroforestry sites under study by environmental zone (Metzger 2018)

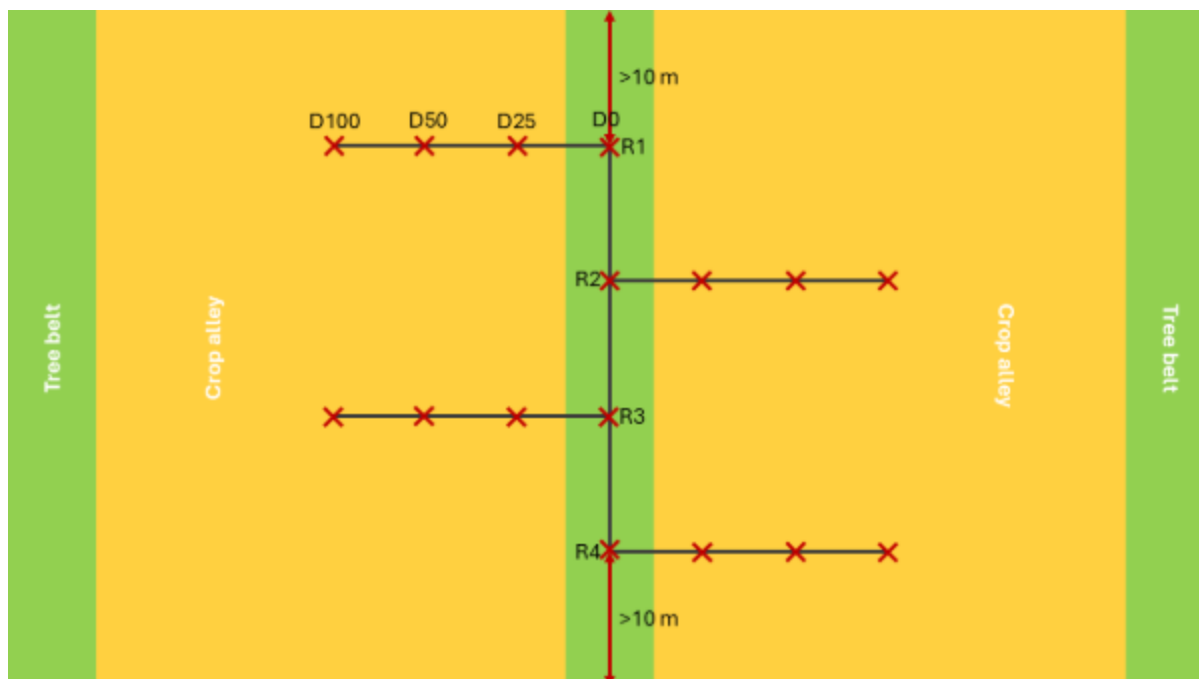


Figure 2

The sampled distances were placed at 0% (D0), 25% (D25), 50% (D50) and 100% (D100) of the crop alley centreline as measured from the middle of the tree belt. At the CFE, extra distances at 4, 7, 12, and 84% were conducted. Four replications (R1, R2, R3, R4) at each distance assured a representative sampling

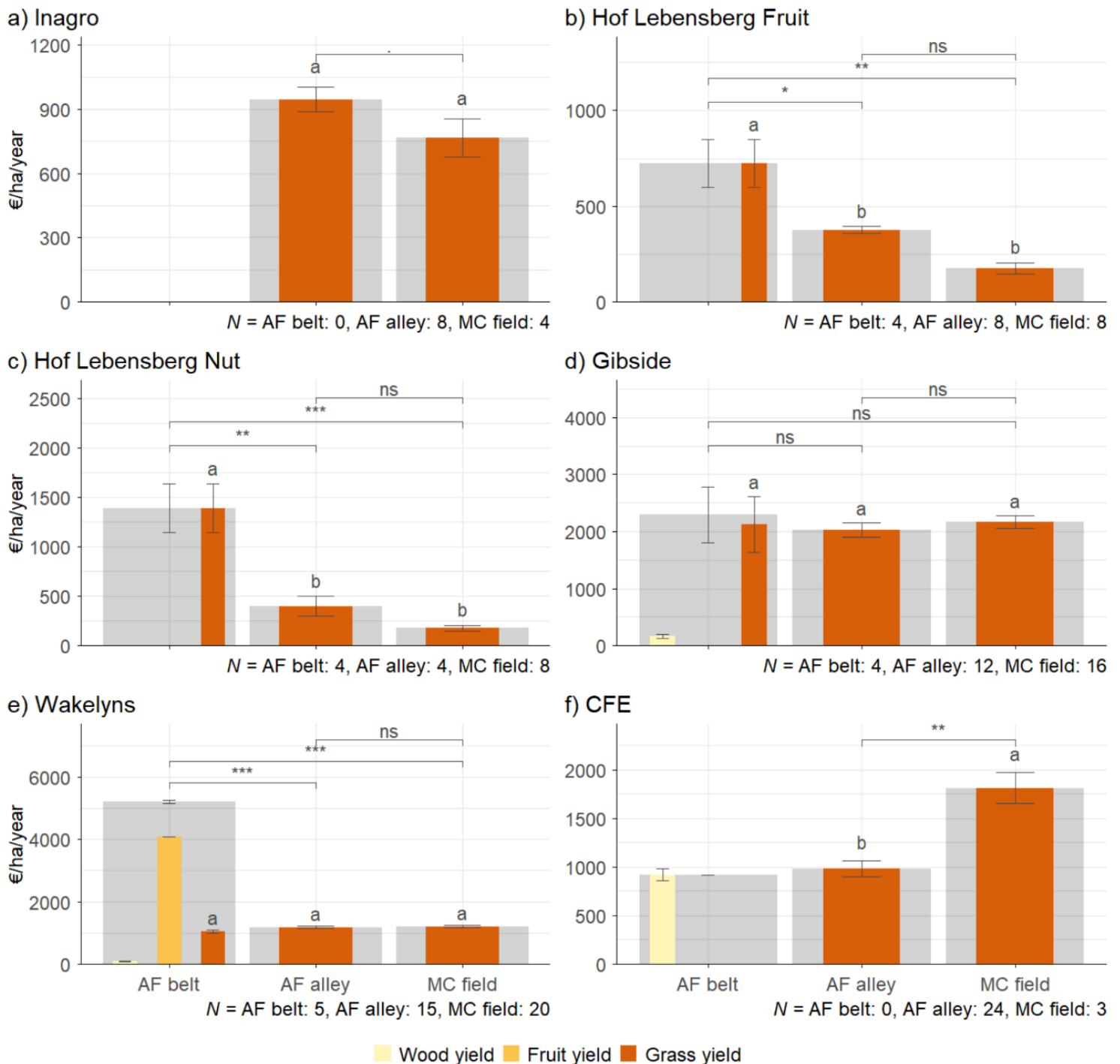


Figure 3

Annual economic values of the multiple provisioning ES assessed (coloured) and their accrued total value (grey). The values in all areas are standardised to a hectare of sole crop. Same colour bars labelled with different letters indicate significant differences across areas at 5% confidence level. Brackets above total ES (grey) indicate statistical differences at $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), and $p < 0.10$ (.), with non-significant differences denoted as ns. N = number of observations in each area

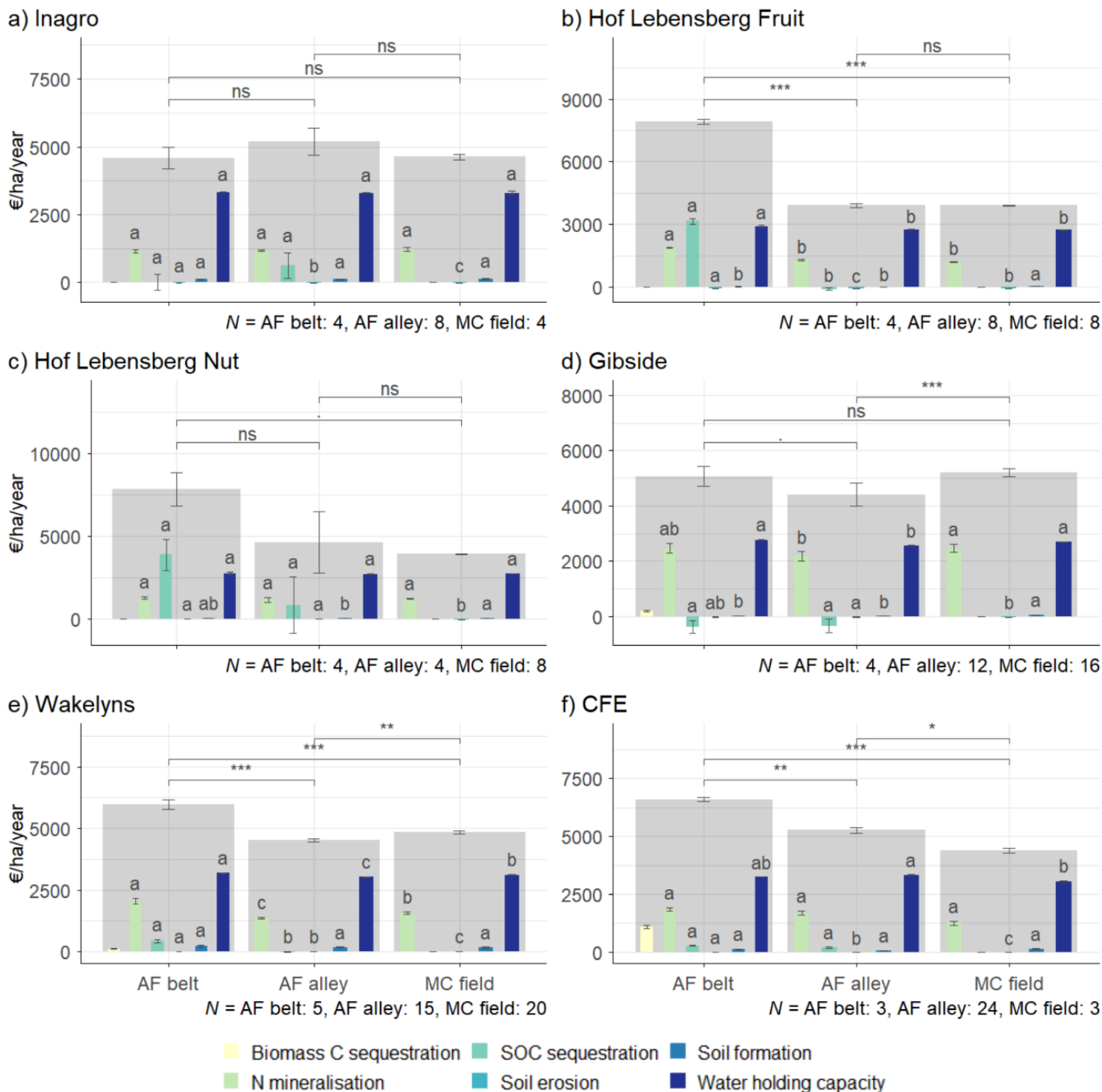


Figure 4

Annual economic values of the multiple regulation ES assessed (coloured) and their accrued total value (grey). The values in all areas are standardised to a hectare of sole area. Same colour bars labelled with different letters indicate significant differences across areas at 5% confidence level. Brackets above total ES (grey) indicate statistical differences at $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), and $p < 0.10$ (.), with non-significant differences denoted as ns. N = number of observations in each area

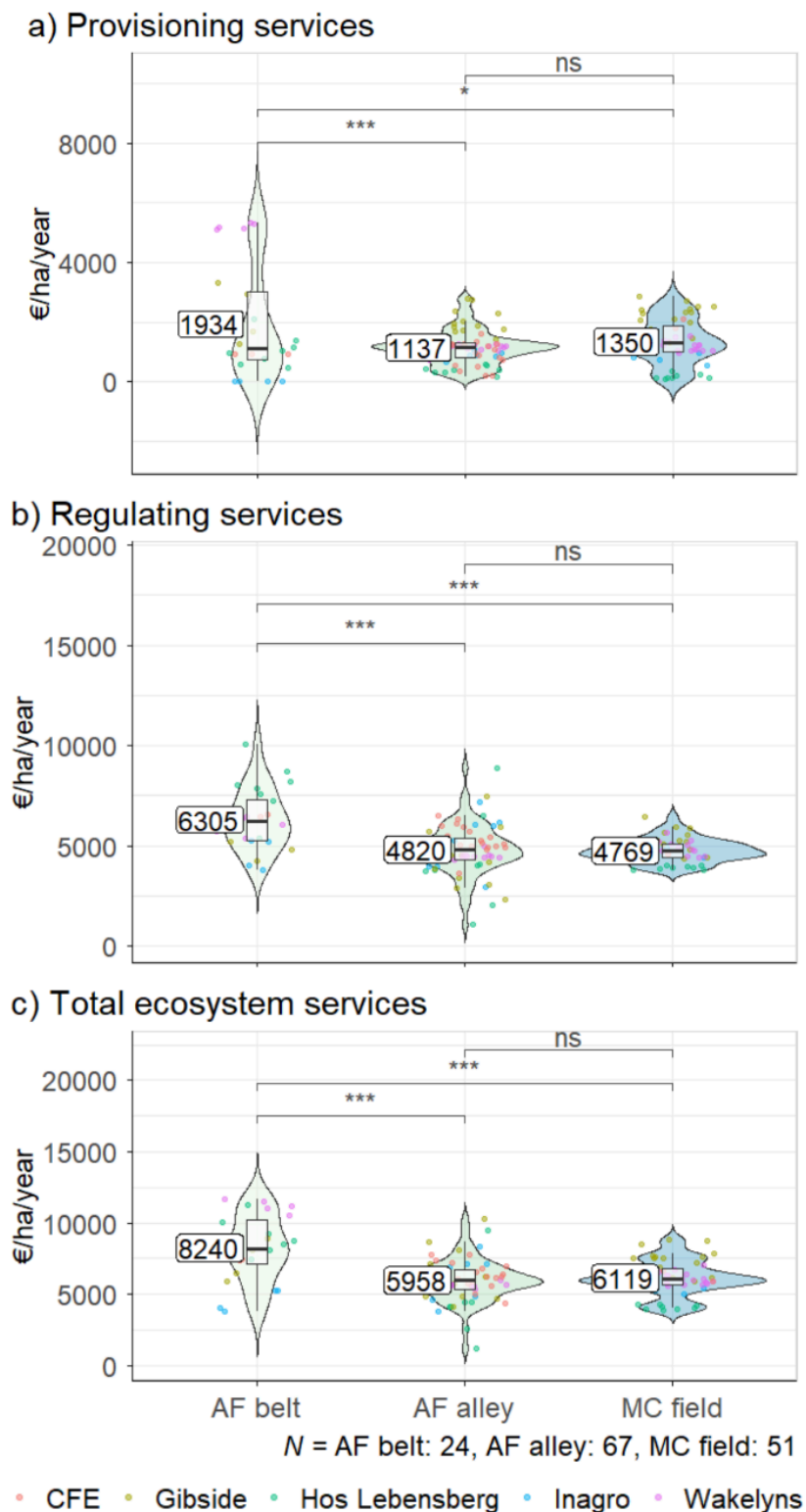


Figure 5

Aggregated economic values of provisioning and regulating ES across all study sites. The values in all areas are standardised to a hectare of sole area. The positions and values of the labels indicate the mean monetary values. Brackets indicate statistical differences at $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), and $p < 0.10$ (.), with non-significant differences denoted as ns. N = number of observations in each area

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [OnlineResource1.pdf](#)
- [OnlineResource2.pdf](#)