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Assessing the multidimensional elements of sustainability in European agroforestry systems

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1. Introduction

The enhancement of land management plays a major role in ensuring the production of sufficient safe, nutritious food and the adequate provision of ecosystem services (e.g., biodiversity, safe clean air and water, climate change mitigation, Godfray et al., 2018; Smith, 2013). Progress must be achieved together with the protection of natural resources and without the expansion of existing cultivated land areas. Addressing this multifaceted problem has been highlighted as one of the greatest obstacles currently faced by humanity (Smith, 2013). Agroforestry (i.e., incorporating trees into cropping and livestock production systems) represents an agroecological approach to production that could address some of the present challenges, for example through the provision of multiple outputs from the same area of land (e.g., fruit, nuts, livestock products) and through increased carbon capture (Lampkin et al., 2015). There is increasing evidence that supports the promotion of agroforestry (AF) in temperate developed countries as a sustainable alternative to the highly industrialised agricultural model (Jose, 2009; Kay et al., 2019a; Kay et al., 2019b; Smith et al., 2012b; Torralba et al., 2016). The positive impact of AF on productivity, resource utilisation and environmental protection could play an important role in maintaining and improving land productivity and protecting resources for future generations. In a changing climate these attributes could prove most valuable.

A wide range of AF systems are currently operating within Europe, encompassing a variety of management types and farm practices, and covering 8.8% (about 15.4 million ha) of the utilised agricultural area of the EU27 (den Herder et al., 2017). Agroforestry systems can be defined by their main agricultural components i.e., silvoarable systems combining trees and arable (and vegetable) crops, and silvopastoral systems including trees and livestock (Burgess and Rosati, 2018). Agroforestry sites can also be classified as either “traditional” or “innovative” (Smith et al., 2012a). Traditional agroforestry systems contain long-established woody, crop and livestock components, managed primarily to produce food, often with high cultural and biodiversity values (Rolo et al., 2020), while innovative agroforestry refers to multifunctional systems designed for the integrated production of food and non-food biomass balanced with resource and environmental conservation (Smith et al, 2012a).

Understanding the range of benefits/drawbacks attributed to the current range of AF systems is essential to develop policies and practices appropriate to land type(s), and to avoid negative impacts such as increased labour costs or reduced land availability. Assessing the sustainability of innovative case-studies of AF can help to identify such trade-offs and “configurations that work” within a specific socio-ecological or socio-economic context. Benefits and costs of management strategies and production systems can be identified through this process to inform the development of support schemes, farmer and land-manager advice provision, and new markets for food or non-food products. A combined approach to sustainability assessment, applying a range of metrics or indicators, could help to reveal costs and benefits from a range of perspectives (environmental, economic, social, governance). This can be particularly valuable in determining the extent to which contrasting agricultural systems can deliver on a range of sustainability objectives (FAO, 2013) and can reduce uncertainty in projecting the consequences of multiple impacts (Kanter et al., 2018). It can also support the development of coordinated policies that achieve the best possible balance between multiple sustainability objectives (e.g., the United Nations Sustainable Development Goals and associated indicators).

The aim of this research was therefore to compare different case-studies of “traditional” and “innovative” AF in Europe to each other, using a comprehensive sustainability assessment tool, the Public Goods Tool (Gerrard et al., 2012; Paraskevopoulou et al., 2020) adapted for agroforestry, to determine stronger / weaker areas of sustainability, and identify key practices and system characteristics that affect performance. The output ranking provided by the sustainability tool was used to identify characteristics that can lead to better/worse across diverse sustainability criteria. Our primary research questions were as follows: i. How do AF systems perform across multiple dimensions of sustainability? ii. What are the key characteristics of AF systems that ensure sustainability in environmental, economic, social and governance domains?

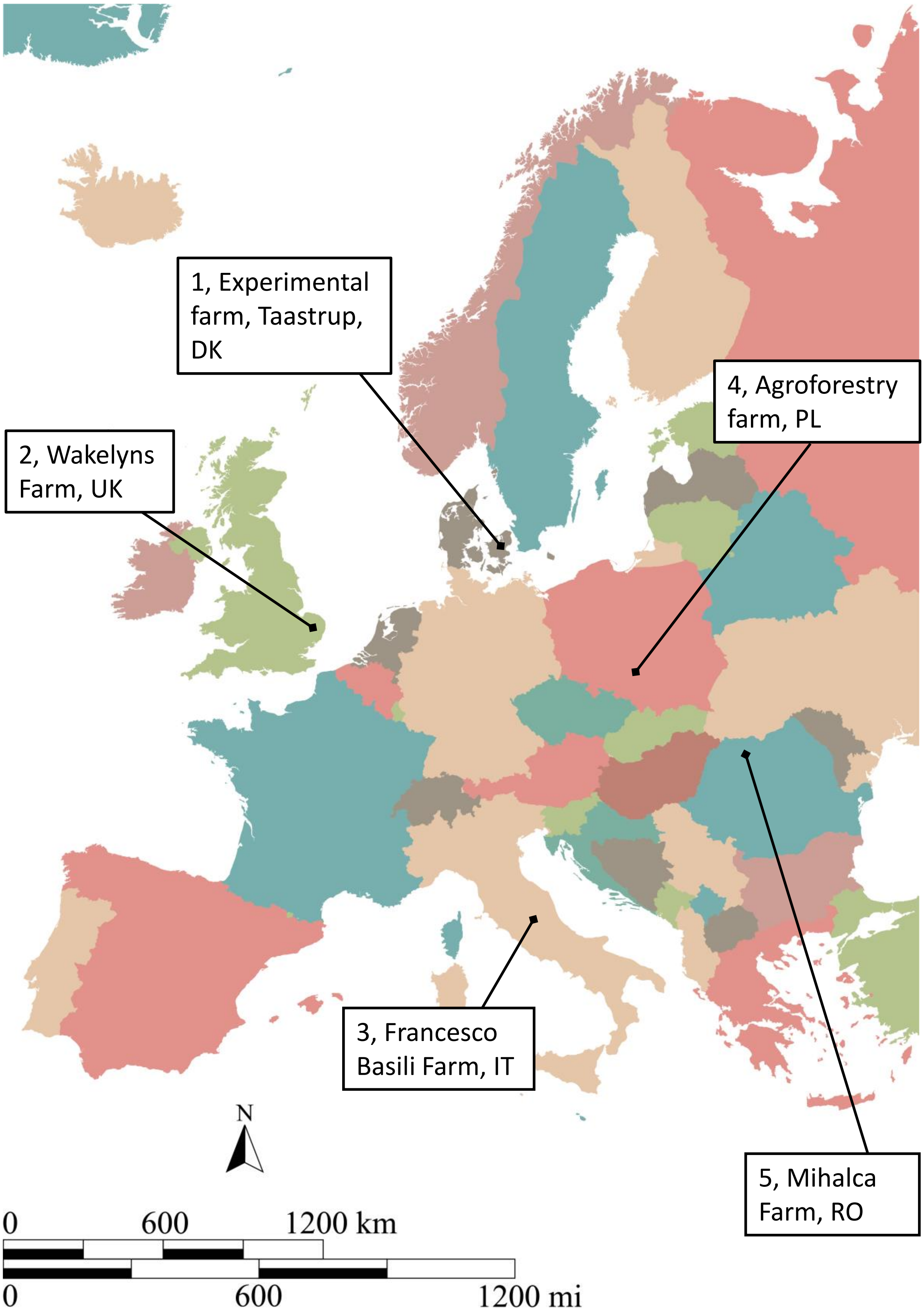
2. Methodology

To achieve the above objectives, we assessed five case study sites from northern (UK and Denmark), eastern (Poland and Romania) and southern (Italy) Europe, covering silvoarable and silvopastoral systems, using an established sustainability assessment tool, the Public Goods Tool (PG Tool, Gerrard *et al.*, 2012, Paraskevopoulou *et al.*, 2020). Sites were selected to cover a range of product types and innovative and traditional approaches to AF, to facilitate a better understanding of key trade-offs associated with a range of modes of production, land types and agri-climatic zones. An overview of each site is provided in the following section, in Table 1 and in Figure 1. A detailed description of the sites is provided in Appendix A: Supplementary Material, S3.

Table 1: Description of each agroforestry site assessed and system type classification

No / Country	Size (ha)	Tree density (% of total agricultural area)	Elevation (m asl)	Average temperature (°C)	Annual precipitation (mm)	Silvoarable (SA)/silvopastoral (SP)	Agroforestry system	Main agricultural products	Main tree products	System type (Innovative = I, Traditional = T)
1, DK	11	4	112	10	643	SA	Alley cropping	Cereals and fodder	Bioenergy	I
2, UK	22.5	23	50	14.4	620	SA	Alley cropping	Cereals, vegetables,	Bioenergy	I
3, PL	34.7	2	147	8.4	576	SA	Alley cropping	Vegetables	Fruit	I
4, IT	39.5	12	430	13.9	466	SP	Olive orchard and sheep	Milk, cheese	Olive oil	T

5, RO	26	44	430-650	18	825	SP	Wood Pasture	Cheese, milk, beef and pork	Bioenergy	T

82 

83 Figure 1: approximate location of the agroforestry sites

2.1 Sustainability assessment method description

The Public Goods Tool (PG tool) is a multi-criteria analysis-based sustainability assessment protocol addressing performance within environmental, economic, social and governance categories (Gerrard *et al.* , 2012, Paraskevopoulou *et al.*, 2020). It was developed as a way for farming advisors to engage with farmers in the evaluation of the delivery of public goods from organic farms and consists of an Excel workbook with a range of questions under each of the categories. The answers, which are either quantitative, qualitative or categorical, are aligned with a scoring system designed to indicate the level of public goods delivery for the farm under each of the categories or 'spurs', and each spur is assessed by asking questions based on several key "activities". Each activity has at least one corresponding question and these allow the researcher/advisor, who is assessing the farm, to evaluate the detailed ways in which the farm provides each public good. For example, through such questions as "what is the amount of your land that is woodland consisting of native species?" and "what percentage of your land is left as over-wintered stubble?". Thus, the activities have been selected to test the range of ways in which a farm might provide each individual public good.

Some activities are assessed using several questions while others require only one. Where multiple questions are asked their scores are averaged and rounded to the nearest whole number to give the score for that activity. Thus, an activity requiring several questions is not weighted more heavily than one requiring only a few or one question.

Scores are provided between 1 and 5, in response to individual questions and activities, and for the spurs. A score of 1 is the lowest mark, indicating that no benefit is being provided and 5 is the highest score. Higher and lower score values were attributed to question responses, based on discussion during stakeholder workshops and a subsequent literature review during the initial tool development (Gerrard *et al.* 2012). Some questions have a "not applicable" (n/a) option. This is where a situation may arise such that the farmer cannot possibly provide that benefit, for instance, a farmer who does not have dairy cows will not have any members of staff looking after them but should not be scored lower for failing to do so and therefore can choose n/a as the answer for this question in the staff resources activity of the animal health and welfare spur.

The scores for each spur are obtained by averaging the scores for all its activities. These are then shown on a radar diagram allowing farmers to see in which areas they perform well, and which areas might be improved. A bar chart showing the activities on each spur gives information on the scores of all activities so if the farmer scored less well on a particular area, they could then identify the specific activities to work on to improve the score in the future. The scoring system and results output were chosen to be as straightforward as possible so that farmers can see concisely, how their farm is performing.

The PG tool was selected as the overarching method due to its coverage of a broad range of sustainability criteria (FAO, 2013; Gerrard et al., 2012; Paraskevopoulou et al., 2020) and due to its adaptability. Within this study the 'default' version of the PG tool (Gerrard et al. 2012) was adapted for AF systems through the incorporation of agroforestry-specific sustainability indicators (Appendix A: Supplementary Material, S1, Mullender et al., 2020). Candidate indicators for the adaptation were selected through a structured literature review of previous studies that have assessed the sustainability of AF systems in Europe. The review grouped indicators in accordance with the SAFA domains of sustainability: Good Governance, Environmental Integrity, Economic Resilience and Social Wellbeing (FAO, 2013). SAFA was selected as a framework in the light of its establishment to be a 'universal' framework for assessing agricultural sustainability.

The resulting long list of indicators was used in a pilot 'Delphi' process across five countries (DK; IT; PL; RO and UK), comprising one online survey and a workshop where experts discussed in groups of eight to select their top indicators in each of the four SAFA sustainability domains. Feedback from this was used to further combine and/or remove similar indicators, adjust the order of the lists to present to stakeholders and elaborate certain indicators with definitions. The narrowed-down list of AF specific indicators and the associated score was added to the 'default' version of the PG tool, within the most relevant spur (Appendix A: Supplementary Material, S2) to produce an adapted version suitable for the assessment of agroforestry systems.

Following online training sessions with researchers in each of the case-study countries (DK, UK, IT, RO, PL), one-day data-collection visits were organised for each of the case study farms (Table 1). During the visits, data were entered manually within the adapted PG tool, through a face-to-face interview with the farmers / land managers within the farm office(s). Data were collected for a 12-month period (i.e capturing all imports/exports from the farm, land/livestock management, land-use, and economic data) for the calendar year 2017-2018, at each case study site. Once data were entered the PG tool calculated “scores” on a 1-5 scale for nine “spurs” (i.e., elements of sustainability). The data collected included productivity information (e.g., crop or livestock outputs expressed as tonnes or litres) use of imported feed, fossil fuel and fertiliser, livestock numbers by type and staff numbers by FTE (Full Time Equivalent) amongst other criteria (Supplementary material, S1).

Whilst the 1-5 scores derived from the PG tool provide a useful overview of performance, exploring specific indicators such as the LER, alongside the reasons behind low or high scores in each case study, can provide a more complete picture and allow for an assessment of trade-offs with regard to aspects such as agricultural land requirements, total production and environmental social and economic performance. A more detailed assessment of each case-study’s performance was therefore carried out using the approaches described in the following section.

2.2 Assessment of specific indicators

A range of quantitive and qualitative data were extracted from the PG tool to assess the performance of the AF systems across the four SAFA domains (Table 2). Throughout this process, fossil energy use data by fuel type was converted to total Gigajoules (GJ) per hectare of Utilised Agricultural Area (UAA) using standard values. Energy use data from the Farm Business Survey (UK) and Eurostat (all other countries) were used as a comparator (Defra, 2013; Eurostat, 2018). Renewable energy was calculated separately based on the total GJ used on each site that was sourced from wind, solar, woody biomass, and other renewable sources. Individual nitrogen, phosphorus and potassium balances were calculated on a “farm-gate” basis (i.e., the sum of atmospheric deposition, nitrogen fixation, feed, fertiliser, bedding and livestock imports and exports, divided by the UAA).

For a financial evaluation, gross margins were calculated from the revenue and variable cost data collected within the PG tool (e.g., seed, fertiliser, feed), although this data was unavailable for the case study in Poland. Labour costs were estimated from national hourly rates, which were combined with the hours of labour at each case study, to provide an estimate of the net-margin (Eurostat, 2019; Garnero, 2018; Nix, 2019; Schröder, 2020; Xu et al., 2019). For the social domain, levels of employment were determined from Annual Labour Units (ALUs) where one ALU is equal to 2200 hours per annum, and compared to survey data on levels of employment on organic farms (Morison et al., 2005). Although only three of the five farms were certified as organic (IT, RO, UK), the remaining two farms (DK, PL) were nevertheless following agroecological techniques (in this case agroforestry) and could be classified as “low input” following the classification approach developed by Bijttebier *et al.* (2017) i.e., with fertilizer and crop protection costs of less than €80 per hectare of UAA. We therefore believe that that Morison et al. (2005) data is still relevant to use as a comparator to such systems, due to the similar management approach. Local and regional sales were classified as those within 25km of the farm and within the same NUTS1 region respectively.

Within the Governance SAFA domain, data on the farms’ adherence to “Permaculture principles” was determined based on new AF questions added to the PG tool which assessed extent to which the three key aspects were being followed: 1. Provision for people to access the resources necessary to their existence; 2. Provision for all life systems to continue and multiply; 3. Living within limits and distributing surplus (Mollison, 1988). The PG tool scores were allocated based on the farmers response (i.e., if all three principles were being applied then a score of 5 was given, if none of the permaculture principles were met, a score of 1 was returned). Data on the case-study farms’ levels of participation were determined based on the extent of any interaction (e.g., with other farmers, advisors, suppliers, control/certifying bodies, and retailers). In a similar manner to the scores for Permaculture principles adherence, scores were affected by the extent to which the farmer was working with other groups / organisations, i.e., a maximum score of 5 was given if the farm was a member of cooperative groups that covered all the above categories, a score of 1 was received if the farmer worked independently, except where input is obligatory.

The Pearson's R test was used to measure the strength and direction of association between each pair of the quantitative variables listed in Table 2 (Weaver et al., 2018). The coefficient takes a value between -1 and 1, indicating the correlation strength and direction. Although the number of case studies (n = 5) within this study is below the recommended minimum for running a Pearson's R (Bonett and Wright, 2000), the test can still provide a broad indication of key relationships to inform further data collection and analysis based on larger sample sizes. Here, it was used to check correlations between and across the quantitative datasets extracted from the PG tool, to identify strongly related variables. An overview of the results for the PG tool spurs, LER calculations and sustainability data is presented in the following section.

Table 2: Quantitative and qualitative data extracted from the PG tool for further analysis of trade-offs against each of the four SAFA domains

Environmental	Social	Economic	Governance
Fossil energy use	Levels of employment	Gross margin and net margins	Extent of application of Permaculture principles

Renewable energy use	Effect of the AF product on the farm workload	Labour costs	Participation with other stakeholders in production chain
Nitrogen, phosphorus and potassium balance per ha	Use of heritage varieties for crops (number)	Sources of farm income	Extent of change(s) to farming practice in recent years in light of new knowledge
Tree coverage as a proportion of total land (%)	Local / regional sales as a proportion of total sales (%)	Farmers' views on economic status of business	

2.3 Land Equivalent Ratio calculation

Following the data collection and analysis of the 1-5 scores and the AF-specific indicators, Land Equivalent Ratios were calculated for each case study. The Land Equivalent Ratio (LER), first proposed by Mead and Willey (1980), is a means of comparing productivity of intercropping and mono-cropping systems. It is calculated as the ratio of the area needed under sole cropping to the area of intercropping at the same management level to obtain a particular yield. Here the LER was calculated as the sum of ratios for each AF site, as shown below:

$$\mathbf{LER} = \sum_{i=0}^{n} (AFT_i \div FM_i) + (AFF_i \div FM_i) \tag{1}$$

Where LER represents the sum of ratios for each crop and livestock product. Individual ratios were produced by dividing total woody biomass production (in tonnes, i) from the agroforestry case study (AFF) by the total tonnes expected to be produced in a conventional forestry system (FM) and by dividing crop/livestock product produced in the agroforestry case (AFF) by expected food crop/livestock production in a monoculture. Within this calculation an LER value of 1 indicates that there is no yield advantage of the intercrop compared to the monocrop, while a LER of 1.1 indicates a 10% yield advantage i.e., under conventional production / monocultures, 10% more land would be needed to match yields from intercropping. Through this approach, the LER was calculated for the whole agroforestry area of each case study. If there were multiple agroforestry systems on the farm, the total production was combined within a single tonnage value and compared with standard country level data to calculate the expected monoculture production on the same land area (ha) as the agroforestry site. Standard yield data for the typical food and tree crop for the specific country were used for each LER calculation as monocrop yields were unavailable for the comparison on each case study (Eurostat, 2018). This means that the LER produced in this study is an indicator of the performance of the AF system, compared with “standard” mono-cropping systems typical of the country, rather than an on-site comparison of differing modes of production.

3 Results

3.1 Overview of PG tool scores

A summary of the 1-5 scores within each of the nine spurs within the PG tool is shown in Figure 2.

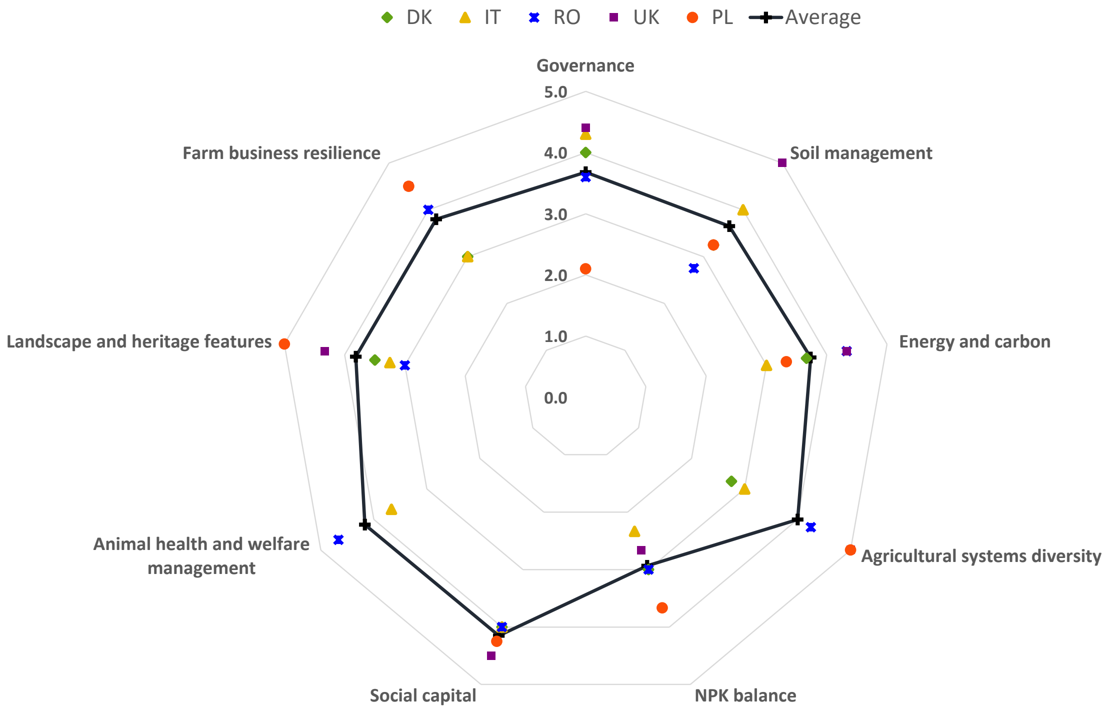


Figure 2: overview of scores from PG Tool radar diagrams produced by the adapted version of the PG tool (Gerrard *et al*. 2012). Results are for each case study and average (mean) score across all five case studies High scores are considered to be those at 3 or above.

Mean scores were at three out of five or higher for all the case study farms (Figure 2) and were slightly higher in the Innovative AF systems than the Traditional ones (3.9 average across, UK, PL and DK vs 3.6 average in RO and IT). The Social Capital and Animal Health and Welfare Management spurs were closely aligned and reached scores of 4 out of five at most case study sites, due to high rates of on-farm employment alongside effective animal health planning and husbandry. High scores for Animal Health and Welfare Management also resulted from a lack of restrictions on natural behaviour and livestock housing being kept in a good condition.

Scores were highly variable for the Soil Management, Landscape and Heritage, System Diversity and Farm Business Resilience spurs. Lack of sustainability awareness, an absence of soil analyses and poor information sharing led to lower scores in Governance and Soil Management, for the case studies in Romania, and Poland. For three out of the five cases farm Business Resilience was relatively high scoring, because of regular financial planning and a diversity of income streams.

Whilst the scores derived from the PG tool provide a useful overview of performance, exploring specific indicators such as the LER, alongside the reasons behind low or high scores in each case study, can provide a more complete picture and allow for an assessment of trade-offs with regard to aspects such as agricultural land requirements, total production and environmental social and economic performance. A more detailed overview of each case-study's performance is therefore provided in the following section.

3.2 Land Equivalent Ratios (LERs) and Environmental indicators

All the case-study based LER calculations were greater than 1, revealing that each case was more productive than a monoculture (Table 3). In four out of five cases, over 70% of the LER is derived from crop / livestock production. The "traditional" silvopasture systems in Italy and Romania had the highest LERs, although there was a low level of timber production (timber was a by-product of food production, rather than a managed element of these farms). The Polish case study was the worst performer in terms of the LER, due to lower crop yields compared to most of the other cases, and the low levels of production from the tree area because of young trees. A relatively low LER was also calculated for the experimental case in Denmark because of the low amount of woodchip harvested in the assessment year, although the high cereal yields at this case study site compensate for this. For the UK site, there is a low LER contribution from crop production, due to the high proportion of ley in the arable rotation (i.e., over two-thirds of the cultivated area) but this is offset by high tree yields. It is possible that the tree harvesting rotations are shorter than standard and the trees may also benefit from reduced competition compared to a forestry plantation. The nitrogen fixation in the ley may also lead to an increased level of production from the tree crop in the UK.

Table 3: Summary of key results from each case study for the Environmental domain. GJ = Gigajoules of fossil energy

Case study No. / Country	Food LER	Non-food LER	Farm system LER	Case study total fossil fuel energy use in GJ	Case study fossil fuel energy use GJ per ha^{-1} of UAA	Average country fossil fuel use GJ per ha^{-1} of UAA *	Renewable energy %	N balance kg per ha^{-1}	P balance kg per ha^{-1}	K balance kg per ha^{-1}
1, DK	1.15	0.04	1.19	115	2.4	9.6	0%	42.0	-6.0	17.2
2, UK	0.44	0.90	1.34	117	6.8	7.4	80%	91.3	-2.4	-12.4
3, PL	0.83	0.32	1.15	1178	54.7	11.2	2%	3.5	-4.8	-30.1
4, IT	1.7	0.21	1.87	54	1.4	8.3	0%	84.4	6.1	35.2
5, RO	1.38	0.21	1.58	801	8.5	1.5	51%	32.7	-8.0	19.0

*Average country GJ – source: UK Farm Business Survey and Eurostat for every other country

Regarding fossil energy use per hectare, three out of five cases were performing better than the country-level average (i.e., UK, IT, DK). This is likely a result of the low input / organic approach to production in these cases that can reduce the need for field operations (e.g., spraying, fertiliser application). The Romanian and Polish systems were found to be much more energy-intensive than the country-average, because of the on-farm processing and the diverse mix of enterprises which can lead to worse performance overall (Smith et al., 2015).

Regarding the amount of renewable energy use, the case study in Denmark sold biomass off-site, instead of using the renewable energy on the farm, leading to a low renewable energy use percentage overall. In Italy there was no renewable energy use, as the wood harvested was used for timber production. For the Polish site there was some renewable energy use from woodchip, although the young trees meant that the amounts harvested were low and contributed only a small percentage of the total energy use on farm. High rates of domestic/ farmhouse fossil fuel also led to worse performance in Poland and Italy. In Romania and the UK renewable energy use was relatively high as in these cases a considerable amount of woodchip was being used for cheese making (in Romania) and for heating the farmhouses.

The NPK balance score was relatively low across the cases because of high N surpluses and/or P or K deficits (Table 3). Considerable P and K deficits of more than 10kg ha yr^{-1} were found in the UK and Polish cases, because of the low-input approaches being applied on each farm.

3.3 Economic indicators

Gross margin (GM) data was positive in Denmark, Italy and the UK, and negative in the Romanian system (Table 4). Despite the GM for the tree component being negative, the UK case study system had the highest gross margin per ha, possibly because of the diversity in income sources. Although a similar system, the combined GM of the Danish case study is only slightly positive, which is primarily due to the GM of the crops offsetting the negative GM of the tree component. However, when the labour costs are included, the net margin becomes negative for the Danish system due to high levels of employment (8.1 ALUs). The GM of the Italian system includes only the tree component and is positive, even when the labour costs are included. In Romania, high costs of production of the tree and crop components are not offset by product revenue, leading to a negative margin overall. In the Italian case study, there were no production costs for the management of the natural grassland underneath the olive trees which is grazed by sheep, and so the total GM reflects only the costs and revenues of the management of the olive trees.

There were notable differences in the costs, revenues, and gross margins between the case studies. The higher gross return in alley cropping in United Kingdom may be due to the diversity of higher value crop species (potatoes, squash and spring wheat) compared with the similar combined food and energy system in Denmark, where only winter wheat is found in the crop component. The gross margin of the tree component was negative in both the UK and Danish systems, both of which are short rotation coppice systems.

Table 4: Summary of key results from each case study for the Economic domain. Data from the case study in PL were unavailable (see Methodology)

Case study No. / Country	Gross Margin (Euros ha^{-1} yr^{-1})			Labour costs (Euros ha^{-1} yr^{-1})	Net margin* (Euros ha^{-1} yr^{-1})	No. of sources of farm income	Response to Q "How is your farm doing?"
	Crops GM	Trees GM	Combined GM				
1, DK	€1,067	-€956	€112	€242	-€130	4	Reasonable living
2, UK	€5,650	-€567	€5,083	€2,342	€2,741	6	Booming
4, IT	No data	€1,520	€1,520	€836**	€684	3	Surviving
5, RO	-€320	-€1,400	-€1,720	€781	-€2,501	3	Reasonable living

* GM minus labour cost **Labour cost of management of tree component (olives) only

3.4 Social Indicators

The case study farms all had higher than average rural employment levels, and farmers reported that this had a positive effect on social sustainability (e.g., through increased employment opportunities and improved staff wellbeing, Table 5). Other indicators within the social domain were more varied between the different case studies; while most of the farms were considered mostly or fully characteristic of the local landscape, the alley cropping system in the UK was recognised as being highly atypical, as most surrounding farms comprise large arable fields surrounded either by small hedges or ditches. All but the experimental system in Denmark used heritage varieties of crops or breeds of livestock. In all but the Danish system, over half of the farm produce was sold locally/regionally. Both farms with livestock (Romania and Italy) performed well with regards to animal health and welfare because of low levels of lameness, good housing conditions and allowing the animals to perform natural behaviour (Figure 2).

Table 5: Summary of key results from each case study for the Social domain

Case study No. / Country	Farm ALUs	Average ALU based on UAA*	How and to what extent does the agroforestry on the farm affect the workload?	Do you farm using heritage varieties of crops or breeds of livestock?	What percentage of your produce (by weight) is sold locally and regionally
1, DK	8.1	1.1	Positive effect	No	20%
2, UK	2.7	0.4	Positive effect	Yes	90%
3, PL	1.9	0.5	Positive effect	Yes	60%
4, IT	3	0.9	No effect	Yes	70%
5, RO	3.8	2.3	Positive effect	Yes	100%

***** Calculation based on Morrison *et al.* (2005)

3.5 Governance indicators

For the domain of Governance four out of the five cases were performing well because of a high level of participation with other farmers and cooperative groups and regular changes to practices following the acquisition of new knowledge on "best practice". In Poland and Romania there were lower rates of participation and in the Polish and Italian cases there was also a lack of awareness of Permaculture principles amongst the farmers participating in the study which meant that the farmers could not answer the question on this element.

Table 6: Summary of key results from each case study for the Governance domain

Case study No. / Country	Permaculture principles	Cooperation with others	Uptake of new knowledge and research

1, DK	Two out of three principles met effectively	Member of cooperative groups that, together, cover all listed stakeholder groups	Multiple changes to practices; follow best practices (by events, farmer groups etc.)
2, UK	All three principles met effectively	Member of cooperative groups that, together, cover all listed stakeholder groups	Multiple changes to practices; follow best practices (by events, farmer groups etc.)
3, PL	NA	Work independently except where input is obligatory	Multiple changes to practices; follow best practices (by events, farmer groups etc.)
4, IT	NA	Member of cooperative groups that, together, cover all listed stakeholder groups	Multiple changes to practices; follow best practices (by events, farmer groups etc.)
5, RO	All three principles met effectively	Work cooperatively with other producers on an irregular basis	Changes to practices but follow irregularly (only if hear about it in passing)

3.6 Trade-offs and synergies between diverse aspects of sustainability

The Pearson's correlation assessment (Figure 3) can provide a broad indicative assessment of relationships between key variables; although the small sample size dictates that the results should be interpreted with caution, it is possible to obtain an overview of possible common relationships across a range of AF systems. The assessment revealed a positive correlation between tree coverage and renewable energy use (0.72 $P>0.05$) and a significant negative correlation between tree coverage and fossil fuel use (-0.98, $P<0.01$) possibly as a result of increased opportunities for using woody biomass on the same holding(s). Interestingly higher rates of tree cover were also correlated with increased local sales (0.81, $P= 0.10$), perhaps suggesting that a more welcoming environment, conducive to direct marketing, is created by the provision of a landscape dense with tree cover, or that farmers who plant trees are more likely to diversify into local sales. Conversely, the farm system LER was negatively correlated with the number of marketing outlets (-0.64, $P= 0.24$), suggesting that a focus on a smaller number of products could lead to increased land use efficiency. At the same time higher fossil fuel use was associated with a smaller LER (-0.47, $P= 0.42$), highlighting that a more efficient land-use could also result in reduced inputs per hectare. Higher N and P balances were correlated with higher gross margins (0.89, P= 0.11 and 0.43, P= 0.57 respectively), highlighting the potential for increased returns associated with higher input / output systems, although also illustrating the higher environmental damage potential of these systems. The importance of labour for the net margin (gross margin minus labour costs) is also highlighted through the positive relationship with the net margin (0.71, P= 0.28). Full Time Labour Units was found to be negatively correlated with total labour costs (-0.71, P=0.30) a somewhat counter intuitive result that is likely related to high levels of volunteer / free labour – a particularly apparent feature of the AF systems in UK and DK, through the farms links to research centres and current/past engagement with student-led research. Increasing the sample size would help to confirm whether the trends observed in Figure 3 are reliable and applicable to a wider range of agroforestry systems in Europe.

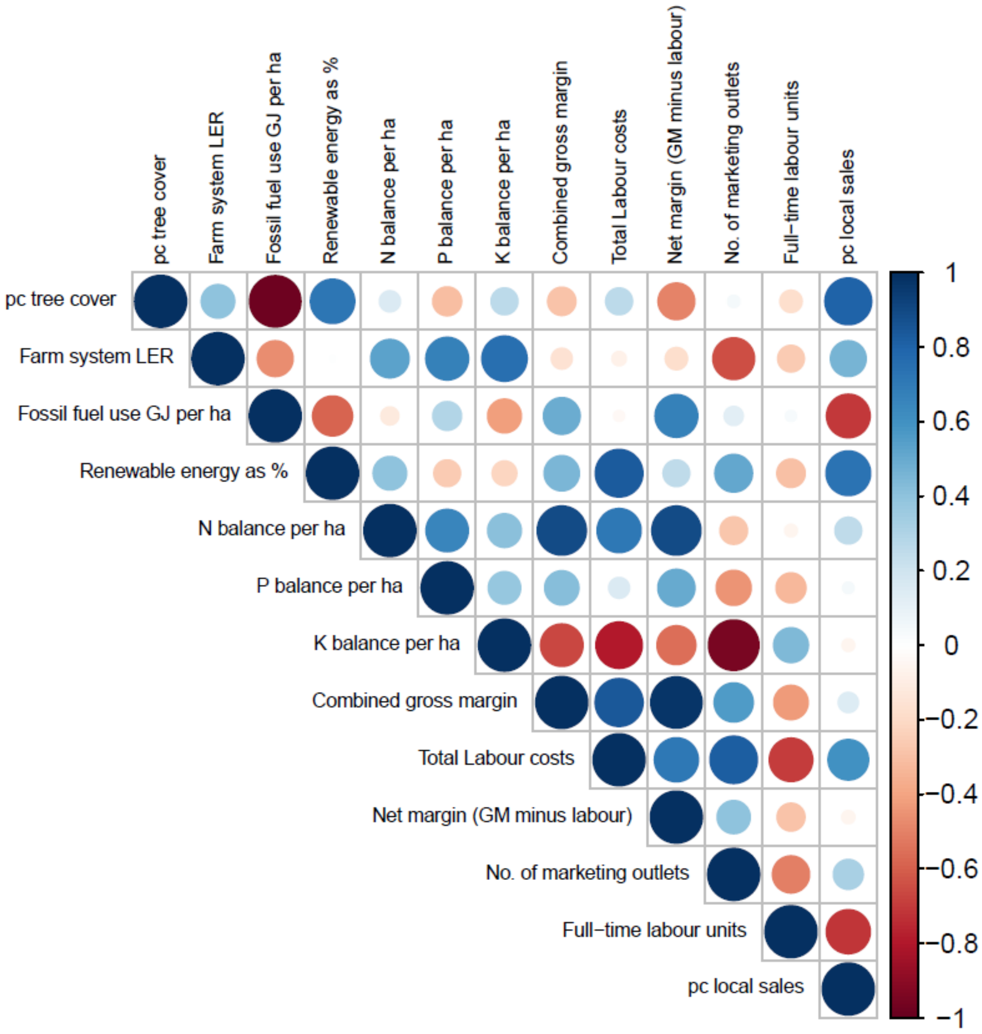


Figure 3: overview of results from Pearson's R test on quantitative variables extracted from PG tool. Positive correlations are displayed in blue and negative correlations in red color. Colour intensity and the size of the circle are proportional to the correlation coefficients.

4 Discussion

While the evidence is growing on the performance of agroforestry as an ecologically sustainable land management practice in Europe (Torralba et al., 2016), most studies focus on quantitative methods and biophysical field measurements that assess only one or two ecosystem services, with limited coverage of socio-cultural aspects of sustainability (Fagerholm et al., 2016). A recent review has shown that while agroforestry has an overall positive effect compared with conventional agriculture and forestry, results can be heterogeneous with differences among the types of agroforestry practices assessed (Fagerholm et al., 2016). This indicates the need for an integrated approach that considers and assesses the multidimensional elements of sustainability of individual systems to identify trade-offs and synergies. By using a combined approach to sustainability assessment of five case studies of European agroforestry we provide first insights into sustainability performances associated with “traditional” and “innovative” agroforestry systems to reveal costs and benefits from a range of perspectives (environmental, economic, social, governance).

4.1 Comparing the sustainability of innovative and traditional agroforestry systems

In common with previous studies, all the farm system assessments revealed Land Equivalent Ratios greater than 1, highlighting the land-sparing potential of integrated food and non-food production systems (Khasanah et al., 2020; Seserman et al., 2019; van der Werf et al., 2020) although such systems can also operate effectively in a land-sharing context through delivery of multiple ecosystem services, and the land-sparing approach often overlooks cause-effect interactions, e.g. with regard to economic drivers for farming system expansion in intensive agriculture, and whether “spared” land will in-fact be allowed to revegetate (Smith et al. 2013, van der Werf et al. 2020). The calculated LERs for the silvoarable systems in DK, UK and PL of between 1.15 and 1.34 were similar to a previous study of contrasting approaches to AF in France and the UK (LERS of between 1.24 and 1.39 in Graves et al. 2010). However, the highest land-use efficiencies were found within “traditional” silvopasture systems in Romania and Italy, suggesting that combining trees with extensive grazing has a greater potential for promoting land-use efficiency than growing of bioenergy / woodfuel crops on arable land (although the latter still had an LER of greater than 1). Such results should be treated with caution, as increases in production effiency could in-fact drive consumption, through direct and indirect product price and income effects (Alcott, 2005).

The particularly high LERs in the silvopastoral AF systems in Italy and Romania could be linked to production benefits obtained from increased shade and water retention (both enterprises were focussed on livestock production and this element was the main contributor to the high "farm system LERs" outlined in Table 3). Improved animal welfare conditions may also contribute to the high productivity and land use efficiencies observed within the silvopasture case studies (Mancera et al., 2018) and both silvopasture systems included within this study received a high score for the "Animal Health and Welfare management" spur within the PG tool (Figure 2). Other studies have also found that improved animal welfare can boost productivity in the livestock sector, through a reduced occurrence of lameness and diseases and improved outputs per livestock unit, although less extensive systems are likely to require more land and high animal welfare can also be achieved under intensive management (Smith et al., 2019; Tiezzi et al., 2019). Tree fodder within agroforestry systems may also contribute to increased production efficiencies by improving the voluntary intake of ruminant livestock (Albores-Moreno et al., 2020) although more research is needed to establish the full benefits of this approach in a temperate climate. The slightly lower LERs in the silvoarable systems (DK, PL, UK) were either a result of poor bioenergy or food crop yields in the year of data collection (DK, PL) and / or the use of an extensive crop rotation (UK) that requires a large land-area relative to the level of production at farm level.

The traditional AF systems were also more connected to the local area, with a higher proportion of local sales compared to the innovative systems in the UK and Denmark, although the traditional systems also had less product diversity compared to the innovative case studies. This is a result of the more flexible nature of rotational arable systems, compared to permanent pasture (i.e., crops can be selected to be in line with market demands every year) and the relatively recent-system design in the UK and DK, which both allow the farmers / land-managers to tap-into recent emerging markets (e.g., for novel crops such as lentils and/or furniture / other high value wood products). The higher gross margins observed in the innovative systems may also be a result of the increased adaptive capacity in-terms of changing the system to suit current / future market conditions.

4.2 Common areas of better or worse performance

Comparing all three datasets (scores, raw indicator value and Pearson's correlation-based assessments) reveals potential negative trade-offs within the case studies from a nutrient management perspective; conflicting with generic claims that agroecological systems can foster improvements in soil quality (Reganold and Wachter, 2016), most of the systems assessed faced considerable surpluses or deficits with regard to N and/or P and K. The N surplus on most of the sites is in-line with a recent meta-analysis of nutrient budgets for agroecological farming systems (Reimer et al. 2020). This surplus could relate to poor synchronicity between N supply and demand in low-input systems relying on biological N fixation (the AF case studies in UK, DK and PL relied heavily on N fixation through clover and lucerne leys) as this can make the efficient supply and utilisation of N more difficult than a system relying on readily available N sources through manufactured fertiliser (Smith et al., 2016). Low crop yields in the year of the assessment could have also contributed, as 2017-2018 was a particularly dry and warm year, particularly southern / south-eastern parts of Europe (C3S, 2021). A pluriannual study could provide an improved assessment of nutrient-use efficiency in AF systems. The deficits of phosphorus across the case study sites are also in-line with previous assessments of agroecological systems and could be partly addressed by sewage sludge application, although this would require a change in international organic standards on the certified farms (Smith et al. 2016).

Contrary to expectations, the assessments also reveal that agroforestry does not always lead to a high rate of renewable energy use on-farm; despite the possible strong relationship between increased tree cover and on-farm renewables (Figure 3). In some cases, this was because of the export of the wood product, either a fuel or as timber. Encouraging greater on-farm self-sufficiency regarding energy use is clearly a challenge that also relates to the relatively high cost of the equipment and/or infrastructure required (e.g., for small-scale Combined Heat and Power generation) and a lack of support from policy to cover increased costs of fuel, as well as lack of trust in suppliers and social acceptance issues (Segreto et al., 2020; Ymeri et al., 2020). Inertia at farm level and/or a lack-of political will to support farmers in this direction is likely to stymie development in this area without coordinated action at an EU level (Arnott et al., 2021; Máté et al., 2020) although biomass combustion is not a panacea for meeting renewable energy targets as it can be a source of fine particulate emissions, which are especially harmful for human health (Daellenbach et al., 2020).

Clear winners in the multi-factorial analysis were identified in terms of the positive environmental and social sustainability impacts of agroforestry systems – system diversity, levels of employment and workforce wellbeing, and animal health and welfare management stand out as stronger areas. High levels of employment on most of the AF case studies is also likely to be considered a positive from a job provision perspective; however these systems could also be viewed as inefficient and more vulnerable to reductions in subsidies within the primary production sector (Loizou et al., 2019). The high level of local sales and participation in cooperative groups are all contributory factors and highlight the potential of agroforestry to promote rural development and equip on-farm employees with the knowledge required for the development of agroecology in Europe. Although levels of participation with other producers were lower in Romania and Poland, this is a possibly a reflection cultural differences in these countries that can reduce levels of active participation between those working in agriculture (Fałkowski, 2017).

At the same time, the benefits of AF environmental and social sustainability will potentially be at a higher financial cost. Financial viability can be difficult to maintain in such a diverse system (i.e., two of the cases had a negative margin at the farm scale when factoring in labour costs). This is in line with recent research which recorded slightly lower market outputs in 11 European agroforestry landscapes, compared with agricultural landscapes (Kay et al., 2019a). However, while studies have found that establishing agroforestry requires higher initial investment than agriculture or forestry due to higher initial inputs, in the long-term, profitability per hectare can be higher (Benavides et al., 2009; Rigueiro-Rodríguez et al., 2009). Additionally, if the value of non-marketable ecosystem services, such as carbon sequestration and soil protection are included, the relative profitability of agroforestry increases (Kay et al., 2019a). The development of agriculture within the EU Common Agricultural Policy and the EU Farm to Fork strategy currently seeks to achieve environmental, and social objectives, alongside economic outcomes. Improved payments for farmers practicing agroforestry in Europe could therefore help compensate for additional costs, if the ecosystem services that these systems clearly provide are determined to be good value-for-money (Burgess and Rosati, 2018).

4.3 Shortcomings of study

The process of collecting the data within this study highlights some of the challenges posed by the assessment approach – in particular, the potential for spurious results due to the small sample size and a reliance on the farmer giving his/her own answer to a question in the PG Tool as opposed to an independent, objective observation. With such a small sample size, it is possible that results such as the high LERs may be biased, for example, as the farms chosen are managed by experienced, innovative or privileged (e.g., access to high quality land) farmers that may not represent the 'average' farmer in their respective areas. Additionally, the PG tool 1-5 scores were developed to provide a 'picture' for discussion with a farmer, and not for a rigorous statistical analysis. Including more assessment categories and indicators (e.g. with regard to biodiversity impacts) and more in-depth questions for a robust statistical analysis could help to improve farmer trust and engagement with sustainability assessment (De Olde et al., 2016). However, there is clearly a balance to be found regarding the number of questions within a single tool and the amount of time required to complete an assessment. The selection of some indicators and associated scores within the PG tool are also based on value judgements, for example within the spur "Social Capital" higher numbers of employees / labour hours result in a higher score, whereas higher labour requirements could also be viewed as a negative from a financial perspective. Moreover, the new AF specific indicators added to the baseline version of the PG tool were mainly selected through participatory research with those supportive of the agroforestry sector. It is therefore possible that the selected indicators are somewhat biased.

Despite the above criticism, the PG Tool does provide a simple and easy to use indication of sustainability. As the questions are universal across assessments, it also provides a base from which to begin to compare the sustainability of different farm systems for a given 12-month period. On an individual farmer basis, the tool also provides information and provokes questioning, awareness of areas for improvement, thought and the development of solutions to sustainability issues. With increasing use being made of farm decision-making support tools (e.g., CropMonitor, Agrometeo) it is also possible that assessments of this kind could play an increasingly relevant role in the development of farmer-facing self-assessments, e.g., for subsidy allocation or retailer-led benchmarking. Economic valuation frameworks could be incorporated within such tools to determine the value for money both farms and society obtains through agroforestry uptake, e.g., in terms of the holistic achievement of greater levels of production, carbon sequestration and on-farm employment. To further improve the application of the PG tool within agroforestry systems, the inclusion of temporal aspects, such as yearly monitoring of the same farm via an online interface, could help to improve accuracy and relevance of the assessment results, by taking account of tree development stage and its interaction with various elements of the farm system.

4.4 Opportunities for further research and development for agroforestry in Europe

Further research into the development of agroforestry systems in Europe could seek to address some of the trade-offs highlighted in this study, for example by ensuring improved design of agroforestry systems (e.g., allowing for a focus on trees with higher value to contribute to financial viability such as fruit, nuts, olives, high value timber). Economic performance, and therefore the popularity of the agroforestry approaches considered here, could be improved considerably through such advances.

Addressing current management challenges could also help to promote the further development of AF in Europe. In particular, the protection of trees in silvopasture, the selection of species adapted to shade / tree competition, and effective understory management could assist with overcoming the current technical challenges associated with the development of agroforestry systems (Rolo et al., 2020). Addressing the high-start-up costs associated with most of the case-studies considered in this study would also help to increase the appeal of the AF approach. Funding for rural development and/or Payment for Ecosystem Service (PES) schemes could provide some of the support needed to promote developments. Sustainability assessments, such as those provided by the Public Goods tool and similar alternatives, can also provide valuable data to feed-into such schemes; however data reliability and validation is key to ensure accuracy in farm-level reporting (Streimikis and Baležentis, 2020).

The importance of assessing the long-term impacts of contrasting farming systems has also been highlighted in the context of sustainability assessment and in particular regarding climate change and the predicted increases in drought and flooding (Altieri et al., 2015). In this respect, there is evidence that AF has the potential to provide a more resilient system, through improved soil health and associated water retention (Lampkin et al., 2015). However more long-term studies of the historical and future potential impacts of AF systems in Europe are required to support such claims. Challenges are also faced in research on the costs/benefits associated with changes in soil carbon stocks within agroforestry systems. Although it is possible to account for soil carbon sequestration gains on a unit of area or country basis, the non-linear nature of any increase, site-specific variation and various timeframes used as a basis for an assessment can make it difficult to express benefits per unit of agricultural product on a consistent basis (Petersen et al., 2013).

From a development perspective, better recognition of the AF approach and associated products could help to improve penetration and market access for producers, whilst helping to diversify income streams and improve resilience. Improved uptake of AF-specific certification and labelling schemes could also help to ensure best practice and give greater confidence to retailers and consumers. On-farm demonstration and increased numbers of field-trials would help to address the current lack of knowledge of AF and stimulate a local demand for produce. At the same time increased provision of education and advice tailored to agroecological systems such as agroforestry could help to overcome current challenges and promote improved practices.

5 Conclusions

A comprehensive assessment of five case studies of European agroforestry provided first insights on the sustainability performance associated with “traditional” and “innovative” approaches to combining trees and crops/livestock. The following trends were identified across the case study sites:

- Land Equivalent Ratio (LER) assessments revealed that agroforestry systems can provide a more efficient approach to land-use than monocultures and could potentially spare land for other purposes such as conservation or carbon storage, depending on economic drivers and conflicting demands for land-use in each area.

- Innovative silvoarable agroforestry systems may have a greater potential for increased financial margins, when compared to traditional approaches, through the ability to tap-into emerging markets through effective rotation designs including high-value crops and/or wood products and associated diversification activities (e.g., on-farm courses / workshops).
- Social sustainability impacts were positive across a range of a range of agroforestry case-studies through high levels on-farm employment, resulting from a diverse range of product types / production systems within the same holding. Nearly all cases were also selling a high proportion of their produce locally, thereby supporting local economies and infrastructure.
- High labour costs may lead to or exacerbate poor business performance in agroforestry systems; overall financial margins were negative in two of the agroforestry case studies with labour costs a major factor.
- In most cases fossil fuel use within a range of agroforestry systems was considerably lower than industry averages, suggesting a lower-intensity of field operations and an increased reliance on human-labour within such systems.
- High levels of on-farm renewable energy use were found in only two out of five case studies, suggesting that the availability and cost of small-scale biomass-based heat and power systems are prohibitive for the small farms included within this research.
- Sustainability assessments encompassing greater sample sizes and longer temporal ranges would help to provide a more complete, long-term perspective on the impacts of agroforestry.

Overall, the case-study assessments carried out within the research presented revealed that agroforestry systems provide a variety of public good to society, and a means of promoting rural vitality and reducing environmental impacts. Promoting the further uptake of such systems in Europe requires coordinated support to enhance producers' capabilities and create an environment that can help to meet current and future policy objectives and foster developing markets. Taking concrete steps in this direction requires a commitment from multiple actors encompassing the entire supply chain and relevant national and European policy makers.

Declaration of Competing Interest

The authors declare that they have no conflict of interest

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Appendix A Supplementary data:

Supplementary information for this article can be found within Appendix A: Supplementary Material at: https://figshare.com/s/a5ff23817ce1403f3c75

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