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Can agroforestry compete? A scoping review of the economic performance of agroforestry practices in Europe and North America

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ABSTRACT

This scoping review looks at the literature published on the economic performance of temperate agroforestry systems in Europe and North America and tries to answers the following research questions: How does agroforestry (AF) perform economically compared to agriculture and/or forestry? And are there any particular system characteristics or conditions that make them more competitive? Results show that generally, AF is not able to compete with agricultural land use but there are notable exceptions. Especially improved policy conditions and internalising environmental externalities can make AF competitive. Compared to forestry AF is generally able to achieve better economic outcomes. The economic performance is, in addition to ecosystem service payments and policy support, dependent on soil and site characteristic, as well as prices and the profitability of the individual system components. Intensive management and increased knowledge of these systems also increase competitiveness. There are various research gaps such as economic risk on farm- and plot-level, economic performance of AF under future climate change, or a comparison of different sustainability enhancing measures in agriculture.

1. Introduction

Agriculture in industrialized countries is and will be facing many challenges simultaneously. Today's agriculture and land use (LU) is responsible for 15–30% of all greenhouse gas (GHG) emissions (FAO, 2013; Steinfeld and FAO, 2006; Tubiello et al., 2013; Vermeulen et al., 2012; Wirsenius et al., 2011) while also being one of the few sectors that actively sequesters carbon. Agriculture is also the largest contributor to biodiversity losses (Dudley and Alexander, 2017). At the same time agricultural production is under pressure from climate change, through e.g. uncertain precipitation patterns or increased risk of extreme weather events (Kurukulasuriya and Rosenthal, 2013) while facing the challenge of feeding an increasing world population and satisfying the demand for renewable resources.

Addressing these complex and interlinked issues is no small task, but one land use system (LUS) that has shown promise is agroforestry (AF). It has the potential to combine high biomass production (Graves et al., 2010; Graves et al., 2007; van der Werf et al., 2007) with soil conservation, carbon sequestration, and the reduction of soil nutrient losses and water pollution (Nair, 2011; Nair et al., 2010). AF can also reduce wind speed which leads to reduced soil erosion and evapotranspiration (Kanzler et al., 2019; Smith et al., 2013). Furthermore, AF has beneficial effects on biodiversity by providing habitat and forage for wildlife, habitat connectivity, and reduced pesticide exposure, especially for pollinators (Bentrup et al., 2019; Graham and Nassauer, 2019; Nair et al., 2010; Smith et al., 2013; Varah et al., 2020).

While there are many environmental benefits to AF, economic viability is an important decision variable for many farmers (Beer and Theuvsen, 2020; Tsonkova et al., 2018). It is also a variable that can be more easily addressed through grants and subsidies than complex social environments. Literature on the economic performance of agroforestry systems (AFS) has little knowledge synthesis. There are only few reviews available which are either dated (Bandolin and Fisher, 1991; Garett et al., 1991; Herzog, 1997), don't focus explicitly on economic performance (Smith et al., 2013) or are unavailable in English and therefore inaccessible for large parts of the scientific community (Langenberg and Theuvsen, 2018).

To gain a better understanding of the economic performance of AF in Europe and North America this paper aims to answer the following research questions:

- How does AF perform economically compared to agricultural land use and/or forestry?

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- What types of AFS, conditions or site characteristics are most competitive?

2. Materials and methods

To answer the above stated research questions the methodology of scoping reviews after von Elm et al. (2019) was applied with some alterations. Scoping reviews are suitable for less precise research questions and to gain an overview over a specific topic or field of research. They also allow the identification of key concepts and boundaries of a research field (von Elm et al., 2019). While scoping reviews are most common in medical and health care research, they are also used in agricultural research (e.g. Amos et al., 2018; Brouder and Gomez-Macpherson, 2014; Molina-Maturano et al., 2020; Park et al., 2019). A scoping review protocol was developed alongside this paper. This article is the concluding report of this protocol (Annex B).

To create a basis for the inclusion and exclusion of papers the relevant LUS were defined (Table 1). Sequential agroforestry practices where trees and agricultural production occupy the same plot as single-use systems over different intervals of time instead of co-existing over the same interval of time were excluded. So were less commercially viable systems like home gardens and urban or forest farming since they only make up small parts of agricultural LU. Working towards decreasing large scale negative externalities generated by conventional agriculture should instead focus on large scale production systems.

The search request for the databases SCOPUS and Web of Science was created by conducting a limited search on SCOPUS using the search terms "agroforestry" and "economic". The resulting keywords were used as input for the final search request:

Agroforestry OR "alley cropping" OR "short rotation coppice" OR silvopastoral OR silvoarable OR agrosilvopastoral OR "agroforestry system" OR "agroforestry systems" OR "silvopastoral systems" OR "silvoarable systems" OR "agricultural wood" OR silvopasture OR dehesa OR dehesas OR montado OR montados OR silviculture OR hedges OR hedge OR hedgerow OR hedgerows OR windbreaks OR "buffer strips" OR "tree rows".

AND

Economic OR "economic performance" OR risk OR "net present value" OR "economic analysis" OR "economic and social effects" OR "environmental economics" OR "decision making" OR productivity OR profitability OR "cost benefit analysis" OR "cost-benefit analysis" OR "socioeconomic impact" OR income OR "risk assessment" OR "economic evaluation" OR "agricultural economics" OR "economic conditions" OR "economic development" OR "socioeconomic conditions" OR costs OR investments OR livelihood OR "economic aspect".

AND

Temperate OR Europe OR USA OR "United States" OR Canada OR "North America" OR Germany OR UK OR "United Kingdom" OR "Great Britain" OR France OR Italy OR Spain OR EU OR "Southern Europe" OR "Northern Europe" OR "Western Europe" OR "Eastern Europe".

The study selection consisted of three phases, each with distinct exclusion and inclusion criteria (Table 2). In Phase 1, Web of Science and SCOPUS returned a combined number of 5′389 references. After removing all duplicates a total of 3′940 publications remained ("Identification" in Fig. 1). Another 53 papers were excluded due to their publication type (Table 2). In Phase 2 papers were screened first by their titles and then abstracts, resulting in 153 remaining papers ("Screening" in Fig. 1). In Phase 3, they were checked for eligibility on a full-text basis. This resulted in 48 remaining papers of which five were not available online and could not be obtained from the authors, leaving a total of 43 included papers ("Eligibility" and "Inclusion" in Fig. 1).

The included studies were grouped by several criteria using Excel spreadsheets. They were separated into review papers and case studies on silvoarable, silvopastoral and/or agrosilvopastoral systems. Within these groups, systems were further classified by tree components, economic indicators and the kind of system comparison. Since economic indicators vary between studies, only papers that compare agroforestry to agriculture, forestry, and/or other AFS were included. The relative performance of AFS to their reference system was then used to answer the research questions. After identifying and grouping the papers by economic performance and types of AFS the range of economic indicators stood out. The most commonly used indicators were net present value (NPV), land expectation value (LEV), equivalent annual value (EAV), net and gross margins, and the internal rate of return (IRR). Less commonly used indicators were revenue, cost-benefit ratio, income, and cost. They are summarised in Table 3.

Except for net and gross margin all indicators in Table 3 use discount rates which vary substantially between studies. According to Mercer et al. (2014), while NPV is the most common capital budgeting tool, LEV is more appropriate if the time horizon of LU options differ. The EAV is

Table 1
Definition of LUS included in this review.

System	Definition
Agroforestry	"Agroforestry is a collective name for land-use systems and technologies where woody perennials are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components" (Lundgren and Raintree, 1983)
Silvopastoralism	Pasture and/or animals with trees or shrubs on the same plot (Nair, 1985) Animals can be housed in stables or on pasture. A system counts as silvopasture if grassland is used as fodder.
Silvoarable AF	Arable crops in combination with trees, shrubs and/or vines (Nair, 1985)
Agrosilvopastoral	The combination of both crops and pasture/ animals with trees and/or shrubs on the same plot (Nair, 1985)
Agriculture	LU where arable or livestock farming is undertaken on a plot of land. Livestock farming can be either on pasture or in stables. No horticulture.
Forestry	LU where trees are grown without intercropping or agricultural component, e.g., in a timber plantation.

Table 2
Inclusion and exclusion criteria for the three phases of the study selection.

	Inclusion Criteria	Exclusion Criteria
Phase 1	• Keyword search in the title, abstract, keywords and subject headings • Languages: English and German • Available on Scopus and Web of Science • Published up to 17th August 2021 • Reviews, qualitative and quantitative primary research articles and books/ book chapters (peer-reviewed) • Studied systems in temperate regions	• Other languages • Articles published after the 17th August 2021 • Not available on Scopus or Web of Science • Other publication (e.g., meetings proceedings, conference proceedings, grey literature)
Phase 2	• Title and abstract review to select studies on economics and agroforestry • Studied systems in the US, Canada, Europe • Whole system evaluation • Comparison of multiple agroforestry systems	• Any other countries or regions (including Hawai'i) • Other systems, disciplines, topics • Studies not containing any (socio-) economic appraisal • Sequential agroforestry systems
Phase 3	• Full text review for economic information on agroforestry systems • Whole system evaluation • Farm, plot and landscape level analysis	• Studies without any economic appraisal • Other systems • Landowner income as sole focus • Stakeholder perception studies • Valuation of ecosystem services, not the AFS itself • No comparison of AF with other LU or of different AF management options

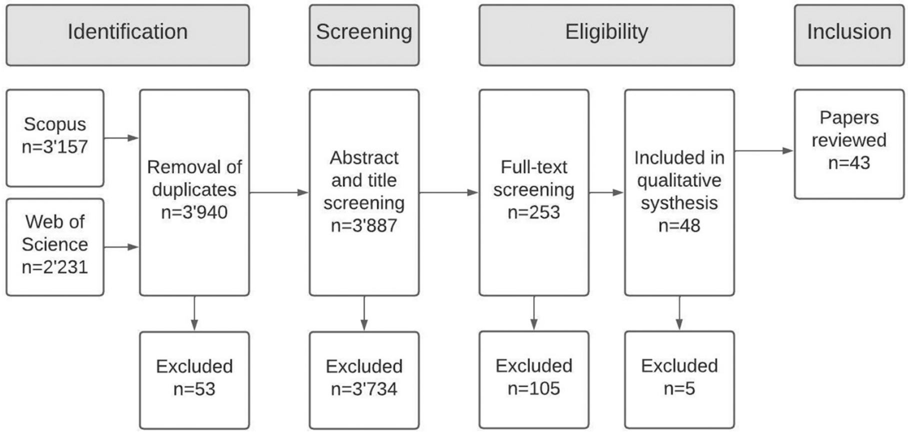

Fig. 1. Phases of literature screening based on Moher et al. (2009) (adapted PRISMA 2009 FLOW diagram).

Table 3
Most frequently used economic indicators used in the included studies.

Indicator	Summary	Formula	Expressions
NPV	Value of all future cash flows over the entire life span of an investment, discounted to the present. It determines the worth of the investment under the consideration of time.	$NPV = \sum_{t=0}^{t=T} \frac{R_t - V_t - A_t}{(1+r)^t}$	*t…Time (in years)* *T…Maximum Time Horizon* *R…Revenue*
LEV	Calculates the value of bare land in perpetual timber production and is often used to value even-aged tree stands and for timberland appraisal. It is also sometimes referred to as soil expectation value (SEV).	$LEV = NPV\left(\frac{(1+r)^t}{(1+r)^t - 1}\right)*r$	*V…Variable Costs* *A…Assignable Fixed Costs* *r…discount rate*
EAV	Calculates the cost or value of owning and operating an asset over its entire life span.	$EAV = NPV\left(\frac{(1+r)^t}{(1+r)^t - 1}\right)*i$	*C…Cost* $= V + A$
Net Margin	Measures the profit earned compared to the overall revenue.	$Net\ Margin = \frac{Net\ profit}{Revenue}$	
Gross Margin	Calculates the difference between revenues and costs of goods sold (COGS) which do not include indirect fixed costs.	$Gross\ Margin = Net\ revenue - COGS$	
IRR	Estimates the profitability of potential investments. It is a discount rate that equates the NPV and all cash flows to zero. The higher the IRR the more desirable is an investment. IRRs can rank multiple projects with similar characteristics.	$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0$	

useful when comparing forestry and agroforestry to agricultural systems which have earlier returns. These capital budgeting tools are especially useful if land is the most limiting factor of production. The IRR is not as theoretically appropriate as NPV but can be used if there is no distinct discount rate and if capital is the most limiting factor (Mercer et al., 2014). Since scoping reviews have a qualitative focus we do not include a quantitative analysis of these indicators or a calculation of averages.

3. Results

3.1. General overview

The included papers cover a time span from 1990 to 2021. After an initial spike in 1991, the number of publication undulates between zero and two until 2018, when they increased. The year 2020 saw the most publications with six papers. Roughly the same number of papers originated in Europe (incl. The UK) and North America. The US dominates the North American publications (Fig. 2) while in Europe origins vary (Fig. 3). Although there is a cluster of traditional silvopastoral AF research in both Europe and North America, the majority of studies focus on silvoarable AF. One paper was found on agrosilvopastoral AF. Nearly a quarter of papers focus on AF on marginal land. The most common tree species were poplar, walnut, pine and oak for silvoarable systems. Silvopastoral papers focused on pine, oak and pecan trees (Table 4). When it comes to system comparison, most studies look at AF in comparison to agriculture and forestry. A comparison with only agriculture was less common, followed by a comparison between different AFS. Three papers compared AF only to forestry (Appendix A).

3.2. Existing review papers

Of the 43 included papers five were reviews. Langenberg and Theuvsen (2018) focus on economics and agronomy of silvoarable alley cropping (AC) systems with short rotation coppices (SRC). Due to limited studies that compared short rotation (SR) AF to tree- or crop-only systems, they also look at the performance of SRC plantations. Results were inconclusive as they found evidence that SRC plantations can be less and/or more profitable than arable production. Profitable SRCs depend on high wood chip prices, tree yields, and prices for arable crops. Operating costs are also an important factor which leads them to recommend a uniform, parallel AC approach. Generally, AF was less profitable than arable farming.

Bandolin and Fisher (1991) characterised different AFS in North America. They found silvopasture (SP) with pine trees had a higher NPV than pine monocultures. Walnut AFS were competitive with conventional agriculture if walnut prices were high and soils fertile. Garett et al. (1991) compared black walnut AF in AC systems with walnut plantations in the US using present net worth (PNW). Systems that combined timber, nuts, and wheat had a positive PNW but were outperformed by more diverse systems (timber, nuts, wheat, soybean, fescue hay, and grazing). Tree-only systems were the least profitable LU option due to a lack of near-term returns. Herzog (1997) focused on European and Swiss AF. Capital accumulation in form of timber can be seen as insurance while the decrease in efficiency and therefore profit of non-monoculture systems is a downside of AF. AFS were generally less profitable than

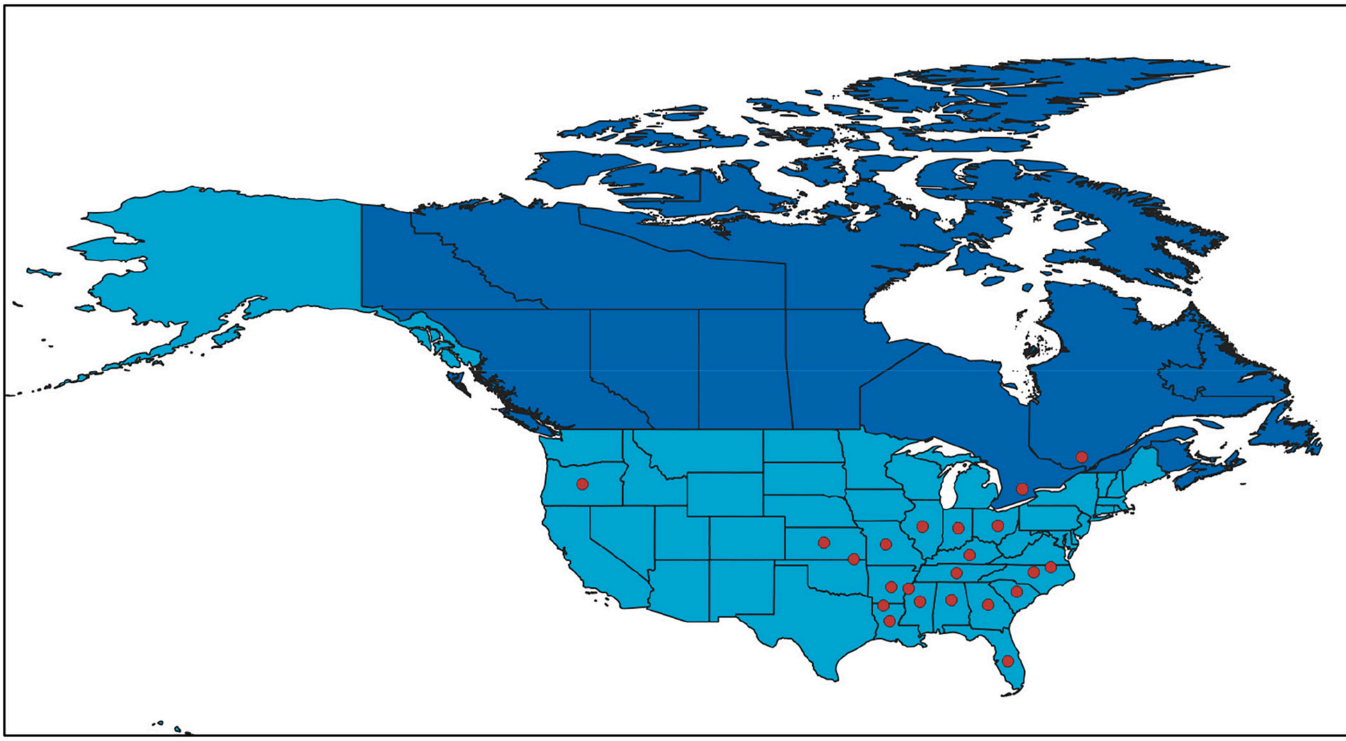

Fig. 2. Study origins in North America (red dots symbolise study origin, multiple studies can originate from the same area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

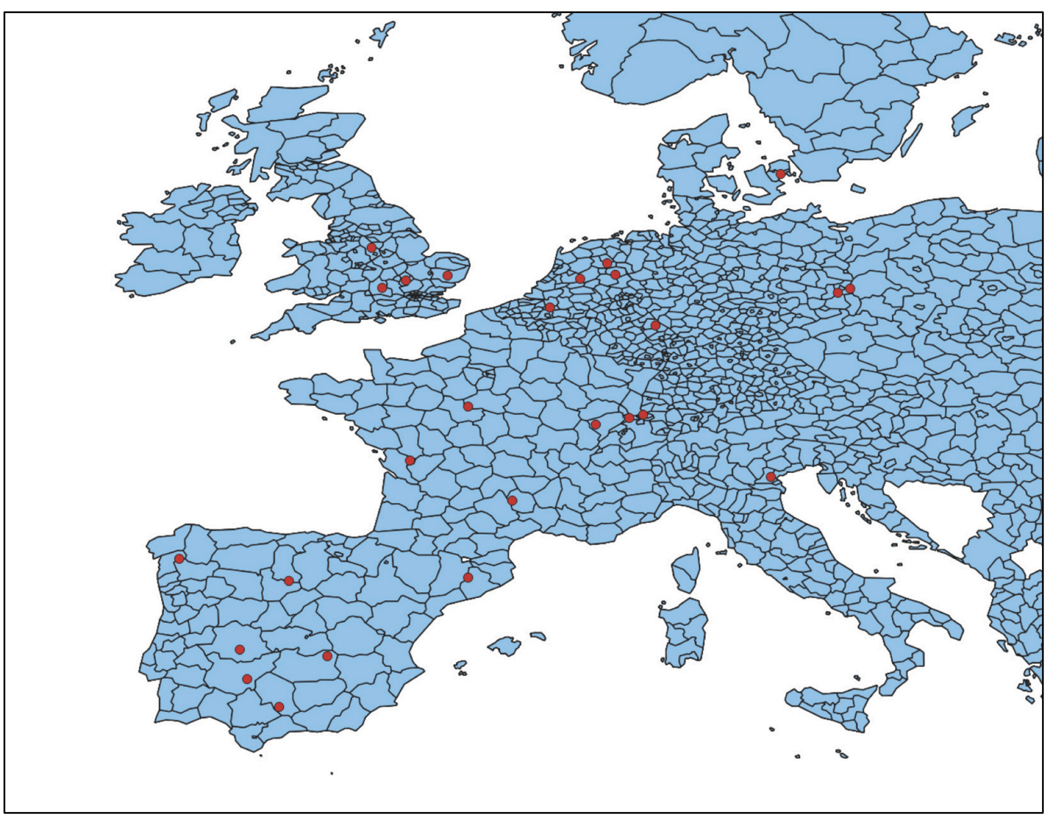

Fig. 3. Study origins in Europe (red dots symbolise study origin, multiple studies can originate from the same area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Most frequently researched AFS and their indicators (many papers include multiple tree species and economic indicators).

Silvoarable AF with	Indicators	No. of studies	Silvopastoral AF with	Indicators	No. of studies
Walnut	NPV, EAV, IRR	7			
Poplar	NPV, EAV, net margin, gross margin, benefit-cost ratio	10			
Pine	NPV, LEAV, EAV	5	Pine	NPV, LEV, benefit-cost ratio, IRR	10
Cherry	NPV, EAV, net margin	3			
Oak	NPV, EAV, LEV, net margin	4	Oak	NPV, LEV, net margin, gross margin, IRR	3
Pecan	LEV, net revenue, real options approach	2	Pecan	NPV, LEV	2
Other: black locust, platanus hybrida, hard hardwoods, cottonwood, willow, hazel, alder, olive, red spruce			Other: beech, birch, ash, cherry		

arable systems. As part of their review Smith et al. (2013) included economic benefits and characteristics of temperate AFS. They were able to recoup initial costs quicker than forestry-only systems, but AF establishment required higher investment costs than agriculture or forestry due to higher initial inputs. AF could outperform especially forestry and traditional pastures but system configuration was crucial (e.g. alley width, management, etc.). AF could also reduce the risk of natural hazards and extreme weather events but how this affects economic risk or performance was not discussed. All included silvoarable systems had a higher IRR than mono-cropping or forestry.

3.3. Silvopastoral agroforestry

Pasalodos-Tato et al. (2009) found that pine SP in Spain outperformed forestry in terms of LEV. If the value of grass was high (through e.g. high livestock prices), the economic advantage of SP over forestry increased until pasture-only systems outperformed SP. When the economic damage from wildfires was included SP outperformed all other LU options since it decreases the risk for wildfires. Studies form the south-eastern US found that pine SP generally outperformed forestry in terms of NPV (Dangerfield Jr. and Harwell, 1990; Harwell and Dangerfield, 1991). It also showed higher benefit-cost ratios than pasture- and tree-only systems while being the most stable financial investment (Clason, 1995). Bruck et al. (2019) found that short rotation trees could make forestry more profitable than SP but both still had lower NPVs than pasture-only production. In the southern US, Grado and Hovermale (2001) found that pasture-only production had consistently higher LEVs than pine SP, which in turn was more profitable than pine plantations. This depended on the type of pasture though, since SP performed better than cow but not steer-pasture due to higher prices for steers. Husak and Grado (2002) found that low discount rate could make forestry the most profitable LU option, followed by SP and then pasture. With increasing discount rates the profitability of pasture-only production increased. Stainback and Alavalapati (2004) reported different results where pine SP always outperformed forestry which in turn outperformed pasture-only production. This study however did not discount their results.

Pecan SP has only been researched in the US. Ares et al. (2006) found more diverse systems with nuts, livestock and timber had higher NPVs than less diverse systems, especially at low nut prices. When nut prices were high, nut-livestock SP could outperform nut-timber-livestock SP. Pecan prices were the biggest driver of profitability. They did not compare pecan SP with other LU options. Frey et al. (2010) compared pecan SP with other SP systems, forestry and agriculture but found uncompetitive LEVs.

In the UK, oak SP with pigs had higher net margins than pasture-only systems if price premiums for woodland pork were included (Brownlow et al., 2005). Similarly, price premiums for woodland chicken drove profitability of chicken SP with oak, ash, cherry and birch (Yates et al., 2007). de Jalon et al. (2018a, 2018b) compared different livestock components in oak Dehesas. Introducing Iberian pigs' increased net and gross margin as well as optimal tree density compared to oak SP with only ruminants.

The biggest impact on the profitability of SP were prices of tree and pasture products and discount rates. Low discount rates positively influenced profitability of SP and forestry (Ares et al., 2006; Dangerfield Jr. and Harwell, 1990; Frey et al., 2010; Grado and Hovermale, 2001; Harwell and Dangerfield, 1991; Husak and Grado, 2002), especially when compared to pasture-only systems. Prices of tree products also had a big impact as did price premiums for woodland meat (Brownlow et al., 2005; Yates et al., 2007). If the relative prices of the livestock components are high, AF seems to have a hard time outperforming pasture-only production (Grado and Hovermale, 2001; Pasalodos-Tato et al., 2009). For more details on included studies see Appendix A.

3.4. Silvoarable agroforestry (SAAF)

The following sections describe the results for SAAF grouped by their tree components. Additional information on methodologies, system comparison, discount rates and economic indicators can be found in Appendix A.

3.4.1. SAAF with poplar

Three studies on poplar SAAF from the UK included government payment schemes and payments for ecosystem services (ESS) in their calculations. With and without grants (Table 8) arable farming had higher EAVs than AF which in turn had higher EAVs than forestry. (de Jalon et al., 2018b; Giannitsopoulos et al., 2020; Kaske et al., 2021). They also accounted for the following environmental externalities: GHG emissions (de Jalon et al., 2018b), CO_2-emissions (Giannitsopoulos et al., 2020; Kaske et al., 2021), soil erosion losses by water, nitrogen and phosphorus balance (de Jalon et al., 2018b; Giannitsopoulos et al., 2020), and C-sequestration in above- (de Jalon et al., 2018b; Kaske et al., 2021) and below-ground biomass and the soil (Giannitsopoulos et al., 2020). Generally, internalising these environmental externalities made AF more profitable than arable production (Sde Jalon et al., 2018b; Giannitsopoulos et al., 2020), but sometimes less profitable than forestry (Giannitsopoulos et al., 2020). Kaske et al. (2021) found that internalising carbon sequestration alone was insufficient to make SAAF profitable if carbon prices were low. Graves et al. (2007) looked at four different grant scenarios based on the EU's Common Agricultural Policy (CAP): no grant payments for any LU, the pre-2005 grant regime and the post-2005 grant regime with two scenarios (Table 8). In France poplar SAAF outperformed arable farming and forestry at all grant levels. In The Netherlands poplar SAAF only outperformed arable farming if no grants were applied, otherwise it had consistently lower NPVs than arable farming. Poplar SAAF was able to outperform forestry with and without grants. A Belgian study found that for both hedgerows and poplar SAAF the available subsidies (here for ecological focus areas within the past CAP) were insufficient to make them competitive with arable farming (Van Vooren et al., 2016). In Spain, riparian buffers with poplar had a lower NPV than arable farming and were only profitable when subsidies compensated economic losses (Blanc et al., 2019). A study from north-eastern Germany focused on economic risk and calculated the expectation value of cost-benefit ratio for two test sites in Hesse and Brandenburg. While poplar AC had a higher expectation value than arable farming at both sites, the standard deviation was only smaller at one site. This suggests that whether AF is suitable for risk-averse or risk-neutral farmers is highly site specific (Langenberg et al., 2018). In Illinois, Campbell et al. (1991) found poplar SAAF had low growth rates and stumpage prices and was therefore classified as an unsuitable tree component. In south-eastern Canada poplar SAAF had lower NPVs than arable farming and forestry (Toor et al., 2012; Winans et al., 2015).

3.4.2. SAAF with pine

A comparison of different pre- and post-2005 CAP scenarios (Table 8) in Spain found pine SAAF was able to outperform forestry but not agriculture if no grants were included. Since Spain offered substantial forestry grants, pine SAAF became less profitable than forestry when they were included. Arable farming was more profitable than pine SAAF and forestry at all grant levels (Graves et al., 2007). In the US, Frey et al. (2010) looked at pine AC on marginal soil in the Lower Mississippi Alluvial Valley (LMAV). They found AC could not outperform arable production even on the most marginal soils and at low discount rates. Pine SAAF was always able to outperform pine forestry. Arable farming was incentivised by high grants, while no grants were available for AF. For AF to be profitable high timber prices would be required (Frey et al., 2010). In Illinois, pine SAAF had low growth rates and prices. It was therefore deemed economically unattractive (Campbell et al., 1991). In the south-eastern US, Cary and Frey (2020) looked at the economic performance of pine SAAF under increased climate risk, mainly under the risk of yield volatility and yield loss. They found the expectation value of LEV was higher for loblolly pine SAAF than for mono-cropping only when climate change increased the risk for yield reduction. If climate change could also lead to yield increases, mono-cropping remained the most profitable option. This held true when the probability of catastrophic events was increased. Mono-cropping was the most profitable LU system, even when yield risk was only lower-tailed (although expectation values for arable and AF became very similar). Another study found pine SAAF only had higher expectation values for LEV at an alley width of 24.4 m and if farmers had perfect knowledge on optimal rotation length. Although perfect knowledge is an unrealistic assumption it suggests that SAAF profitability is strongly linked to farmer knowledge and skill. Mono-cropping remained the most profitable option even when government grants (here cost-share payments) or carbon prices were included (Table 8). Pine SAAF did not reduce financial risk compared to mono-cropping (Cary and Frey, 2020). Lastly, Susaeta et al. (2012) found that pine SAAF with switchgrass was unprofitable compared to switchgrass monoculture unless stumpage prices were high and biophysical competition limited. Switchgrass prices had the biggest impact on AF profitability.

3.4.3. SAAF with oak

In Spain arable farming had higher EAVs than oak SAAF and forestry even if externalities (Table 7) were internalised (Giannitsopoulos et al., 2020). Graves et al. (2007) also found that oak SAAF had a lower NPV than arable farming under both pre- and post-2005 EU policy support (Table 8). Without grants oak SAAF was competitive in six of 16 locations. Compared to forestry, oak SAAF was more profitable at all locations when no grants were applied but was frequently outperformed by forestry if they were (due to high forestry subsidies in Spain). In Illinois, oak SAAF performed better on more fertile soil but was only profitable if stumpage prices were high and discount rates low. Oak species with shorter rotations were suitable for poorer soils with high erosion risk. They did not compare AF to other LU systems (Campbell et al., 1991). Frey et al. (2010) found that oak SAAF had lower LEVs than AF with shorter rotation trees. Oak SAAF was also less profitable than agriculture, even with policy support. In southern Ontario NPVs for oak SAAF were only positive with high crop prices but always remained below NPVs for arable farming (Toor et al., 2012).

3.4.4. SAAF with walnut

According to Graves et al. (2007), walnut SAAF was able to outperform both forestry and arable farming with and without grants (Table 8) at four of five sites in France. In The Netherlands however, walnut SAAF was always less profitable than arable farming but performed better than forestry (Graves et al., 2007). In a nitrate vulnerable zone in Spain, walnut and ash AC had higher NPVs than arable farming when the crop component was barley. Arable farming performed better than the AFS when the crop component was wheat. This shows crop prices heavily influence profitability. However, walnut and ash SAAF had more economic robustness and more reliably returned positive NPVs, even if they were lower than for arable farming (Blanc et al., 2019). In Switzerland, walnut SAAF was less profitable than arable or grassland monocultures at low government payments (15 Swiss Francs/tree). With increased payments (45 Swiss Francs/tree) walnut SAAF for timber and nut production could achieve higher NPVs than forestry and arable production. Walnut SAAF for nuts was often more profitable at the end of rotation and usually had a negative NPV in the first 10 years of establishment. This suggests NPV for walnut SAAF also depends on time (Sereke et al., 2015). In Midwestern US, high NPVs for walnut SAAF were dependent on soil suitability. Marginal or poor sites were not necessarily the best locations. Suitable soil and resulting high growth rates allowed walnut SAAF to outperform arable farming at high stumpage prices (Wolz and DeLucia, 2019). Similarly, Campbell et al. (1991) found that walnut SAAF achieved higher NPVs on fertile than on poorer soil although it couldn't outperform arable farming on either. Benjamin et al. (2000) found that walnut plantations were more profitable than arable farming and extensively managed walnut SAAF. Intensively managed walnut SAAF was able to outperform arable farming and forestry. This suggests increased knowledge on competition vectors and system management can increase profitability. They also found wider alleys more profitable (12.2 m vs. 5.5 m alley width). In Ontario, Dyack et al. (1998) found that walnut SAAF could only outperform arable production at low discount rates. Profitability was further improved by increased tree density within the wood strips and high timber prices.

3.4.5. SAAF with pecan

Frey et al. (2013) used a real option approach for a variety of silvoarable systems on marginal soil in the US, among them pecan AC. They found the adoption and dis-adoption thresholds for this long-rotation tree were higher than for short rotation trees. Generally, AFS were unlikely to be adopted by landowners, especially at high agricultural prices. Agricultural profitability however did not need to be poor for long before landowners would consider switching systems, especially on very marginal soil. They also found real-option thresholds were higher than LEV thresholds, showing that landowners would be more hesitant to adopt AF than suggested by deterministic models. In another study, Frey et al. (2010) looked at the effect of different policy schemes on AF profitability on marginal soil in the LMAV. Pecan AF had lower LEVs than AF with shorter rotation trees and was less profitable than agricultural production even with policy support. Generally, AF was more profitable on more marginal soil, including pecan AF.

3.4.6. SAAF with cherry

Most papers on cherry SAAF focus on extensive fruit orchard meadows in Switzerland with a comparatively low tree density. Giannitsopoulos et al. (2020) found that the EAV for cherry SAAF was always lower than for arable production, with and without grants (Table 8). Only combining grants with payments for ESS (Table 7) allowed cherry SAAF to outperform arable farming. Similarly, Sereke et al. (2015) found that under current policy conditions (15 Swiss France/tree) cherry SAAF was outperformed by arable and grassland monocultures. Only if direct payments in combination with high tree product prices were available could cherry SAAF outperform grassland monocultures. When ESS were internalised (45 Swiss Francs/tree) cherry SAAF had a higher NPV than both grassland and arable monocultures. Graves et al. (2007) looked at cherry AC in France and found that it outperformed arable cropping at nine of 12 sites if no government grants were included (Table 8). When grants were included arable systems were the most profitable LU option at all sites. Single farm payments for the entire AF system plus investment grants for tree planting made seven of 12 sites competitive.

3.4.7. Others

On post-mining and therefore marginal soil in eastern Germany, Böhm et al. (2011) found that black locust for SR-AC was not competitive with arable farming. Wood chip prices had the biggest impact on profitability and were low, suggesting higher prices could make black locust SAAF competitive. Two studies in the US looked at cottonwood AC. They found this fast-growing tree to be one of the few profitable AC systems on very marginal soil and at low discount rates (Frey et al., 2010). Using a real options approach, cottonwood had positive adoption thresholds when higher and less volatile prices for timber or government support (simulated by assuming a 15% increase in agricultural net returns and 15% decrease in agricultural price volatility) was included. Without government support cottonwood AC had a negative adoption threshold, but it was less negative than for AFS with longer rotation trees (Frey et al., 2013). In Italy, riparian buffers with *platanus hybrida* for firewood had low and therefore unprofitable mean revenue. Only when government subsidies compensated economic losses from reducing the arable area did it become profitable (Dal Ferro et al., 2019). Lehmann et al. (2020) looked at AC with diverse wood strips of hazel, alder, willow and other mixed timber and bushes. Higher crop prices in the UK made that system more profitable than a system with similar wood strips in Denmark. Lastly, intercropping with legumes and durum wheat on an abandoned olive grove on marginal soil increased olive yield due to nitrate fixation. The practice also provided an additional source of revenue, making AF more profitable than olive monoculture (Panozzo et al., 2020).

3.5. Agrosilvopastoral AF

The only paper on agrosilvopastoral AF by Willis et al. (1993) looked at hybrid poplar with sheep and arable crops. While it was possible for AF to be profitable this was highly dependent on soil quality, tree hybrid, and policy support. Without grants only few systems with very productive trees were economically viable.

3.6. Relative performance of AFS compared to agricultural production and forestry

This review looks at a wide range of AFS with varying livestock, arable and tree components from a range of locations. This limits comparability which is further complicated by the variety of methodologies and economic indicators used in the included studies. While many studies use discount rates many do not. Since AFS are long standing LUS it can be problematic to leave out discounting, especially when the AFS is not yet established. If a system is based on already established woodland this might be more appropriate since initial investment costs are lower. Because of the variety of discount rates, economic indicators, and system and site characteristics this paper does not include averages of economic performance. Instead, this review focuses on the comparative performance of AF to either arable/livestock-only production, forestry or different AF scenarios. This provides an opportunity to look at conditions that make AF more or less competitive compared to alternative LU options. A majority of studies found AF has a higher economic performance than forestry, both silvopastoral and silvoarable AF. In comparison to agricultural production, however, AF is mostly less competitive. Although it is noteworthy that some studies found AF to be competitive to agriculture under certain market and policy conditions (Table 5). There seems to be a broad trend that agriculture is usually more profitable than AF which in turn is more profitable than forestry, with notable exceptions.

Table 5
Relative performance of AFS compared to agriculture and forestry (no. of studies providing evidence of stated relative performance. One paper can be entered into more than one category).

	SP performs	SAAF performs
Worse than forestry	2	5
Better than forestry	10	10
Worse than agriculture	8	15
Better than agriculture	4	16 (incl. Scenarios with grants, C-prices or other financial incentives)

3.7. Factors influencing the economic performance of AFS

While AF tends to be less competitive than agricultural LU under current market and policy conditions there are scenarios under which AF can be more profitable than agriculture (Table 6). Those are internalisation of environmental externalities, government grants, cultivation of AFS on marginal land, as well as on soils well suited to the specific tree species, low discount rates and high price premiums for AF products (e.g. woodland meat, fruits, nuts, timber). Comparing different AFS showed more diverse system with both fruits (or nuts) and timber had a higher economic performance than less diverse systems (Ares et al., 2006; de Jalon et al., 2018b; Garett et al., 1991).

European studies also found internalising ESS (through prices and/or specific subsidies) in AFS can improve their profitability (Table 7) (de Jalon et al., 2018b; Giannitsopoulos et al., 2020; Kaske et al., 2021; Sereke et al., 2015).

De Jalon et al. (2018) found that AFS sequestered more carbon (C) than they emitted and had therefore a favourable emission balance

Table 6
Conditions under which AF can outperform agricultural production.

Silvopasture	Silvoarable agroforestry
• Low discount rates (Husak and Grado, 2002) • High premium prices for woodland meat (Brownlow et al., 2005; Yates et al., 2007)	• Payments for ESS (Sereke et al., 2015; de Jalon and Garcia, 2018; Giannitsopoulos et al., 2020; Kaske et al., 2021, Frey and Cary, 2020, Frey et al., 2010; Stainback and Alavalapati, 2004) • Policy support (Graves et al., 2007; Sereke et al., 2015; de Jalon and Garcia, 2018; Giannitsopoulos et al., 2020) • Increased/ perfect knowledge on system management (Frey et al., 2010; Benjamin et al., 2000) • Marginal soil (Campbell et al., 1991; Frey et al., 2010, 2013; Blanc et al., 2019) • Soil suitability for trees (Willis et al., 1993; Wolz and DeLucia, 2019) • Low discount rates (Dyack et al., 1998; Frey et al., 2010) • Intensive AF management (Benjamin et al., 2000) • Short rotation trees (Frey et al., 2010, 2013) • Increased risk of yield loss under climate change (Cary and Frey, 2020) • Wider alleys (Benjamin et al., 2000; Frey and Cary, 2020) • Low profitability of arable farming (Frey and Cary, 2020)

Table 7
ESS and their economic valuation.

Source	ESS	Valuation of ESS
De Jalon et al.	GHG emissions (in CO2-equivalent), carbon sequestration (aboveground biomass), soil erosion/ loss by water, N and P surplus	CO_2e price = 7.8€/t N price = 8.4€/kg P price = 5.2€/kg Price for sediment loss = 6.41€/t
Giannitsopoulos et al.	CO_2 emissions, carbon sequestration (in timber, branches, roots and the soil), soil loss by water, N and P-balance	CO_2 price = 57.1€/t N price = 0.2€/kg P price = 1.58€/kg Price for sediment loss = 6.41€/t
Kaske et al.	GHG emissions (in CO2-equivalent), carbon sequestration (aboveground biomass)	Current Carbon price = 7.8/ t CO_2e Central Carbon price = rises from 14.3 to 90.62€/t CO_2e after 2030
Frey and Cary, 2020	CO_2 sequestration	$10/m3 of timber or $7.25/ tCO2
Frey et al., 2010	CO_2 sequestration per ha	Break-even net revenue per metric ton of CO2 sequestration needed for LEV of forestry and AF to be equal to SEV of soybean
Stainback and Alavalapati, 2004	CO_2 sequestration in above- and below ground biomass of trees	Increase of C-price from 0 to 50 $/t C

compared to arable farming. AF sequestered less carbon than forestry. AFS also reduced nitrogen (N) and phosphorous (P) surplus as well as soil loss through water compared to arable farming. Without internalising these ESS arable farming was the most profitable LU option. When they were internalised AF showed a similar economic performance to arable farming and a greater performance than forestry. Additionally, AF had a higher biomass output than both forestry- and arable-only systems. Giannitsopoulos et al. (2020) primarily looked at threshold values for ESS payments at which AF and forestry would become as profitable as arable farming. Since the profitability gap between AF and arable production is smaller than between forestry and arable farming, comparatively low prices for C, P, and N would make AF catch up with arable production. However, profitability increases would not automatically lead to farmers adopting AF since opportunity and administrative costs cannot be neglected and were not accounted for (Giannitsopoulos et al., 2020). Kaske et al. (2021) discuss the trade-off between private and public benefits provided by AFS. Arable systems provided the highest private benefits for farmers but also produce substantial externalities. AFS provide more public benefits (ESS) but could not compete with the private benefits of arable farming. Carbon prices would decrease the profitability of arable systems more than the profitability of AFS due to their emissions balances. Using current carbon price, arable farming stayed the most profitable LU option. Increasing carbon prices to central carbon price levels made forestry the most profitable LU option over arable farming and AF.

Frey et al. (2010) looked at the net revenue from CO_2 sequestration in AF and forestry that is necessary for them to break-even with soybean monoculture. On more marginal land the break-even value was lower than on more fertile land. Forestry also had lower break-even values than AF due to their higher CO_2 sequestration potential (Cary and Frey, 2020; Frey et al., 2010). There are however barriers to carbon markets for farmers, namely cost of verification and registration as well as ensuring permanent carbon storage. Stainback and Alavalapati (2004) increased carbon payments from zero to 50$/t but even without carbon payments traditional pasture was the least profitable LU option. Their results however were not discounted.

Another influential factor for the economic performance of AFS seems to be policy support in form of grants and subsidies. Table 8 details policy schemes and their effects on economic performance. In Europe, polices are based on the CAP which provides the basic

Table 8
Description on government subsidies and grants and their effect on the economic profitability of AFS.

Source	Policy	Effects
Dal Ferro et al. (2019)	CAP direct payments + payments for maintaining vegetated buffer strips (207 €/buffer strip)	Buffer strips are only profitable when they are eligible for subsidies. Then, buffer strips could increase returns by 33–42% compared to crops-only, depending on crop prices.
de Jalon and Garcia (2018)	Direct payments (235€/ha/ year) + woodland planting grant (1888.9€/ha in year 1 + 472.2€/ha in years 2–5)	Subsidies increased profitability of all LU options. Alone they were insufficient to make AF more profitable than arable farming. AF was the most profitable option only when combining subsidies and ESS payments (Table 7).
Frey and Cary (2020)	Commodity and cost share payments: Agricultural Risk Coverage – Individual Coverage (ARC–IC) program (farmers receive payments if revenue from sold crops is lower than the official benchmark) plus a 50% cost share program for site preparation and planting trees	AF became most profitable LU option, followed by mono-cropping and forestry. The ARC-IC leads to mono-cropping having a lower standard deviation that AF.
Frey et al. (2010)	Average Crop Revenue Election (ACRE) program, Fixed Direct Payment (FDP) program for agricultural systems, plus wetland restoration payments (WRP) ($223/ha) and the conservation reserve program (CRP) (111–222$/ha) for forestry and AF.	With government payments, agricultural profitability rises strongly. When including conservation payments, forestry becomes competitive with arable farming on more marginal land. AF was only more profitable at 5% discount rate with pine AF. The WRP was more popular with farmers, partly because it is payed up-front.
Giannitsopoulos et al. (2020)	England: Direct payments (235€/ha), no tree grants; Spain: 187€/ha for oats and 107 €/ha for grass, tree payments for forestry with holm oak (2013€/ha) and Dehesas (30€/ha); Switzerland: payments for wheat (1232€/ha), oilseed rape (1848€/ah) and grass (880€/ha) plus payments for cherry trees (2182€/ha years 1–10, 3449€/ha years 11–60)	Grants generally improve profitability. Grants could not make AF outperform arable farming in any of the tree countries. When both subsidies and ESS payments were provided this was possible (Table 7). In Spain, profitability of arable remained above AF and forestry even with ESS payments. In Switzerland the profitability of AF and arable farming were very similar using the combination of ESS payments and grants. Without grants AF was unprofitable.
Graves et al. (2007)	Pre-2005 government support (DP only);post-2005 government support (single farm payment scheme) in 2 scenarios: (1) single farm payment for crop area, no tree payments, (2) single farm payments for whole AF system plus 50% cost share of investment spread out over 4 years	Without any grants, some AFS were more profitable than arable farming. The pre-2005 grant regime increased arable profitability more than for AF. The post-2005 grant regimes improved profitability for arable and AF, less for forestry. Scenario 2 of the post-2005 regime increased profitability of AF more than scenario 1. Scenario 2

(continued on next page)

Table 8 (*continued*)

Source	Policy	Effects
		reduced the profitability gap between AF and arable farming. At some sites AF could even match or outperform arable farming.
Kaske et al. (2021)	Basic payments of 235€/ha	Grants alone did not make AF competitive with arable farming. Only in combination with high carbon prices (Table 7) would AF become competitive.
Sereke et al. (2015)	Basic payments (15 SFR/ tree), ESS payments (45 SFR/ tree)	Basic payments did not make AF competitive but ESS payments and/or high prices for tree products did.
Van Vooren et al. (2016)	Hedgerows and AC as ecological focus areas counting towards 5% area set aside for greening requirement in past CAP programming period.	Hedgerows and AC were not profitable compared to arable farming. Subsidies were insufficient to compensate for economic losses.
Willis et al. (1993)	Woodland Grant Scheme (establishment costs for trees), Better Land Supplement (planting trees on arable or grassland)	Without grants only very productive tree species are profitable, more tree species become profitable with increasing grants.

framework for government payments. Member states submit a strategic plan to the EU in which they detail the options they are activating within their countries from a list provided by the EU. Generally, payments consist of direct per area payments (basic payments) plus additional payments for ecologically beneficial practices or payments for woodland planting. Overall, AFS did not profit as much from government grants as arable systems. There are also very limited policy schemes that are directly targeted at AF. In many studies grants alone are insufficient to make AF competitive and a combination with ESS payments is necessary. In the US, few studies look at government payments. Those that do look mostly at set-aside schemes that focus on conservation and land restoration. No direct incentives for agroforestry were discussed.

AF profitability also depends on relative prices of the products generated by the different system components. If AF products from trees (i.e. timber, fruits, and nuts) can be sold at high prices, AFS are more competitive (Ares et al., 2006; Böhm et al., 2011; Dyack et al., 1998; Sereke et al., 2015; Toor et al., 2012; Wolz and DeLucia, 2019). If agricultural prices are low AFS can also become more profitable than arable production. If agricultural prices are high AF can become more profitable than forestry but is usually less profitable than arable farming (Blanc et al., 2019; Grado and Hovermale, 2001; Lehmann et al., 2020; Pasalodos-Tato et al., 2009; Susaeta et al., 2012). Additionally, profitability increased if premium prices were available for the agricultural products because they originated from AFS (Brownlow et al., 2005; Yates et al., 2007). Generally, if prices for agricultural products are low and tree-product prices are high farmers may be more willing to adopt AF (Frey et al., 2013).

Since AFS usually have a rotation period of multiple decades, economic indicators to assess these systems often use discount rates. The included studies use heterogeneous discount rates between two and 10 % (Appendix A). High discount rates symbolise a strong preference of consumption in the present compared to the future. The opposite applies to low discount rates. Therefore, low discount rates are often a requirement for competitive AFS (Campbell et al., 1991; Dyack et al., 1998; Frey et al., 2010; Husak and Grado, 2002). This can be an issue when considering generational equity because current market conditions often favour less sustainable production systems that will decrease resource availability and quality for future generations.

Included studies come from a range of locations with varying soil conditions. Often, marginal soil alone did not make AF competitive with agriculture (Ares et al., 2006; Böhm et al., 2011; Frey et al., 2013; Frey et al., 2010) without additional factors (Blanc et al., 2019). With certain incentives (e.g. government payments) marginal location were the first and often only places where AF became an alternative at relatively low payments (Frey et al., 2013, Frey et al., 2010). Marginal land is however not suitable for all tree species. Especially higher value trees for fruit, nut or timber production need more fertile land to support high yield potential and growth rates (Willis et al., 1993). Generally, it is important that tree species are well suited to local conditions (Campbell et al., 1991; Willis et al., 1993; Wolz and DeLucia, 2019).

There is very limited evidence of how AF effects risk. The only studies explicitly addressing this issue were by Langenberg et al. (2018) and Frey and Cary (2020). While the former did not find AF to reduce financial risk relative to mono-cropping, the results by Langenberg et al. (2018) are not as conclusive. At one of two experimental plots AC had second order dominance over arable farming and therefore reduced risk. On the other experimental plot this did not hold and arable farming hat a lower standard deviation than SAAF. More research is needed here.

4. Discussion

Studies included in this review focused mostly on silvoarable system using AC approaches. However, most European AFS are extensive traditional silvopastoral systems in Mediterranean regions (den Herder et al., 2017) which are underrepresented in this review. This could be problematic since land abandonment and intensification is an ongoing threat to these systems (Rodríguez-Rigueiro et al., 2021). Therefore more targeted research on how to make and keep these systems profitable is warranted.

Another topic for further research is risk, specifically plot- and farm level economic risk under changing climatic conditions. While some studies state benefits from portfolio diversification that reduce financial risk and increase resilience there is insufficient scientific evidence for it. We can also make no definitive statements on the economic performance of AFS under changing climate conditions since we lack knowledge on how AF and their systems components would behave. Research on plot-level risk is available from very few locations and only one study took future climate events into accounts.

Nearly all included studies rely on modelling approaches to predict the profitability of AFS. They used a multitude of methodologies and indicators to assess economic performance which limits the comparability of papers. Few on-farm trials are available. This makes model validation difficult especially since data on performance under changing climate conditions is uncertain and under-researched. Included modelling approaches did not routinely look at climate risk and extreme weather events (i.e. droughts or floods) which may increase AF profitability in the future. In summary, there is limited historic data for validation and limited knowledge of how future climate scenarios will impact AF performance. This might skewer economic profitability in favour of more conventional agricultural practices. Due to discounting, the economic benefit of AFS can quickly become low since producers have to wait several years or decades for returns on their investments. Often only low discount rates make AFS competitive. AFS can provide higher generational equity than production systems with more negative externalities. Hence, a discussion is needed on appropriate discount rates for sustainable projects and how to value present against future consumption.

Economic performance was highly dependent on local context, soil and climatic conditions as well as system components. There seems to be no "one-size fits all" solution that guarantees a profitable AFS. It is therefore key to provide farmers and other land users with site specific advice to establish a successful system. More field trials and communication with farmers is needed.

Especially in Europe much of the literature recognises the multifunctionality of agriculture as it not only provides income to farmers through biomass production but also environmental services and disservices. The negative externalities of agriculture (i.e. GHG emissions, nutrient leakage, erosion, biodiversity loss, etc.) have been widely recognised but so far are not included in product prices. There is also no market for positive externalities and no product differentiation beyond conventional and organic. If agricultural products were priced by their true cost, AF products would have an advantage due to fewer environmental externalities. Our results suggest that valuing ESS and the carbon sequestration in AFS can improve profitability even beyond the profitability of more conventional agricultural production. Therefore, the carbon price in combination with the mitigation potential of these systems could be an attractive future business model. Furthermore, premium prices from direct marketing or labels that differentiate AF from non-AF products could increase economic performance.

Timber prices are often a deciding factor for the profitability of AFS. Due to the current energy and cost of living crises the attractiveness of wood as an energy source and its prices may increase in the future. This could be an incentive for farmers to incorporate fuel wood in their production systems. However, economic performance is not the only decision variable for farmers. The inflexibility of AF can be a deterrent and AF would become an option only if relative prices for agricultural goods are low. Taking into account flexibility in farmer decision making showed that deterministic approaches often overestimate the likelihood of AF adoption at given prices (Abdul-Salam et al., 2022; Frey et al., 2013). Additional barriers to AF adoption as perceived by farmers in Europe are increased labour demand, complexity of work, management cost and administrative burden (Silvestre Garcia de Jalon et al., 2018). This suggests that addressing economic profitability alone is insufficient for widespread AF adoption. Lastly, AF is not the only tool to improve the environmental sustainability of agriculture and it is unclear how AF performs compared to other LU options (e.g. crop diversification, fallow). Comparisons of how much different LU options contribute to specific goals (e.g. erosion control, biodiversity, carbon sequestration, etc.) are not available and urgently missing since committing to one will lock farmers in for a long time. It is also unclear how much AF can contribute to overall climate change mitigation since sequestration potential is site specific and depends on the use of tree biomass after harvest. Still, AF increases C sequestration compared to mono-cropping which gives it a favourable emissions balance (de Jalon et al., 2018a). Studies on the mitigation potential of AF on a landscape or regional level would be needed.

The findings of this review are limited by language skill of the authors and online-availability of literature. It only includes knowledge from scientific, peer-reviewed sources. Informal knowledge from farmers or other practitioners could be a valuable addition to this body of knowledge. We also exclude papers published after the 17th of August 2021. Nevertheless, this review can be seen as a valuable addition to knowledge synthesis in the field of AF economics and an introduction for those interested in the field.

5. Conclusion

AFS have a disadvantage of delayed cash flows which decreases their economic profitability and in many cases make them less profitable than agricultural LU. Compared to forestry, AF can generally generate higher economic returns. However, the economic performance of silvoarable and silvopastoral AFS highly depends on context, i.e. local soil and climatic condition, prices, government grants and payments for ESS. AF also seems best suited to highly skilled and knowledgeable farmers. Research gaps exist for silvopastoral and agro-silvopastoral AF, economic risk, and economic performance under future climate conditions. More field trials are needed to find successful and site specific AFS over a wide range of locations. The discipline of AF economics uses diverse methodologies which makes comparison difficult. The positive ESS that can be generated from AF and their valuation through either subsidies, carbon prices, or payments for ESS seems to be a key issue to make AF competitive over a range of locations.

Author declaration

The corresponding author chose and adapted the methodology and wrote the original draft of the manuscript. They also identified literature, conducted the screening process and analysed the included papers.

The co-author and the corresponding author collaborated on conceptualisation, reviewing and editing.

The co-author acquired the funding, administrated resources and the project itself as well as supervised progress.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

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Appendix A. Supplementary data

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