Exploring the potential of silvopasture integration in Dutch dairy farms.

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An ex-ante assessment at field and farm level

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Abstract

Dairy farming systems in temperate regions are characterised by intensive land use and dependency on external supply of feed and fertilisers, which adversely affect ecosystem functioning. Integrating trees into pastures, known as silvopasture, is considered a promising practice with positive effects on environment and cow welfare without reducing farm profitability. The complexity of agricultural systems however, and the lack of knowledge about the performance and labour intensity of silvopasture, hinder farmers from applying this sustainable form of agroforestry.

In this study a model-based ex-ante analysis of the consequences of silvopasture integration on the environmental and economic performance of dairy farms was conducted, supported by literature review and expert interviews. We found that Walnut pasture and Orchard mix outperformed open pasture at field level in terms of gross margin, mainly because of the profitability of trees. We demonstrated that 2.3 hectares of silvopasture could be successfully integrated into an existing dairy farm, increasing operating profit by 2%.

These encouraging results provide a starting point for research into the positive effects of silvopasture on the climate and nitrogen crisis in the Netherlands. More research is needed into the effect of trees on pasture feed quality and cattle diseases. Improvements in (boguard) grass and (fruit) tree species combinations, cultivation techniques and spatial configuration may enhance positive effects and boost the implementation of silvopasture into dairy farms.

Keywords: *Agroforestry, Cost-benefit analysis, Ecosystem services*

1. Introduction

1.1 Context

Intensification of agriculture has led to high food production levels. However, intensive agriculture exerts high pressure on the environment through biodiversity degradation and chemical pollution, thus threatening ecosystem functioning and food security. Dutch farmers are urged to reduce greenhouse gas emissions to mitigate climate change (*Klimaatakkoord*, 2019). In addition, nitrogen losses must be reduced to protect water quality and vulnerable nature (Tiktak et al., 2021). Furthermore, there is competition for agricultural fields for housing, solar parks and nature development. There is an urgent need to transition to a sustainable, future-proof agriculture and explore alternative practices.

A promising alternative is agroforestry. Agroforestry is a "*collective name for land-use systems and practices in which woody perennials are deliberately integrated with crops and/or animals on the same land-management unit*" (Leakey, 1996, p. 5). Mitigating climate change and increasing biodiversity are among the main benefits of introducing trees into agricultural land (Jose et al., 2017). Silvopasture is the specific form of agroforestry that intentionally integrates woody perennials, grassland and livestock into one agroecosystem (Jose & Dollinger, 2019). Until about 50 years ago, several types of silvopasture were common in the Netherlands, such as grazed forests and orchards (*"boguards*") (Edelenbosch, 1994; Everts, 1994; Oosterbaan & Kuiters, 2008). Because of mechanisation, intensification and specialisation, fruit production moved to intensive low-stem orchards and most silvopastoral systems were abandoned.

1.2 Potential of silvopasture

Silvopasture regained attention because of the multifunctionality of trees (Sales-Baptista & Ferraz-De-Oliveira, 2021). Trees provide multiple ecosystem services like wood, food and fodder production, carbon sequestration, habitat generation for beneficial insects and birds and microclimate stabilisation (Broom et al., 2013). Implementing silvopasture can be a strategy for dairy farmers to diversify income by selling additional products and services. Rising timber and fuel prices could encourage farmers to plant trees, since wood can be used for fencing, wood chips, wood stoves and green power generators (CBS, 2021a). Livestock may form a secondary source of income in a silvopasture system focused on high quality timber production (Dunn et al., 2020). More specifically contributing to food security, is the production of nuts and fruits on trees. Dutch citizens are encouraged to shift to a plant-based diet in which protein rich nuts and vitamin rich fruit would form a greater share (Faasen et al., 2021; Willett et al., 2019).

Implementing silvopasture can also be a strategy to improve livestock welfare and production (Álvarez et al., 2021). Ruminants can feed on leaves of trees like willow, alder and hazel which contain important minerals and trace elements (Bestman et al., 2014; Kendall et al., 2021; Luske et al., 2017). Treated as a supplement, fodder trees could improve cow health and milk production and possibly reduce veterinary costs (Luske & van Eekeren, 2018; Mahieu et al., 2021). Livestock in temperate regions will benefit from trees in extreme climate events (Pent et al., 2021). By reducing (cold) wind speed and buffering extreme temperatures, trees prevent milk losses up to 1 litre per cow per day (4.2%) (Kallenbach et al., 2009; Van laer, 2015; Van laer et al., 2014).

Implementing trees into pasture will influence forage production. Trees can moisten dry topsoil by hydraulic lifting and improve nutrient cycling by acquiring nutrients from deep layers and capturing leaching nutrients (Alagele et al., 2021; Allen et al., 2004; Nair & Kalmbacher, 2005). In spring, grass productivity is higher in open pasture, but in early spring and late summer and on hot days, productivity can be higher in silvopasture (Kallenbach et al., 2009; Miguel & Tiezzi, 2020; Pent, 2020). Spreading the grass production peak in spring over the seasons could expand the grazing period and reduce the need to mechanically harvest grass and feed it in the non-grazing period. It is not clear what tree cover is most optimal, although it is expected to be about one third of the farm (Jose et al., 2017; Kallenbach et al., 2006). Increasing tree canopy cover to 50% is expected to reduce pasture yield to less than 70% of open pasture yield due to increased competition for light (Franke, 2017). Optimal silvopasture systems can be 42 to 55% more productive in terms of food, forage and livestock production than open pastures by capturing more sunlight, water and nutrients (Pent, 2020).

1.3 Challenge

Despite its potential, the vast majority of farmers is not adopting silvopasture (Prins et al., 2021). To meet the European climate agreement and Natura2000 requirements, the Dutch Ministry of Agriculture, Nature and Food quality stated in their Forest strategy the ambition to expand the Dutch forests by 19,000 ha by 2030, of which 7,000 hectares could be achieved by agroforestry (Ministerie-van-Landbouw, 2020; van Maaswaal, 2021). Grassland covers 54% (983,580ha) of the total Dutch agricultural land area (CLO, 2021). Dairy farmers are managing about 70% of the total area of Dutch grassland (CBS, 2021b). Implementing silvopasture on only 1% of the grassland managed by dairy farmers is sufficient to achieve the ambition of 7,000 ha agroforestry. This emphasises the key role of dairy farmers in meeting the policy ambition to mitigate and adapt to climate change, restore biodiversity and increase animal welfare (Erisman et al., 2014).

However, due to past investments, many dairy farmers are limited in their financial space for experimentation. Designing and managing silvopasture systems correctly is crucial for success, but requires specific tools, knowledge, skills and time, which are often lacking. Implementing silvopasture requires long-term investments and planning, while effects of silvopasture over time are largely unknown (Vandermeulen et al., 2018). Unfortunately, the Ministerial Forestry Strategy is a non-coercive policy that does not provide farmers with the long-term certainty they need (Kistenkas, 2021). In fact, planting trees is sometimes not even allowed due to zoning regulations for meadow birds and open landscape. In addition, the complexity of tree-pasture-animal interactions in such agroecosystems complicates the scientific underpinning of the performance of silvopasture in terms of productivity. Only when a silvopasture system is designed and managed properly, all elements can benefit (Franke, 2017; Jose et al., 2017). Improved silvopasture systems need to be developed that provide the desired ecosystem services while maintaining high production and dignified income.

Although there is increasing understanding of the performance of silvopasture systems, redesigning farming systems remains complicated (Groot et al., 2012). Model-based support that allows for strategic thinking and early understanding of the implications of farm reconfigurations is valuable in the process of decision-making and planning. Developed for this purpose, the tool FarmDESIGN (FD) allows to (ex-ante) evaluate economic and environmental trade-offs and synergies of farm reconfiguration options (Groot et al., 2012). To achieve this, the farm balance in the static bio-economic modelling tool is connected to a Pareto-based multi-objective optimization algorithm (Groot et al., 2012). In this project of integrating silvopasture practices on existing dairy farms, the trade-off analysis will be useful to explore and discuss optimal (re-)design options. In a previous study, FD has been applied by Prins (2017) to explore the potential of agroforestry practices in Dutch farms. Our study represents a further exploration of the farm-level consequences over time of integrating different configurations of silvopasture in Dutch dairy farms.

1.4 Research questions

The purpose of this study was to design and quantify the performance of silvopasture configurations at the field level and to explore the associated trade-offs and synergies at the farm level over six time periods. The study aimed to provide answers to the following questions:

1. *What are promising Silvopasture Configurations (SPCs) for Dutch dairy farmers and how do these SPCs perform in terms of the selected indicators pasture, livestock and tree production, profitability and labour requirements?*
2. *How does the case study dairy farm perform currently in terms of the selected indicators?*
3. *How does the case study dairy farm perform over time in terms of selected indicators after optimized integration of silvopasture?*
4. *What are the trade-offs and synergies between the selected performance indicators?*

This investigation into and ex-ante evaluation of integrating silvopasture into Dutch dairy farms aimed to support farmers and policy makers in their decision making by providing insight into the potential of silvopasture and could therefore contribute to agroecological intensification tackling existing challenges in Dutch dairy farms.

2. Methods

2.1 Case study farm

A conventional dairy farm was selected to explore opportunities for integrating silvopasture practices. The farm is located in the north-western part of the province North-Brabant, in the south of the Netherlands with annual precipitation of 800mm and an average temperate of 10.1 degrees Celsius (Figure 1). Located adjacent to the farm yard, the farmer owns 32 ha of permanent pasture with fields oriented north-west to south-east. From the time of reclamation, the fields were used as orchards, arable croplands, and for several decades as pastures. In this home parcel, the soil texture is mainly clay. The water table ranges from -0.2m in peaty parts to -0.9m in a few rather sandy parcels. The groundwater level is stable due to seepage. On a second location (60 ha), the farmer grows maize silage and grass silage on a clay soil. All fields are fertilized with artificial fertiliser and on-farm produced slurry manure, of which the surplus is exported. Grazed pastures are additionally fertilized with manure from grazing animals. Concentrates, roughage, maize silage and bedding material are imported. The herd consists of 283 dairy cows with a replacement rate of 0.18. The average milk production of the cows is over 10000 kg/cow/year (for farm details, see Supplementary Materials (SM) 1). In the past five years, a portion of the milk (<1%) is being processed into ice-cream that is sold in about 40 locations. Ice-cream ingredients like fruits and nuts are currently purchased at local growers. For daily work with the cattle and on the land, the farmer is supported by two permanent employees. Besides maintaining or increasing the operating profit, the farmer's aim is to increase the milk production rate from own roughage. As protein is the most expensive feed component, the farmer's objective is to increase the protein self-reliance. The farmer has been closely involved throughout the research, in particular during designing promising silvopasture configurations (SPCs), the parameterization of the farm and the exploration of SPC integration on the farm.

Fig. 1. *Map of the Netherlands divided into 12 provinces. The arrow locates the case-study dairy farm in the province of North-Brabant (orange).*

2.2 Design of promising SPCs

To acquire information about promising silvopasture systems and their performance, a literature review was conducted in Dutch, Flemish and English journals, books and scientific magazines, using the snowball technique. In addition, twelve experts were interviewed using semi-structured interviews, which aimed to complete a list of questions but allowed for follow-up questions on relevant topics (for interview templates, see SM2). Information about design, management, costs, production and returns was acquired from seven farmers adopting silvopasture and an agroforestry scientist. Specific tree production details were acquired from two walnut experts and a food forest expert. Finally, a veterinarian was interviewed about tree-livestock interactions. This information formed the basis for the design of the SPCs and the calculation of costs and benefits over six time periods, namely years 1-5, 6-10, 11-15, 16-25, 26-40 and 41-60. All trees are at full production within this period.

To determine what promising means for dairy farmers, the case study farmer was interviewed. The farmer's objectives of planting trees are to improve landscape aesthetics, to meet society's desire to plant trees and to produce local ice cream ingredients. All trees in the silvopasture should support these objectives. Planting trees should not decrease operating profit (OP), but rather increase it to maintain a viable business. Milk production will remain the core business, therefore maintaining high pasture productivity is desired. Because of rising prices of imported feed, the farmer wants to reduce the import of feed and increase the proportion of protein from his own land, referred to as crude protein self-sufficiency (CPSS). The trees should not cost the farmer more labour, so labour required to manage the trees will be outsourced.

2.3 Calculation of SPC performance

Grass in a silvopasture will compete with trees for light, water and nutrients (Rao et al., 1997). Based on interviews with silvopasture experts and earlier studies of plantations with walnuts, poplars and other deciduous trees, we were able to translate the effect of tree canopy cover on grass production in a formula, extracted from a linear scatterplot trendline (for scatterplot and sources, we refer to Tab 1 of SM3). This formula was used to calculate SPC grass production yields. We found a linear decrease in grass production with increasing tree canopy cover:

$$GP = -0.0075TC + 0.9979 \quad (1)$$

Where:
GP = Grass production in silvopasture compared to open pasture (fraction)
TC = Tree canopy cover (%)

Tree product yields for the six time periods were acquired from online databases and above mentioned expert interviews. Prices were based on Dutch local farm shops, long-term wholesale market averages and estimations by crop experts. Carbon sequestration in tree biomass was estimated based on literature (Baltissen, 2020; Cardinael et al., 2018) and calculations using the estimated above-ground tree weight based on trunk diameter and the tree height (UNM, , n.d.). Carbon certificates are financial incentives by companies that want to offset their carbon footprint by buying a certificate. This income was merged with the standard subsidies for agricultural land. It was assumed no other subsidies were provided for the SPCs, because these changeable revenues are uncertain on the long term.

For each SPC, an overview of cultivation activities and costs was created, mainly derived from Agroforestry Vlaanderen (Nelissen et al., 2017; Reubens et al., 2019) and expert interviews (see Tab 2, 4, 6 and 8 of SM3). Tree cultivation activities include planting, placing protection, pruning, harvesting, processing and weeding. In consultation with the farmer it was decided that planting and pruning would be outsourced to a skilled (FarmDESIGN (FD) calls this: regular) labourer and harvesting and weeding to unskilled (FD: casual) labourers. Labour requirements for these activities were estimated based on literature and expert interviews and separated from the cultivation and contract work costs. Tree cultivation costs include the purchase of trees, hives, poles, ties, voracity protection, wood chips and harvesting tools such as walnut rollers and ladders. General assumptions for SPC calculations can be found in Table 1 of SM4.

2.4 Farm model parameterization and exploration

To explore opportunities for integrating SPCs on the case study farm and evaluate its performance over the years after integration, the computer model FarmDESIGN (FD) has been used (Groot et al., 2012). This model formalises crop and livestock farming practices as production activities, which are described as the cultivation of a crop and the husbandry of livestock in a specific physical setting, defined by its inputs and outputs (Groot et al., 2012). FD aids (re-)design of farming systems and multi-objective optimization. It follows the DEED-cycle of Describe, Explain, Explore and Design (Giller et al., 2008). These phases are reflected in the four graphical user windows of the computer model.

In the FD 'Describe' window, input parameters were entered which represent the components and characteristics (e.g. biophysical environment, socio-economic setting, crops, animals and manures) of the farm. In the 'Explain' window, the model outputs (e.g. nutrient cycles and feed balance) are calculated, which reflect the farm performance (Groot et al., 2012). A parameter data sheet was used to collect case study farm data by interviewing the farmer and by researching documents provided by the farmer. The data sheet and all farm parameters can be found in SM1.

To execute the Pareto-based multi-objective farming system optimization, decision variables, constraints and objectives were set in FD (see Table 2). Decision variables are parameters that are formed when the model is allowed to change the parameter in the process of optimization. Constraints are predetermined ranges for selected indicators to get realistic and preferable results. Objectives are indicators for assessing the performance of the farming system that can be minimized or maximized (Groot et al., 2012).

***Table** 2. Important adjustments made in FD during the exploration process. For a detailed overview of objectives, constraints and decision variables, see Tab 1, 2, 4 and 6 in SM5. FD calculations are described by Groot et al. (2012). ([a]) Specific feed balance constraints can be found in SM5.*

	Adjustments in FD
Objectives	Maximise area with SPCs (ha) Maximise OP (€ yr^{-1}) Maximize CPSS (%)
Constraints	Constrain labour surplus to 0 h yr^{-1} Constrain N-losses to 20-300 kg N ha^{-1} yr^{-1} Constrain feed balance [a]
Decision variable	Introduce SPCs (ha) Milking cow number (-) Hire (regular and casual) labour (h yr^{-1})

The Pareto-based Differential Evolution algorithm was conducted with 1000-1500 iterations and 250-500 solutions, which generated sufficient options for optimal reconfiguration of the farm components (C. Timler, personal communication, January 27, 2021). First, reconfiguration options without SPC introduction were explored to improve the current performance of the case study farm (Tab 1 in SM5). Then, reconfiguration options with SPC introduction were explored (Tab 2 in SM5). To evaluate the integration of all SPCs into the farm, explorations were also carried out for each SPC separately (Tab 3-6 in SM5). Due to an unknown cause, explorations with Walnut Pasture and Multifunctional hedge were not successful, farm configurations with these SPCs were manually entered and evaluated.

The results of the exploration were discussed with the case study farmer, and based on his preferences, marketability and the soil conditions, a desirable and realistic farming system with two silvopasture fields and a hedge was spatially designed. One of the optimal reconfiguration options from the exploration with SPC introduction was modified to fit the spatial design. A new exploration resulted in an optimized farm with silvopasture (Tab 7 in SM5). From this average farm configuration, six new configurations were created for each of the six periods by adjusting the parameters of the silvopasture crop and crop products according to the period. Finally, the farm configuration of each period was optimized again. The optimized farm configurations can be found in Tab 8-13 of SM5. Exploration results were used to analyse trade-offs and synergies in objectives.

3. Results

3.1 Case study farm performance

In the reference year 2020, the case study farm consisted of 74.89 ha pasture and 16.56 ha maize crop land. Of the total pasture production (13625 kg DM ha^{-1}), 15% was grazed and 85% was processed into grass silage. Maize crop land produced 19749 kg DM ha^{-1} of maize silage. To meet feed requirements, 1159243 kg DM concentrates, 373725 kg rough forage and 191730 kg DM maize silage were purchased. As bedding material, 130000 kg DM sawdust was imported. In artificial fertiliser 13717 kg N was imported. 61.5% of on-farm produced slurry manure was used to fertilize pastures and maize cropland (6500 kg ha^{-1}), the rest was exported. The contract work costs for grass cultivation amount to €127.50 ha^{-1} year^{-1}. The crude protein self-sufficiency was 40.98% and the operating profit was €90225. For a detailed overview, we refer to Tab 1 of SM5.

3.2 Promising SPCs

3.2.1 SPC design considerations

Four SPCs were designed, namely Walnut pasture, Fruit Orchard, Multifunctional hedge and Orchard mix, which are visualized in Figure 2. In general, tree rows are preferably oriented North-South to minimize competition with pasture (Shepard, 2013). The maximum crown width determined the ideal distance between trees, which varies from 7.5m for some fruit tree species to 12-15m for walnut trees (Reubens et al., 2019). The ideal distance between rows and edges is determined by (a multiplication of) the widest machine, for the case study farmer this was 10m, so rows of trees were placed 20m apart (detailed spatial configurations can be found in Tab 3, 5, 7 and 9 of SM3).

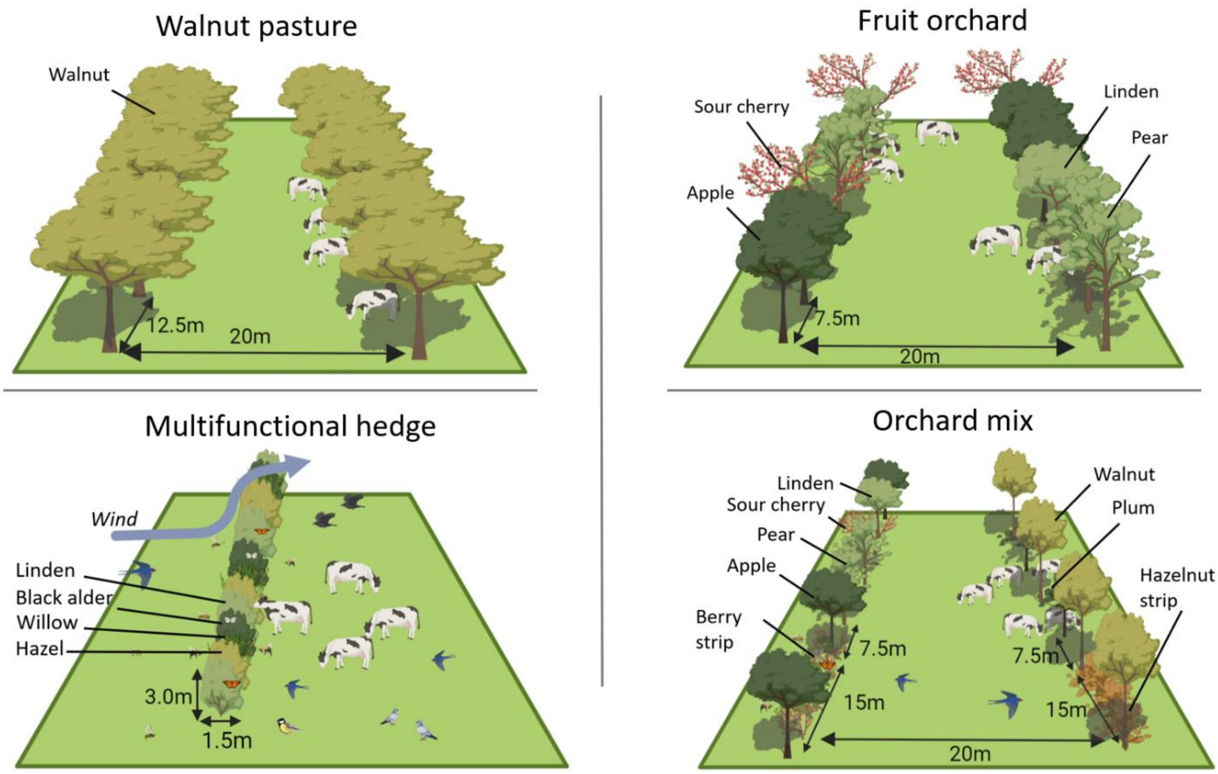

Fig. 2. Visual impression of the four silvopasture configurations with the tree species. Not true to scale. For detailed spatial (and true to scale) visualisation of the SPCs, we refer to Tab 3, 5, 7 and 9 of SM3.

The farmer is conventional but does not want to use pesticides to protect the trees. By choosing resistant varieties, diseases and pests should have little impact. To protect susceptible tree species and prevent disease transmission, trees and varieties are mixed. This is possible to a certain extent, because grouping species is expected to be beneficial for pollination and management. To stimulate pollination and natural pest control by insects and birds, natural elements are planted, like linden (*Tilia spp.)* and willow (*Salix spp.)* which are indigenous tree species that are cheap to obtain and edible for cows. These trees provide shelter and nesting opportunities and support general pollinators like bumblebees, by providing nectar during the period when fruit trees are not flowering (for monthly nectar supply in silvopasture, see SM6). Planted as a hedge, these trees protect fruit and nut trees by reducing wind speeds. Other assumptions and ecological considerations can be found in Table 1 of SM4.

3.2.2 SPC design characteristics

Distinguishing features of the SPCs are summarized in Table 3. SPC1 Walnut Pasture is mainly suited for dry fields and characterised by a long-term investment since it will take 30-40 years before walnut trees *(Juglans Regia*) will reach their peak productivity stage (H. Janssen, personal communication, November 9, 2021). Trees are widely spaced, which means normal grass production levels can be expected in the first decades. The design could also be used for chestnut trees (*Castanea sativa*), which have a similar growth habit, and are more drought tolerant, however the Dutch market is better developed for fresh and processed (cracked, oil) walnuts (Cem Altan, personal communication, December 11, 2021). Walnut trees are not yet susceptible to pests and diseases (H. Janssen, personal communication, November 9, 2021), although there is an increasing risk on damage from the walnut borer (*Rhagoletis completa*) and the *Xanthomonas arboricola pv. Juglandis* bacterium which causes blight (Kim et al., 2021; Koops, 2010). Planting a range of varieties can spread risks and stimulating and mimicking natural pest suppression can reduce pest damage (*Walnussfruchtfliege*, 2021).

Table 3*. Characteristics of the four SPCs. ([a]) Low groundwater level is >0.8m, high is <0.8m below surface. ([b]) U-pick system is where costumers pick their own food and pay afterwards. ([c]) Payment for ecosystem services like carbon sequestration and biodiversity restoration.*

Characteristic	Unit	SPC			
		1.Walnut pasture	2.Fruit orchard	3.Multifunctional hedge	4.Orchard mix
Tree density	N ha^{-1}	40	60	-	58
Shrub density	N ha^{-1}	-	-	10000	32
Species diversity	N species	1	4	4	10
Groundwater level	High/low [a]	Low	Low-high	Low-high	Low
Flowering period	-	May	Apr-July	Jan-Mar, June-July	Jan-Aug
Strength	-	Profitable	Cultural-historic	Multifunctional	Resilient
Weakness	-	Long-term	Labour intensive	Cultivation costs	Complex
Opportunity	-	Mechanisation	U-pick system [b]	Payment for ESS [c]	U-pick system [b]
Threat	-	Walnut borer pest	Fire blight disease	Weed infestation	Light competition

SPC2 Fruit Orchard has a relatively high tree density of apple (*Malus domestica)*, pear (*Pyrus communis)*, sour cherry (*Prunus cerasus)* and linden (*Tilia spp.)* trees. The landscape and cultural-historical value of a standard fruit orchard can be important. It is particularly suitable for wet fields, although groundwater levels up to one metre deep are possible. Apple and pear trees come into production within five years, with peak production after 25 years (J. van Buuren, personal communication, November 11, 2021). Their labour intensity is constant and outside labour peaks of

common farm management. Sour cherries on the other hand have high labour intensity during summer months. Fruit could be sold fresh, stewed or processed into juice and ice cream. As sour cherry trees are self-fertile, these trees together with a few linden trees (*Tilia spp.*) will interrupt the apple and pear rows to suppress pest and disease distribution (*Prunus cerasus*, 2021).

In SPC3 Multifunctional hedge, consisting of willow, linden, hazel (*Corylus avellana*) and black alder (*Alnus glutinosa*), the functions of windbreak, forage hedge, and biodiversity corridor are combined. These edible species with medicinal properties can be used by cattle as a pharmacy and snack bar (Luske & van Eekeren, 2018). Black alder is less tasty, but has the capability to fix nitrogen from the atmosphere and provide surrounding plants with nitrogen through leaf litter (Côté & Camiré, 1985). A hedge next to a ditch acts as a filtering buffer strip by reducing nutrient leaching to surface water (Cropeye, 2017). With a height of three meters, there will be a positive influence on pasture production, prevention of wind damage to trees and protection from cold winds for cows behind the hedge for 30 meters (Van Vooren et al., 2016). Annual hedge maintenance is done by contract workers (R. van Zandbrink, personal communication, November 19, 2021). This design is characterised by low labour intensity and a low direct financial return, since barely any valuable products are produced. Pruning material can be used as fodder in summer and as wood chips in winter. Subsidies and payments for ecosystem services (ESS) could cover the high costs (van Noordwijk et al., 2012). The hedge provides food, shelter and nesting places for natural pest control agents and pollinators, which is especially beneficial when the hedge is combined with Walnut pasture, Fruit Orchard and Orchard mix.

SPC4 Orchard mix is a complex and resilient system with walnut, apple, pear, sour cherry, plum (*Prunus domestica)* and linden trees and hazelnut (Corylus avellana), raspberry (*Rubus idaeus*), blackberry *(Rubus fruticosus*) and red currant *(Ribes rubrum)* shrubs*.* Like SPC1 Walnut pasture, it is particularly suitable for drier fields with a winter groundwater level deeper than 75 cm. Unique for this SPC are the strips with berries and hazelnuts and the plum trees that alternate walnut trees. These early producing strips are providing income sooner. Due to the high labour intensity, moderate quality expectation, grass loss and blockage of cattle passage by berries, berry strips are planted in limited numbers. Over a period of 15 to 30 years, berry bushes, hazelnut and plum trees are removed when production levels decline and light competition increases. After 40-60 years, only walnuts are left and the vacant space can be filled with new shrubs and trees as desired. Because of the diversity of Orchard mix, more enabling processes can take place between trees, such as pollination and pest control, which can improve production. For example, hazels, raspberries and blackberries provide the pollination population with nectar when fruit trees don't, which can increase pollination rates and with that fruit quality (Garratt et al., 2014). Fruit and nuts can be processed as described above, and as with Fruit Orchard, a self-picking (U-pick) system at Orchard mix could save labour costs and increase profitability.

3.2.3 SPC field-level performance

Of each SPC, the performance at field level was calculated (see Table 4 and Tab 2, 4, 6 and 8 of SM3). Performance in terms of productivity (Land Equivalency Ratio), profitability and labour requirements has been compared and visualised with current monoculture crops pasture and maize in Tab 10 of SM3.

Table 4. *Calculated revenues, costs and gross margin of the reference crop (open pasture) and the four silvopasture configurations (average over 60 years). All values are per hectare per year (hedge is calculated as hectare of hedge). For detailed calculations and sources, see Tab 2, 4, 6 and 8 of SM3).*

Crop revenues, costs and gross margin	Price per unit	Crop				
		Open pasture	1.Walnut Pasture	2.Fruit orchard	3.Multi-functional hedge	4.Orchard mix
Revenues						
Grass	€0.15 kg DM^{-1}	€2044	€1571	€1864	€94	€1723
Walnut	€3.50 kg $^{-1}$	-	€4585	-	-	€2292
Apple/pear	€0.70 kg^{-1}	-	-	€420	-	€189
Sour cherry	€3.00 kg^{-1}	-	-	€1172	-	€293
Plum	€1.50 kg^{-1}	-	-	-	-	€255
Hazelnut	€5.00 kg^{-1}	-	-	-	-	€38
Berries	€4.00 kg^{-1}	-	-	-	-	€28
C02-certificates	€80 Mg CO2^{-1}	-	€59	€22	€323	€42
Subsidies	€303 ha^{-1}	€303	€303	€303	€303	€303
Total revenues	**-**	**€2347**	**€6518**	**€3781**	**€720**	**€5164**
Costs						
Cultivation	-	€402	€706	€514	€1827	€514
Contract work	-	€128	€128	€128	€5700	€128
Regular labour	€25 h^{-1}	€288	€610	€770	€105	€833
Casual labour	€15 h^{-1}	-	€407	€1412	€470	€612
Total costs	**-**	**€818**	**€1851**	**€2823**	**€8102**	**€2085**
Gross margin	**-**	**+€1529**	**+€4667**	**+€958**	**-€7382**	**+€3079**

SPC1 Walnut pasture is the most profitable of the four configurations, with an estimated gross margin of €4667 ha^{-1} year^{-1} over 60 years. Walnut yields are on average 1310 kg ha^{-1} year^{-1} with peak production in years 26 to 40. Under an average tree cover of 30%, 10475 kg DM grass ha^{-1} year^{-1} is produced, which is 77% of open pasture (see Figure 3). Of the four SPCs, Walnut pasture has the lowest casual labour requirements. SPC2 Fruit orchard is less profitable than open pasture (€958 ha^{-1} year^{-1}), with most of the returns from the grass component (91% of open pasture). Although sour cherry trees lead to high returns, the labour costs are 13% higher than the returns. The labour costs for apple and pears are 33% higher than the returns. SPC3 Multifunctional hedge is the least profitable with a gross margin of -€7382 ha^{-1} year^{-1}, mainly due to high contract work costs to trim the hedge. The average regular labour requirement consists 100% of the labour cost for planting the hedge in year 1. To avoid misunderstanding, we emphasise that the calculations are based on one hectare of hedge. SPC4 Orchard mix performs better than open pasture with an operating profit of €3079 ha^{-1} year^{-1}. The average grass production is 82% of open pasture. Labour is especially required in the first 15 years. Like the sour cherry and fruit trees, the berry shrubs are not profitable due to high labour requirements.

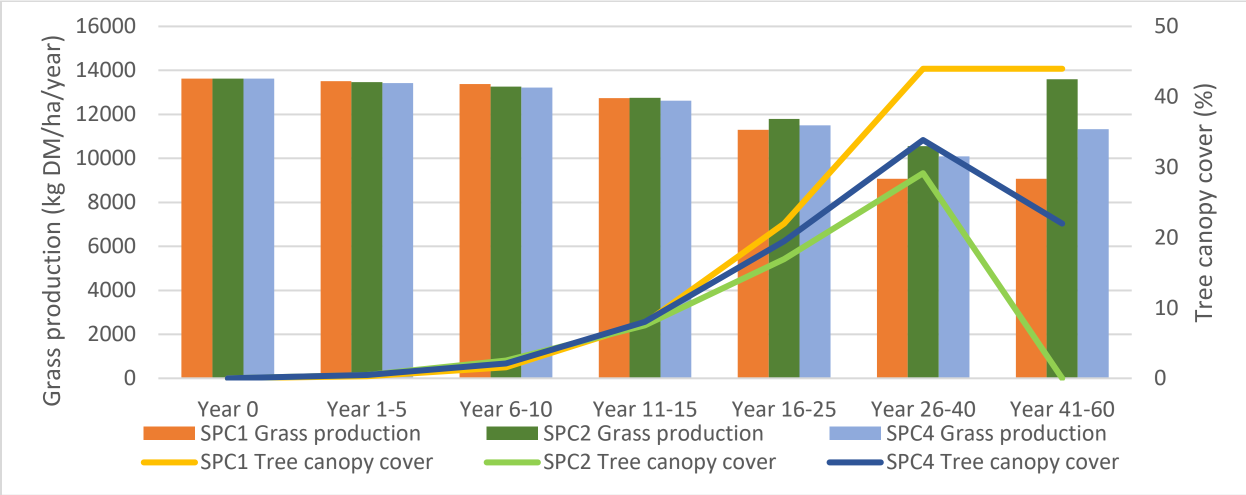

Fig. 3. *Grass production under tree canopy (y-axes) in the reference period (year 0) and the six time periods after planting (x-axis) for SPC1, 2 and 4.*

Due to weather conditions or other marketing strategies, the price of fruit and labour can fluctuate. The effect of changing prices on gross margin of Orchard mix is illustrated in Table 5. If due to bad weather conditions the quality and price of all products are lower, the gross margin could decrease by €584 to €2499. If value is added by a label or processing, the higher price could lead to a €699 higher gross margin. When pruning is done professionally by a contract worker, gross margin could decrease with €497 ha^{-1} (see Table 6). Alternative marketing strategies like self-picking systems can increase gross margin with €611 ha^{-1}, due to eliminated harvesting (casual) labour costs. Eliminating tree purchase costs through a campaign like "donate a tree," can increase SPC4's gross margin by €2114. Additional subsidies or funds acquired would also increase the profitability. This could even make the hedge of SPC3 profitable with a gross margin of €4276 ha^{-1} year^{-1}, if the farmer is paid a fee of €1.74 per running meter (*Agrarisch Natuur- en Landschapsbeheer*, 2020).

Table 5*. The effect of price per kg of tree crops on the gross margin of SPC4 Orchard mix.*

	Price (€ kg^{-1})	Effect on gross margin (€ ha^{-1} year^{-1}) *(standard = €3083 ha^{-1} year^{-1})*
Walnut	3.00	-328
	3.50	*= standard*
	4.00	328
Apple/ pear	0.50	-54
	0.70	*= standard*
	1.00	81
Sour cherry	2.00	-98
	3.00	*= standard*
	4.00	98
Plum	1.00	-85
	1.50	*= standard*
	2.50	170
Hazelnut	3.50	-12
	5.00	*= standard*
	6.00	8
Berries & currants	3.00	-7
	4.00	*= standard*
	6.00	14

Table 6*. The effect of labour price on the gross margin of SPC4 Orchard mix. ([a]) Scenario with contract worker, ([b]) scenario where costumers pick their own fruit and nuts.*

	Price (€ h^{-1})	Effect on gross margin (€ ha^{-1}) *(standard = €3083 ha^{-1})*
Regular labour	15	331
	25	*= standard*
	40 [a]	-497
Casual labour	0 [b]	611
	10	204
	15	*= standard*
	25	-408

3.3 Exploration results

3.3.1 Current situation

The results of the exploration of farm reconfiguration options without SPCs indicate a trade-off between operating profit (OP) and crude protein self-supply (CPSS) at farm level, meaning that increasing OP will lead to lower CPSS (see Figure 4F). OP can be increased when milk production is increased by increasing herd size, milk production per cow and external feed import (Figure 4E), but this will result in higher N-losses and a lower CPSS. Increasing the CPSS appears to be difficult without reducing total milk production (Figure 4C). For more details, we refer to Tab 1 in SM5.

3.3.2 Performance with silvopasture

With the option to integrate silvopasture, it is possible to diminish this trade-off, meaning that OP can be increased at a given level of CPSS (Figure 4F). OP can be increased by replacing up to four hectares of current fields with SPCs and by decreasing milk production per cow (Figure 4D, E). Without reducing CPSS, the highest achievable OP is €107902 ha^{-1} $year^{-1}$, when 3.4 ha of open grassland is replaced by SPC1 Walnut pasture (option 355 in Tab 2 of SM5). Without reduction of OP, the highest achievable CPSS is 41.4%, which is achieved with 0.6ha of silvopasture and a 1.4% lower milk production (option 443 in Tab 2 of SM5). Indicated by the black triangle in Figure 4, one of the most optimal reconfiguration options based on the Pareto-ranking, has 3.4ha of Walnut pasture and 0.1ha of Orchard mix resulting in an OP of €100001 (10% higher) and CPSS of 41.2 (0.5% higher) (option 51 in Tab 2 of SM5). In this option, 2.8% less concentrated feed is purchased than in the initial situation, which, despite the 284 cows, results in 1.0% lower milk production due to a lower milk yield per cow (28.2 kg milk/cow/day).

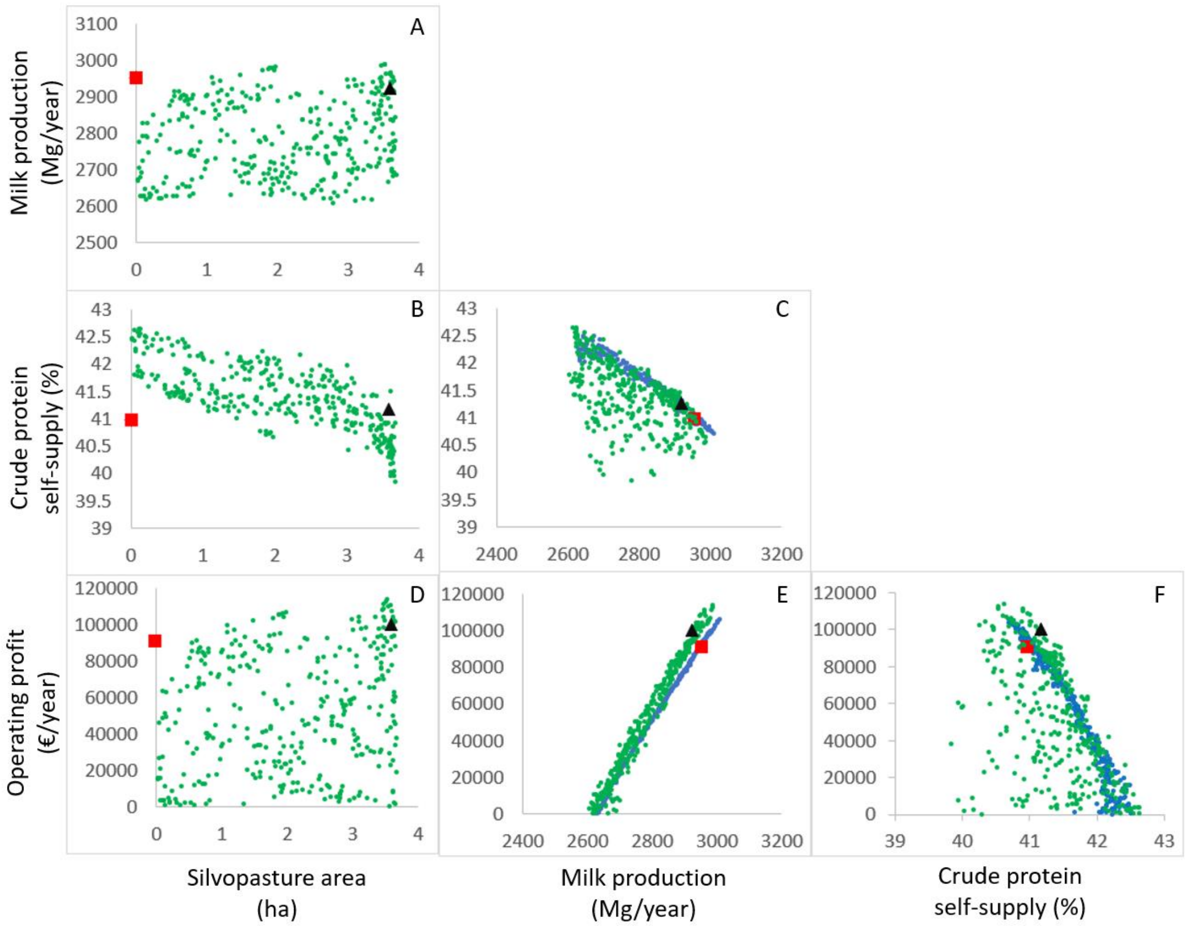

Fig. 4. *Relationships between the objectives silvopasture area, operating profit, crude protein self-supply and milk production for the case study dairy farm. Each blue dot represents an alternative farm configuration without silvopasture, each green dot indicates an alternative farm configuration with silvopasture, the red square and the black triangle mark the performance of the reference and selected optimized farm configuration respectively.*

Manually raising the area with silvopasture resulted in even better performance for the selected indicators. A farm configuration with 10 ha of open pasture replaced by Walnut pasture and a herd size reduction from 283 to 270 cows resulted in an OP of €104087 (15% higher) and CPSS rate of 41.8% (2% higher) (see Table 7). In this configuration 6.3% less concentrates and 7.3% less roughage has to be purchased and N-losses reduced with 4% to 270 kg N/ha. Explorations with the Fruit Orchard and Multifunctional hedge indicated that these SPCs did not directly benefit the objectives. Exploration results with Orchard mix indicated that introducing this SPC will increase both OP and CPSS. With 2.4ha of SPC4, the OP can increase by 9% to €98072 without reducing CPSS. An extreme farm reconfiguration with 35ha SPC4, 40 ha open pasture and 16.45 ha maize was manually optimised. With a herd size reduction to 250 dairy cows, an OP of €110200 and a CPSS of 42.8% could be achieved. Details about exploration and reconfiguration options can be found in Tab 3-6 of SM5.

***Table 7**. Effect of decreasing herd size and implementing 10ha of Walnut pasture on the performance of the case study dairy farm.*

Management decision	**Effect on performance**		
	OP	**CPSS**	**N-losses**
Decrease herd size by 5%	-1%	+5%	-8%
Convert 10ha pasture to Walnut pasture	+24%	-2%	+3%
10ha Walnut pasture & 5% herd size reduction	+15%	+2%	-4%

In all reconfiguration options above, extra labour force was acquired. Without additional workforce, a maximum of 1.1ha of SPC1 could be implemented in a farm configuration with 74.4 ha open pasture, 16.0 ha maize crop land and 281 dairy cows, resulting in an CPSS of 41.1% and an 1.9% lower OP of €88500 (Tab 4 of SM5).

3.4 Silvopasture design case study farm

3.4.1 Design

In consultation with the case study farmer, spatial designs were made for two silvopasture fields on the farm (see Figure 5 and SM4). In the northern field, two 230m long tree rows and one 100m long tree row will be planted in a 1.5 ha field parallel to the street, taking landscape aesthetics into consideration. To slow down the wind from the open field, a multifunctional hedge is constructed south of the ditch. Fruit trees will mainly be planted in the more humid (northern) area. In the southern field, four rows of 60m and one row of 45m will be planted on a 0.6 ha plot. A hedge is not desirable at this location, thus 3 linden trees will be planted and the most southern tree in the row will be a (pollarded) linden tree. These match with the seven old linden trees in the landscape and have the function of blocking strong gusts of wind. In total, 151 trees and shrubs will be planted.

The designs allows for mechanical operation and gives the cattle freedom of movement around the barn and in the field. Municipal zoning regulations were respected by having a gap in the tree rows to give an open view. The selection of species and varieties was mainly based on the utilization as ice-cream ingredient, soil and climate suitability and potential for other forms of processing. Details about and numbers of selected species and varieties can be found in Table 2 and 3 of SM4.

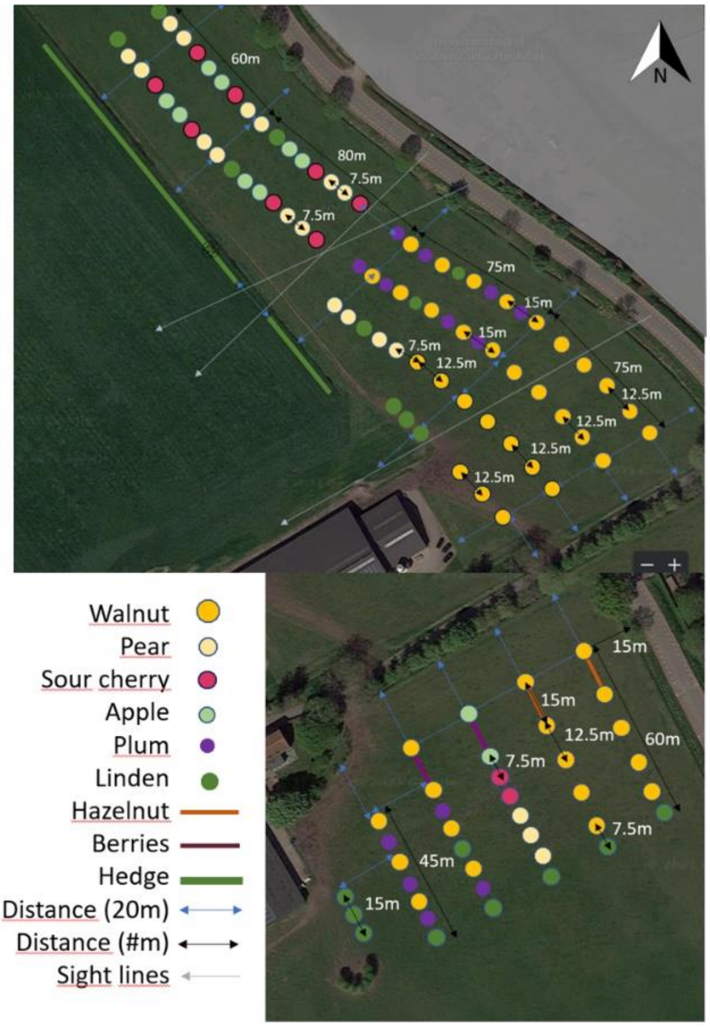

Fig. 5. Spatial design of two silvopasture fields on the case study dairy farm. For design considerations and details, we refer to SM4.

3.4.2 Performance over time

In total, 2.178 ha of pasture (2% of total farm) will be transformed into silvopasture with 0ha of SPC1, 0.5ha of SPC2, 0.028 ha of SPC3 and 1.8ha of SPC4 (for complete farm configuration, see Tab 7 of SM5). After manual correction of the balances, a 2% higher farm OP of €92085 per year could be achieved on average, with a CPSS of 40.9% (0.1% lower). Total annual pasture production is on average 2000 kg DM (0.3%) lower than on the original farm. On average, 44 hours of regular labour and 121 hours of casual labour are hired annually in addition to the existing labour force.

The performance in terms of OP, CPSS, productivity and labour requirements of the farm with silvopasture over time can be found in Tab 12 of SM5 and is summarized in Figure 6. In the first five years, the farm has 2% more pasture area (72.9 ha open pasture and 2.3 ha silvopasture) and produces 0.4% more grass than in the original situation. Maize cropland area is 2% smaller, resulting in higher feed costs (€719001). The high cultivation and labour costs for planting the trees result in an OP of

€82614 (Figure 6A). CPSS rate remains at 41.0% for the first 15 years (Figure 6B). From year 6-40 the rest of the farm can best contain 72.7 ha of open pasture and 16.4 ha of maize fields. In years 6-10, €718166 of feed is purchased annually. In this period, shrubs are in full production and the trees start to produce, resulting in an expected annual OP of €88317. In years 11-15 the tree canopy cover in the silvopasture fields grows to 7.8% resulting in annual grass yields of 1020 Mg (Figure 6C). Like in the previous period, the casual labour requirements increase while the regular labour requirements decrease. During this period, for the first time, the OP is higher than on the original farm (€90551).

Then in years 16-25, the fruit trees reach their maximum production levels (Figure 6D). The peak of labour requirements is also reached during this period, with a cumulative additional labour demand of 263 hours annually (Figure 6E). With the silvopasture fields under an average tree canopy of 18.7%, the decline in grass production (1017.3 tons DM year^{-1}) needs to be balanced with more external feed, costing €718599 per year. The expected OP rises to €92638 year^{-1} and the CPSS rate decreases to 40.9%. In the following 15 years (year 26-40) the farm is at its most productive and profitable phase with an annual OP of €94082. With the maximum tree canopy cover of 32.4% in the silvopasture fields, the total grass production level reaches its lowest level of 1014.2 ton DM year^{-1}. To compensate this the annual feed costs are €719179. The CPSS is at its lowest level of 40.8%. In the final period of years 41-60, the farm with 72.9 ha open pasture and 16.2 ha maize cropland needs only 41 extra labour hours, because all trees except the walnut trees are expected to have been removed. This results in a silvopasture tree cover of 17% and total grass production level of 1020.6 ton DM year^{-1}. During these 20 years, the average annual OP is €93413. For each period, a detailed overview of the set-up and performance of the farm configuration can be found in Tab 8-13 of SM5.

3.4.3 Trade-offs and synergies

Although increasing grass and milk production would normally lead to a higher OP, the results show a synergy between implementing silvopasture and profitability of the farm. For apples, pears, cherries and berries, there is a slight trade-off between profitability and productivity, meaning that a higher yield leads to a lower gross margin, because the extra labour costs for harvesting and processing are not sufficiently compensated for in the returns. However, synergies existed between profitability and production of walnuts, hazelnuts and plums, because the higher these yields, the higher the gross margin. Even though a trade-off exists between grass and tree production, as higher tree production comes at the expense of grass production, the synergies outweighed this trade-off for Walnut Pasture and Orchard mix. Without silvopasture there was a trade-off between profitability and N losses, but with silvopasture there could be higher profitability and lower N losses due to a smaller herd size and less feed imports.

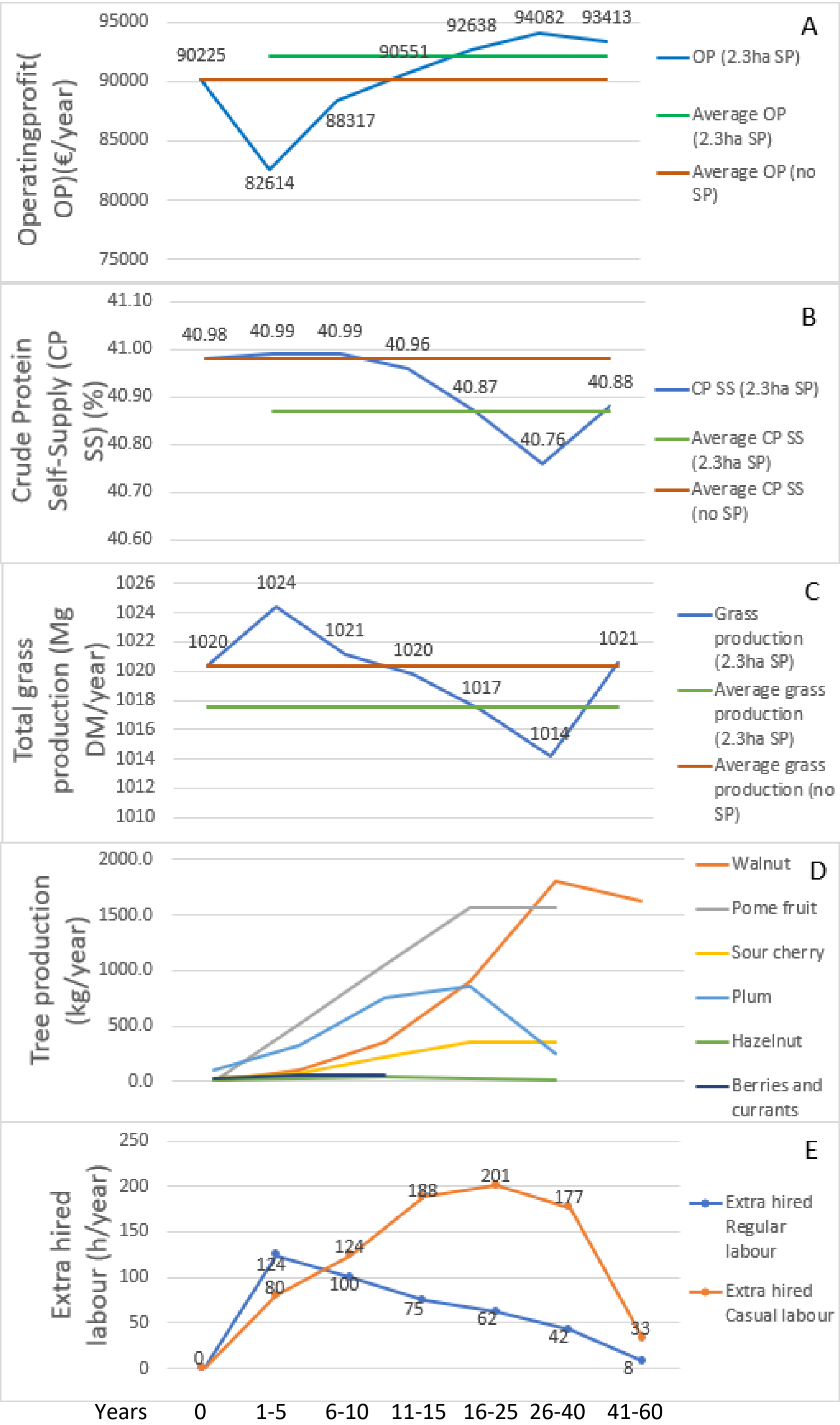

Fig. 4. *Case study farm performance in terms of operating profit (A), crude protein self-supply (B), grass production (C), tree production (D) and labour requirements (E) over six time periods after integration of the silvopasture fields. For more details, we refer to tab 12 of SM3.*

4. Discussion

In this study, productivity, profitability and labour requirements of a dairy farm with and without silvopasture configurations (SPCs) were compared and opportunities for improvement were explored. We found that two out of four SPCs outperformed the current open pasture in gross margin at field level and resulted in higher profit at farm level. This study provided distinctive insight in the performance of silvopasture at field level and the integration of silvopasture in an existing dairy farm and its consequences at farm level for six time periods. This ex-ante analysis of consequences meets the call from farmers and policymakers to gain insight into the future sustainability of this agroforestry practice.

In the current situation, the case study farms OP can hardly be increased without decreasing CPSS. Increasing the CPSS appeared to be difficult without reducing milk production or herd size. None of the SPCs outperformed the open pasture in CPSS at field level. Decreasing grass production levels in silvopasture generate the dilemma for farmers to either purchase more external feed or reduce the herd size. However, the results suggest that decreasing grass revenues can be compensated by increasing revenues from tree products. Although the reduction in herd size leads to lower milk production, an optimised farm with Walnut pasture or Orchard mix leads to an increase in OP without a reduction in CPSS, provided additional labour is available or can be hired. This means that the social performance remains equal, while economic and environmental performance improved.

4.1 Modelling limitations

The SPCs were designed in square formation, which is ideal but not always suitable. Also, every SPC has an ideal soil condition, but soil conditions vary over fields. While farm level analysis is the very strength of FD, this means that FD does not consider field heterogeneity. Thus, reconfiguration options should be aligned with the actual situation. For example, FD automatically distributes manure evenly over all fields, while more intensive fertilisation may be required in open pasture than in shaded pasture. Also, field orientation and edges will limit the area suited for silvopasture.

Being a static model, FD did not provide insight into management decisions within seasons or over several years. For example, peaks in labour requirements within a year could not be visualised in FD. Changing grazing management could increase CPSS, since fresh grass has higher protein levels. However, grazing period duration and whereabouts have to be determined in front and are not directly linked to grazing quantities. The limiting factor in some explorations appeared to be labour required to manage silvopasture. Manually replacing open pasture by silvopasture and increasing hired labour hours to correct the labour balance led to innovative insights into the positive performance results of integrating silvopasture on a significant part of the farm.

4.2 Tree-pasture-livestock interactions

To parameterise the SPCs, assumptions and simplifications have been made that affect the calculations (see Table 1 in SM4). Combined tree and pasture productivity resulted in Land Equivalent Ratio-values of 0.97-1.17 (for explanation and calculation, see Tab 10 of SM3), which are lower than the estimated values of 1.42-1.55 by the meta-analysis from Pent (2020). This difference is expected to be caused by comparing fruit production to intensive low-stem orchards and underestimating total silvopasture production by not including woody biomass and not accounting for positive effects on livestock. Also, estimated tree yields may vary widely due to variety choice, growing conditions and management.

To reflect the tree-pasture interaction, a simplified formula was constructed that estimates grass production under tree canopy. This formula should be adjusted to specific climate conditions, management and tree (light transmission) and grass (shade tolerant) species. For example, a future study could examine the leaf area index of fruit and nut trees, which represents leaf area per ground surface (Den Ouden et al., 2010). The formula could also be improved by taking into account other interactions, like the water storage and nutrient availability effect of increased soil organic matter through leaf litter and root exudates, or the effect of hydraulic lifting (Alagele et al., 2021; Prins, 2017). In this study, competition for water and nutrients was considered negligible because of constant groundwater infiltration and high fertilisation rates on the case study farm. More research is needed on the effect of over-fertilization on the susceptibility of trees to diseases, such as walnuts to blight (Koops, 2010).

Exploration results indicate that increasing milk production per cow would increase OP. Trees could improve milk production indirectly by increasing the forage quality of grass (Kallenbach et al., 2006; Paciullo et al., 2014; Sousa et al., 2010). A higher N concentration in the grass is hypothesized due to less photosynthesis (lower productivity leads to more N per kg DM) or due to higher N uptake thanks to improved soil organic matter and fungal networks (Kephart & Buxton, 1993; Serrano et al., 2018; Van der Meer, 2022). However, there are studies with contradictory results (Pent, 2020). Probably only a few grass species have a higher protein value in shade, such as Italian ryegrass and orchard grass (Kephart & Buxton, 1993; Pang et al., 2019). This emphasizes the need for thorough investigation and development of shade-tolerant grass species.

One of the main arguments for planting silvopasture is that livestock benefit from shade from trees. Exposure to radiation on hot days can reduce milk production by 1 litre/cow/day, even in temperate regions (Van Iaer, 2015). For this reason, the case study dairy cows are kept inside during warm periods. However, milk losses can be prevented by providing about 7 m^2 of shade per cow (Van Iaer et al., 2014). When this shade level can be achieved by trees, a farmer can decide to extend grazing hours, which reduces the need to produce and feed silage, and to store and apply slurry manure. Since fresh grass has higher feed quality, this could improve the CPSS. Sowing nitrogen-fixing clovers will also increase CPSS.

Controversially, trees can also have a negative impact on cows through increased disease distribution. The dangerous parasite Corynebacterium pyogenes, which causes mastitis, is transmitted by flies, which are particularly prevalent in warm, humid weather in forested areas and stables (S.M. van Roekel, personal communication, November 22, 2021). The worst condition for the flies seems to be open pasture with good air flow. Paradoxically, open pasture is also the worst condition for livestock during hot periods, since it causes heat stress. For cows grazing in silvopasture, adequate parasite control is essential and more research into the risks of mastitis is needed (S.M. van Roekel, personal communication, November 22, 2021).

The micro-climatic effects of the hedge could improve pasture production and the medicinal effects of the hedge could improve cow health and production (Luske & van Eekeren, 2018; Van Vooren et al., 2016). However, these effects were difficult to quantify and expected to be marginal on an intensive dairy farm and were therefore not considered (S.M. van Roekel, personal communication, November 22, 2021) (Mahieu et al., 2021). More research is needed into the structure and saturation values of leaves and the effect of individual health problems and summer droughts on the grazing volume and its consequences for cow health.

Despite the potential of silvopasture with trees for quality timber (Bervaes et al., 1997; Edelenbosch, 1994; Everts, 1994), the focus in this study was on fruit-bearing trees. Fruit and nut trees could also benefit from timber trees, such as when pioneer tree species are planted in a small circle around a walnut tree to mimic a climax stage, which could enhance walnut establishment and growth. Low labour requirements and high carbon sequestration rates make timber trees attractive for large scale implementation. A future study could examine the potential of trees for timber on dairy farms.

4.3 Environmental benefits

Increasingly popular are payments for ecosystem services, like carbon certificates (van Noordwijk et al., 2012). There is a multitude of factors that influence CO2 sequestration, such as climate conditions, tree species, soil quality, water supply and pruning management. In this study, carbon sequestration values could have been estimated ten times higher by considering sequestration in grass biomass and soil organic matter (Keur & Selin-Norén, 2019). Supporting other ecosystem services like biodiversity provisioning and landscape restoration could also be financially rewarded. In the Netherlands, this happens through subsidies that compensate for cultivation costs. Providing additional subsidies could make even the Multifunctional hedge a profitable practice.

Nitrogen losses have detrimental effects on water quality and biodiversity (Erisman et al., 2021). Previous studies have demonstrated the safety-net and nutrient-pump function of trees (Allen et al., 2004; Nair & Kalmbacher, 2005). Trees would allow grazing hours to be extended by providing shade on hot days, allowing more solid and liquid manure to be separated naturally, which reduces greenhouse gas emissions (Aguirre-Villegas et al., 2019). This study demonstrated that silvopasture allows the livestock population to decrease without losing income. If silvopasture can help to solve the nitrogen crisis, this would be an additional incentive to promote silvopasture and make subsidies available, but further investigation is needed to quantify the effects.

4.4 Management and marketing

One of the main barriers to integrating silvopasture is the large amount of manual labour. A farming systems embedded in the social landscape opens up opportunities to involve (urban) people in management activities. Firstly, labour is required to plant trees in year one. Having volunteers plant the trees can save labour costs. Secondly, as harvesting is the most labour intensive activity, a self-picking (U-pick) system, in which costumers pay after they have harvested the products, can save labour costs, for example up to €75 per tree per year for sour cherries. Disadvantages of self-picking are the labour costs of self-picking guidance, a lower price per kilo and more selective and less thorough harvesting. Thirdly, mechanisation developed for monoculture systems could be adapted for use in silvopasture systems and shared among farmers (Selin-Norén & Dawson, 2020). In the run-up to the full-production period, marketing channels and collaborations with other silvopasture farmers must be developed for fresh and processed products. By proper communication about the positive effects of silvopasture and adding value by processing fruit and nuts into juice, jam, oil or, like the case study farmer, ice cream, premium prices could be received.

A non-quantifiable factor is the expertise and dedication of the farmer. Developing required skills will take time, which is often not available. Therefore, to make silvopasture accessible to farmers not willing to develop expertise or to use expensive mechanisation, a new profession is suggested, the silvopasture contract worker. In partnership with multiple farmers, this person plants and maintains their silvopasture and receives a salary or profit margin (E. Prins, personal communication, September 30, 2021). This specialisation paves the way for future-proof scaling up of ecological intensification through silvopasture.

4.5 Further recommendations

The results of this study help to inspire farmers and policy makers to expand the area of silvopasture practices and to build a joint knowledge base aiming at development and optimisation of future-proof dairy farms. An important contribution to this knowledge base would be regular, collaborative updating of the Knowledge Centre of Agroforestry Flanders and the Factsheets Agroforestry of the WUR (Reubens, 2021; Selin-Norén et al., 2018). Farmers decision making will be dynamic and change from year to year. Shifts in market demand and growth conditions due to climate change will concentrate attention and time on the most promising components of the system. The SPCs discussed need to be treated as baseline systems that can be tailored to local soil conditions, local regulations, farmer preferences and marketing options.

We recommend farmers willing to adopt silvopasture to carefully consider species, varieties and planting distances. Thorough preparation is decisive because once a tree is planted it will be there for several decades. Proper planting and protection of the tree can give a head start. Artificial inoculation of mycorrhizal fungal networks could increase water and nutrient uptake and make trees more resistant to diseases and pests, but further investigation is needed (Van der Meer, 2022). Walnut trees become more susceptible to blight with high nitrogen levels, so we recommend to prevent overfertilization (Koops, 2010; Weinbaum et al., 1992). Further recommendations from silvopasture practitioners for dairy farmers considering adopting silvopasture are listed in Table 1 in SM2. Municipal 'open agricultural' zoning regulations hinder tree planting, therefore we recommend policy makers to discuss whether or not the positive effects of tree planting outweigh the positive effects of open agricultural land. Finally, we emphasize the importance of reliable and future-proof policies and financial rewards for farmers who invest in ecological intensification.

5. Conclusion

This study demonstrated that gross margin of silvopasture fields can be two (Orchard mix) to three (Walnut Pasture) times higher than the current open pasture. Without these SPCs, the farms OP could only be increased by purchasing additional feed and increasing milk production, resulting in lower CPSS. The SPCs improved OP by producing and selling fruits and nuts, diminishing this trade-off. SPCs could improve CPSS indirectly, as higher profits from the tree component allow for livestock extensification. Of the SPCs, Fruit orchard has the highest grass production level, but it is less profitable than open pasture due to high labour demands. Multifunctional hedge could not be integrated without reducing OP due to high cultivation costs. Integration of Orchard mix, Fruit orchard and Multifunctional hedge on 2.5% of the case study farm area is expected to result in lower OP during the first 15 years and an increase in OP during the following 45 years, resulting in an average OP that was 2% higher than in the current situation. Acquiring additional labour is a prerequisite for all SPCs, especially during labour peaks in year 1 and years 16-25. OP could be further increased by payments for ecosystem services, which requires quantification of the environmental benefits. Further research is needed to find and develop combinations of grass and tree varieties that minimise competition and maximise facilitation.

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