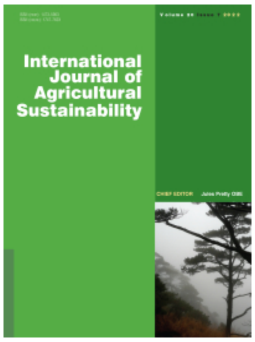

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The introduction of legume-based crop rotations: an impact assessment on cereal cropping farms in Finland

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ABSTRACT
Grain legume production offers multiple environmental benefits and can enhance the sustainability of farming, but the legume area has been small and declining over the last decades in most European countries. Recently, grain legumes have gained importance because of the increases in prices of feed and food proteins, fertilizers and fuel, in addition to sustainability concerns. This study investigated the impacts of introducing grain legumes [faba beans (*Vicia faba* L.)] in cereal-dominated crop production systems typical for southwestern Finland. To investigate the economic effects as well as the effect grain legumes have on production and land use a dynamic optimization model was used. The results suggest significant crop yield gains if farmers consistently utilize the pre-crop value of legumes and other crops in crop rotations over several years. The farm economic gains of diversified legume rotations were found to be positive but relatively small assuming past prices, but they can be significantly higher if legume and nitrogen fertilizer prices increase in the future. Overall, faba bean-based rotations have positive long-term implications on soil quality and biodiversity and thus future viability and societal reputation of farming.

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Grain legumes; agricultural economics; farm management; dynamic optimization; pre-crop effects; yield effects

1. Introduction-background

Diversified arable farming is recognized as a necessity when aiming to increase cultivation resilience and ecosystem services and mitigate the effects of climate change on agriculture (Degani et al., 2019). There is an urgent need to find emission reductions in all sectors and countries. For example, the European Green Deal and Farm to Fork Strategy have established a legally binding target of net zero greenhouse gas emissions by 2050 (Europa, 2022). These goals require a transition to more sustainable food systems.

Legume production with many ecosystem services provides opportunities for diversification of land use, the conservation and enhancement of biodiversity and healthy diets with more plant-based proteins replacing part of livestock-based protein. Protein crops, such as faba bean (*Vicia faba* L.), pea (*Pisfum sativum* L.), chickpea (*Cicer arietinum* L.), lupins (*Lupinus* sp.) and soybean [*Glycine max* (L.) Merr.], can fix nitrogen from the air, which makes them especially valuable for low-input cropping systems when trying to reduce greenhouse gas emissions (Lemke et al., 2007). These crops may provide a significant quantity of nitrogen to the subsequent crop in rotation, resulting in reduced mineral fertilizer requirements (Watson et al., 2017). They also improve soil health and support crop protection (Jalli et al., 2021). Other studies have shown that adding legumes to cereal rotations has positive effects on cereal yields and gross margin in comparison to monocropping (Yigezu et al., 2019).

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Protein crops in the EU are grown on only 1.5% of European arable land compared to 14.5% worldwide (Watson et al., 2017). Additionally, only a small portion of peas (11–15%) and faba beans (9–14%) grown in Europe are used for human consumption (Bues et al., 2013), while the majority are used as animal feed instead, with much lower efficiency in terms of protein production for food (Watson et al., 2017). In northern Europe, grain legumes, such as peas and faba beans, have been historically cultivated for a long time (Stoddard et al., 2009). In 2020 in Finland, the total harvested area of legumes was 43,000 hectares (Official Farm Statistics [OFS], 2022; Peltonen-Sainio & Jauhiainen, 2020), focusing on the southern part of Finland due to growing conditions (The Finnish Cereal Committee [VYR], 2022a). Almost 70% of the faba bean area is located in the southern part of Finland, but there has been a shift towards more northern regions especially due to climate warming, longer growing seasons and the introduction of new cultivars (Peltonen-Sainio & Jauhiainen, 2020).

Grain legumes' competitiveness, as a profitable crop at the farm level, is frequently constrained by relatively low gross margins and relatively high production risks in the short term (Preissel et al., 2015). Longer-term benefits, which are easily overlooked, may be significant for example, considering impacts on yield of the subsequent crop(s) in rotation and reduced reliance on inputs, especially fertilizers, but possibly also crop protection agents, tillage, machinery and labour (Preissel et al., 2015). Preissel et al. (2015) reviewed the literature on pre-crop and farm economic benefits of including grain legumes in European cropping systems. According to their findings, legumes as pre-crops contributed to the highest yields of subsequent crops under low fertilization. When the aim was to maximize crops' yield potential, legumes contributed to lower fertilizer use (23–31 kg/ha less) for subsequent crops, while cereal yields were 500–1600 kg/ha higher than the cereal yields after cereal pre-crops. When tillage and the associated costs were considered, grain legume rotations were more competitive under conservation tillage systems. The tools to increase the cultivation of grain legumes in a larger area in cereal farm types in France were studied by Mahmood et al. (2017). Assessing different scenarios such as the proposition of new grain legume-based cereals rotations, higher premium on grain legumes, increase in sale price, etc., they concluded that the alternative scenario of provision of more premiums on grain legumes was more efficient in increasing the grain legume area than the other scenarios.

Investigating the relative contribution of legumes in terms of farm economy, production and land use requires consideration of pre-crop effects in extensive dynamic economic profitability calculations of crop rotations which include legumes (Meynard et al., 2018). The reported farm-level economic effects of diversifying production using grain legumes are typically focused on relatively few alternative crop rotations on few field parcels and a few years, which reduces their value when trying to reach a comprehensive view on the impacts of legumes on farm-level economic profitability.

A farm-level analysis evaluated the possible impact of legume-supported crop rotations in the arable crops sector in Italy (Cortignani & Dono, 2020). For this analysis, a mathematical programming model was used on data from about 2800 Italian farms utilizing data from the FADN database. They used three scenarios and under each scenario, the land share allocated on legumes was gradually increased. Their findings showed that legume-supported crop rotations contributed to less environmental pressure, while they helped offset some of the economic losses due to reduced production of the main crops. However, the reduced production, due to lower cereal area, can be offset by the increase in yields of subsequent cereals due to nitrogen fixation.

Relatively a few existing studies that examine the economic effects of legumes on a typical farm in a dynamic model which is explicit and comprehensive in terms of crop rotations, input use and resulting production and income effects over several years. This study, explicit in pre-crop effects between several crops and dynamics of crop rotation, contributes to the limited existing literature regarding the economic benefits of legumes in crop rotations. The aim of this study is to evaluate the long-term avenue the grain legumes may provide for Finnish farmers in terms of income and production, crop yields and land use. Furthermore, this study aims to examine if producing grain legumes is still a profitable choice at different prices of crops and fertilizers. To this end, it was analysed to what extent introducing grain legumes to the crop rotations of a typical cereals-producing farm in southwest Finland contributes to the farm economy and production over a 30-year period, which is a typical length of a farming career. Some of the key findings suggest significant crop yield gains if farmers consistently utilize the pre-crop value of legumes and other crops in crop rotations over several years. Farmers could benefit economically from diversified legume rotations particularly if high legume and nitrogen fertilizer prices occur in the future.

2. Materials and methods

2.1. Study area

This study considers the province of Southwest Finland, one of the most important agricultural regions in Finland. Approximately half (56%) of the farms in the region are cereal farms, 7% of the farms are horticulture farms and 19% of the farms are other crop farms (not producing primarily cereals). Approximately 5% of the farms raise cattle and only 3% are specialized in dairy production (Official Farm Statistics [OFS], 2021). Significant quantities of pig or poultry meat are produced in the region (by 6% of the farms). Unlike dairy and beef farms, pig and poultry farms have been long dependent on imported protein feeds (especially soya) and domestic protein crops have been minor crops. Areas under grasslands, oilseed, sugar beet (*Beta vulgaris* var. *altissima*), potato (*Solanum tuberosum* L.) and other crops have been small and approximately 70% of agricultural land area has been allocated for spring cereals crops, such as barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.) and oats (*Avena sativa* L.). This region in Finland has probably the highest opportunities for diverse crop choices and land use (Peltonen-Sainio & Jauhiainen, 2020).

Requirements of EU CAP for farmers before and after 2022 are considered. According to CAP's strategy for biodiversity, 10% of agricultural land is required to be withdrawn from production and to be set aside for enhanced ecological protection (European Commission, 2022a). Farmers with arable land exceeding 15 ha, which is typically the case in Southwest Finland where the average farm size is over 60 ha (Official Farm Statistics, 2022), must ensure that at least 5% of their land is an Ecologically Focused Area (EFA) – an area of land subjected to agricultural practices that are beneficial for the climate and the environment – to safeguard and improve biodiversity on farms (European Commission, 2022b). Consistent with the 2022 practice in Finland, it is assumed in this study that to receive full CAP payments, the maximum crop area under the main crop is 75% of the total area,and at least 5% needs to be ecological region, such as set-asides or nature managed fields.

The size of farms specialized in cereal production in the region is gradually increasing: The average size was 44 ha in 2010 and 65 ha in 2022 (OFS, 2022). There has been significant variation in the farm size among specialized cereals farms and farms with more than 100 ha are already common. The diversification potential is higher on large farms with more suitable land for minor crops and with better logistic advantages than on small farms in Finland (Peltonen-Sainio & Jauhiainen, 2019). Hence, we analyse the adoption of grain legumes in cultivation on a 100-ha farm instead of an average 65-ha farm. Furthermore, there is an increasing trend in farm size in the region which increases the relevance of analysing a large farm. This study presents results specific to the farm economy, net present value (NPV) and total production (tons per farm) per 100 ha, while fertilization and crop yield results are presented per ha.

2.2. Scenarios

The economically optimal farm management over 30 years was studied in nine different scenarios where faba bean is introduced as a new seventh crop to the cropping system of the case study farm, initially with six crops.

The first scenario or baseline represents the currently typical cropping system in the region with cereals (winter wheat, spring wheat, spring barley and spring oats), oilseeds and (grass-covered) set aside, but does not include grain legumes in the crop rotation. The second scenario concerns the introduction of faba beans (**ins_f**) to analyse how much land can be optimally allocated to faba beans.

The third simulation (**1.3N_no_Fa**) assumes an increase in N fertilizer price by 30% (from the baseline level) to capture the possible future of high N fertilizer prices, in the scenario when legumes are not cultivated at a farm. Thirty per cent higher fertilizer prices may result from (e.g. national or EU level) fertilizer taxes imposed in the future for promoting a shift away from N fertilizers which have been long produced using fossil fuels and natural gas. Similarly, the fourth simulation (**1.3N_yes_Fa**) assumes 30% higher N fertilizer prices but in this scenario, faba beans are cultivated. These scenarios with high N fertilizer prices were chosen to cover the foreseen increase in the prices of fossil-based inputs, such as chemical N fertilizers (dependent on natural gas prices) due to climate change mitigation strategies.

The fourth scenario (**1.3_fab**) concerns the increase in the price of faba beans by 30%, representing a future with increased demand and prices of grain legumes for food and feed. The fifth scenario (**1.3_Fab&N**) concerns the simultaneous increase of faba beans and N fertilizer prices by 30%. Two more simulations were considered to examine how the production of each crop changes in case of an increase in all crop prices by 10% when faba beans (**1.1_prices_yes_Fa**) are cultivated in the model and when no faba beans are cultivated (**1.1_prices_no_Fa**). A uniform increase in all crop prices might represent a future with globally increasing demand and/or challenges in the global food supply, resulting in increased crop prices compared to input prices. The last scenario (F**a_subsidies**) assumes the use of price support, subsidies for faba beans and a government tool to encourage faba bean production. In this scenario, the subsidies for faba beans were increased by €100/ha.

2.3. DEMCROP model

In DEMCROP (Dynamic Economic Model of CROP rotations and farm management) (Liu et al., 2016; Purola et al., 2018; Purola & Lehtonen, 2020), dynamic optimization is utilized to combine crop production and farm economics with various technical data and response functions, such as crop yield response to nitrogen levels, effects of liming and fungicide treatments. Parameters used in the model as input data (e.g. crop yields, variable costs, subsidies, crop prices, etc.) are typically based on empirical estimations.

The model considers the dynamic effects of crop rotation at several field parcels annually over 30 years, the use of fertilizers and fungicides per crop and liming per field parcel. Considering discounting of profits, the model provides a consistent tool to evaluate how and why faba beans might contribute to productivity, land use, production and profits at a typical cereal-producing farm. DEMCROP has been applied earlier for cereals-producing farms in Finland (Liu et al., 2016; Purola et al., 2018; Purola & Lehtonen, 2020) and for a dairy case farm (Tzemi & Lehtonen, 2022). Legumes have not been considered in earlier applications of the model. The model structure, as it was during this study, is presented briefly below.

Assuming that the farmer is a profit maximizer he/she can choose from six possible crops while considering their related input use, as well as options for setting the parcel aside as fallow or as a nature-managed field. Net present value is maximized with a 6% interest rate over a 30-year time horizon which approximately reflects a farming career. The interest rate (discount factor) was decided to be 6% because it has been estimated that Finnish stock markets have yielded a 7% annual return for invested capital, on average, during the last 100 years (Pörssisäätiö, 2023) but farmers as small-scale private investors face some transaction costs. Denoting the interest rate with r, and the discount factor with $b = 1/(1 + r)$, the optimization problem is as follows:

$$\max_{A_{tpi},N_{tp},L_{tp},F_{tp}} \sum_{t=0}^{T}\sum_{p=1}^{P}\sum_{i=1}^{n} b^t(p_iY_{ti}(\ldots) + S_i - C_{tpi}(\ldots))A_{tpi} \tag{1}$$

subject to

$$C_{tpi} = V_i + G_p + c_L(L_{tp}) + c_F(F_{tp}) + c_N(N_{tp}) \tag{2}$$

$$Y_{tpi} = \hat{Y}_i\left(\alpha_i(N_{tp},p_i,p_N,L_{tp},F_{tp})(1+\beta_{ij})A_{t-1,p,j} + \sum_{d=t-5}^{t}\gamma_i A_{dpi}\right) \tag{3}$$

$$\sum_{p=1}^{P}\sum_{i=1}^{n} A_{pit} = 1\ \forall\ t \tag{4}$$

where p_i is the price of crop i, Y_{ti} is the yield of crop i at time t, S_i is the agricultural subsidies for crop i, C_{tpi} is the total costs of cultivating crop i on parcel p at time t and A_{tpi} is the land allocation of crop i on parcel p at time t. Denoting nitrogen fertilizer use, fungicide use and liming at parcel p at time t with N_{tp}, F_{tp} and L_{tp}, respectively, with C_L, C_F and C_N as the respective cost functions. Finally, V_{itp} and G_p denote the variable and logistic costs, respectively.

Denoting the statistical yields for crop i with $\hat{Y}_i$, we can use α_i *as* the crop-specific effects of nitrogen use (N), liming (L) and fungicide (F) on the yield on parcel p at time t, β_{ij} the pre-crop value of crop j on crop i, γ_i the yield losses due to monoculture to calculate the yields of each crop, and p_N is the price of nitrogen fertilizer. The functions for calculating the crop yield effects of nitrogen use, liming and fungicide use are presented in detail in the Appendix.

The optimization problem, described in equations 1–4, was using the CONOPT solver of the general algebraic modelling system (GAMS) software (GAMS, 2021).

The production activities available within the model include the management of a specific piece of farmland, composed of 10 equally sized parcels

(parcels 1–10) within the farm, with parcel 1 being closest to the farm centre and parcel 10 being furthest away. The distances of the parcels to the farm centre are uniformly distributed and they range between 0 and 7 km with a mean of 3.5 km. Oilseeds and grain legumes such as faba beans were combined with a large yield penalty due to monocropping, and this yield penalty was inherited even after 5 years if the same crop was cultivated again in the same field parcels. For the rest of the cereals, the yield penalty due to monocropping was not as large. The current strong recommendation is that oilseeds or grain legumes should not be cultivated on the same field parcel more often than once per 4–5 years, to avoid significant crop losses due to pests and diseases (The Finnish Cereal Committee [VYR], 2022b). The yield penalties of oilseeds (Liu et al., 2016) and grain legumes in the DEMCROP model were set after consultation with crop protection and crop science experts.

All land-use constraints were based on CAP subsidies: a single crop can cover a maximum of 75% of the total farm area, and at least 5% of the total area needs to be under ecological area (Finnish Food Authority, 2022).

2.4. Input data

The pre-crop value measures the field parcel-specific yield benefit of a crop for another crop to be cultivated next year or production season in crop rotation (Peltonen-Sainio et al., 2019). This yield effect is often measured as higher yield or biomass (positive pre-crop value) compared to monoculture crop sequencing. The pre-crop effects used in the current study (Table 1) were obtained by Peltonen-Sainio et al. (2019) who applied a large dataset of pre-crop and subsequent crop combinations using two-year Sentinel-2 satellite images. Four Sentinel-2 satellite data tiles were used from South Finland (34VEN, 34VEM, 34VFN and 34VFM). To estimate the pre-crop value, parcel scale data (i.e. boundaries of each parcel and previous and subsequent crops, both from the registry of Finnish Food Authority) were linked to the Normalized Difference Vegetation Index (NDVI) – values derived from satellite images. The Sentinel-2 image was cut using the boundaries of the parcel, and the NDVI value was calculated from Sentinel-2 pixels located within the boundaries. All parcels with one crop were included in the analyses as well as parcels where one crop covered at least 70% of the parcel area: often such parcels had buffer stripes next to the waterway. For example, if spring wheat (row 1) is cultivated after spring wheat (column 1) there is zero pre-crop effect, while if spring wheat is cultivated after winter wheat a 3% increase in spring wheat yields is observed compared to a case with monoculture. Table 1 shows that faba beans and oilseeds have the highest pre-crop values

Table 1. Pre-crop values for each crop combination are based on Peltonen-Sainio et al. (2019). Pre-crop value means the yield effect inherited from the preceding crop, e.g. 3.0% higher yield of spring wheat realizes if winter wheat was the preceding crop in the same field parcel, compared to the case when the same crop is repeated in the field parcel.

Subsequent crop in rotation	**Preceding crop** Spring wheat	Winter wheat	Feed barley	Malting barley	Spring oats	Spring oilseed rape	Green fallow	Nature managed field	Faba bean
Spring wheat	0.0%	3.0%	6.8%	6.8%	0.1%	7.5%	4.4%	0.5%	7.8%
Winter wheat	1.3%	0.0%	6.1%	6.1%	4.9%	8.8%	3.3%	9.4%	9.6%
Feed barley	0.0%	3.0%	0.0%	0.0%	-1.6%	4.9%	-2.7%	-4.5%	6.5%
Malting barley	0.0%	3.0%	0.0%	0.0%	-1.6%	4.9%	-2.7%	-4.5%	6.5%
Oats	3.8%	3.0%	5.9%	5.9%	0.0%	5.3%	0.5%	-2.6%	7.9%
Oilseed	5.8%	5.2%	7.2%	7.2%	5.4%	0.0%	4.9%	9.5%	9.1%
Fallow	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
NMF	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Faba bean	1.6%	5.3%	5.2%	5.2%	-3.0%	1.8%	1.3%	-5.9%	0.0%

Color shades indicate the level of pre-crop effects, with dark blue representing the highest value and dark red representing the lowest.

Table 2. Parameter values applied in numerical analysis. Sources: Crop prices are the average farm gate prices of crops in Finland over 2017–2020 and crop yields are the average yields observed in southwest Finland 2010–2020 (OFS, 2021). The average variable costs and subsidies of the crops specific to southsest Finland are derived from a recently updated version of a dynamic multi-regional sector model of Finnish agriculture (DREMFIA), (Lehtonen and Rämö 2022) which relies on validated approximations of the average use of inputs per crop in each region. Optimal pH, to be achieved by liming, and fungal disease losses, possible to be avoided by fungicide use, are based on Purola et al. (2018); Purola & Lehtonen (2020).

Crops	Yields Y_i (kg/ha)	Subsidies S_i (€/ha)	Prices P_i (€/ton)	Variable costs V_i (€/ha)	Optimal pH	Fungal disease losses (%)	Initial N use requirements (kg/ha)
Spring Wheat	2851	542.6	167.4	759.1	6.5	5.85	110
Winter Wheat	4385	542.6	167.4	759.1	6.5	5.85	140
Feed barley	3848	542.6	150.3	736	6.1	6.35	90
Malting barley	3851	542.6	174.2	736	6.5	6.35	90
Oats	3893	542.6	160.4	769	6.1	0	90
Oilseed	1654	661.6	371.0	778.3	6.1	0	100
Setaside	–	467	–	244	–	–	0
NMF	–	567	–	264	–	–	0
Faba beans	2140	661.6	214.3	731.5	6.5	5.85	30

when they precede cereals. However, their yields can be substantially reduced if they are cultivated in the same field parcel for less than five consecutive years.

The DEMCROP model was applied with historical data for 2010–2020 for average crop yields in the Southwest Finland region, as well as subsidies, variable costs, optimal pH and fungal diseases (Table 2). Average crop yields are collected from the official farm statistics (OFS, 2021) for Southwest Finland. Crop prices were taken from the Finnish official farm statistics. Because faba bean prices are only available for 2017–2020, the average cereal prices of the period were also used. The average variable costs associated with crops (such as seeds, fertilizer, liming, crop protection chemicals, machinery, buildings, logistic costs and other variable costs,) were derived from a recent version of a dynamic regional sector model of Finnish agriculture (DREMFIA) (Lehtonen, 2001; Lehtonen & Rämö, 2023) which utilizes annually validated input prices and approximations of the average input use per crop in each region. It was assumed that a farmer receives all basic farm subsidies provided. Similarly, it was assumed that a farmer receives only the basic agri-environmental subsidies, not the ones with special commitments since they vary greatly across farms and their economic significance and production implications are minor on cereals farms (Hyvönen et al., 2020). Labour use per ha was obtained from Palva (2015). The cost per hour of labour (appr. 15 €/hour) was derived from the national-level FADN system (Luke, 2023).

3. Results

The objective function calculates the farm net present value (NPV) of a case farm in the Southwest Finland region. In the baseline scenario, the maximized NPV calculated over 30 years was found to be €390,000 per 100 ha. That is €13,000 per year which is slightly higher than the average farm income of cereal farms (€9400 per farm during 2000–2021) in the study region (Luke, 2023). However, considering that the average size of the cereals farms was 49–64 ha for 2000–2021 (Luke, 2023), the average NPV per ha per year is close to the farm income reported by Luke (2023). Table 3 presents the estimated NPVs across all different scenarios. The scenarios that included faba beans showed slightly or significantly higher

Table 3. Net Present Values (1000 euro per 100 ha) over 30 years, and the expected average profit per year.

		Without faba beans	With faba beans	Percentage difference between without and with faba beans
Baseline	NPV	390.0 (13.0)	394.2 (13.1)	1%
N fertilizer price increase by 30%	NPV	340.3 (11.3)	355.4 (11.8)	4%
30% increase faba bean price	NPV	390.0 (13.0)	429.8 (14.3)	10%
30% increase in N fertilizer and faba bean price	NPV	340.3 (11.3)	383.8 (12.8)	12%
10% increase in crop prices	NPV	482.3 (16.1)	473.8 (15.8)	2%
Increase in subsidies for faba beans by €100/ha	NPV	390.0 (13.0)	415.2 (13.8)	6%

NPVs compared with the scenarios without faba beans.

Introducing faba beans as a seventh crop at a farm and assuming the same prices and subsidies as in the baseline results in a very small 1% (NPV €394,000 per 100 ha) increase in NPV over 30 years. This means that faba bean is a competitive crop, it replaces some cereals area cultivated, but the net gain is small in economic terms. However, this result shows that it is profitable, partly due to positive pre-crop effects, to cultivate faba beans in the scenario where baseline prices and subsidies apply.

If there is a 30% increase in N fertilizer prices over 30 years, NPV drops by 12.7% in the **1.3N_no_Fa** (no faba beans in cultivation) scenario and by 10.4% in the **1.3N_yes_Fa** (faba beans in cultivation) scenario compared to the baseline. NPV is slightly (4%) higher in the scenario with faba beans cultivated than in the scenario without faba beans. This NPV gain due to legumes is relatively small, despite positive pre-crop effects, because legumes, such as faba, beans cannot be cultivated more than once per 4–5 years on the same field plot without significant yield losses. Hence the relatively small share of land areas under faba beans (appr. 20%) does not lead to significantly higher NPV in the Baseline, or in the scenario when N fertilizer prices increase by 30%. This can also be explained by relatively low N fertilizer costs per ha in the Baseline. However, it is noteworthy that in both scenarios '30% increase in faba bean price' and '30% increase in N fertilizer and faba bean price' NPV is significantly higher (10% and 12%, respectively) if faba beans are cultivated. The option to cultivate faba beans becomes valuable for a farmer in such a situation.

The scenario regarding an increase in all crop prices by 10%, showed that when faba beans are not cultivated NPV is slightly higher compared to the scenario where faba beans are cultivated. This might imply that a potential increase in crop prices might make cereal crops such as malting barley or wheat even more competitive, while faba beans may not be among the most profitable crops if prices for all crops are high. Lastly, an increase in faba beans subsidies by €100/ha will result in 6% increase in NPV compared to the baseline.

Land-use changes due to the introduction of faba beans are the main driver of the NPVs reported above. Figure 1 illustrates the average optimal land use share for the 30 years of each crop across all

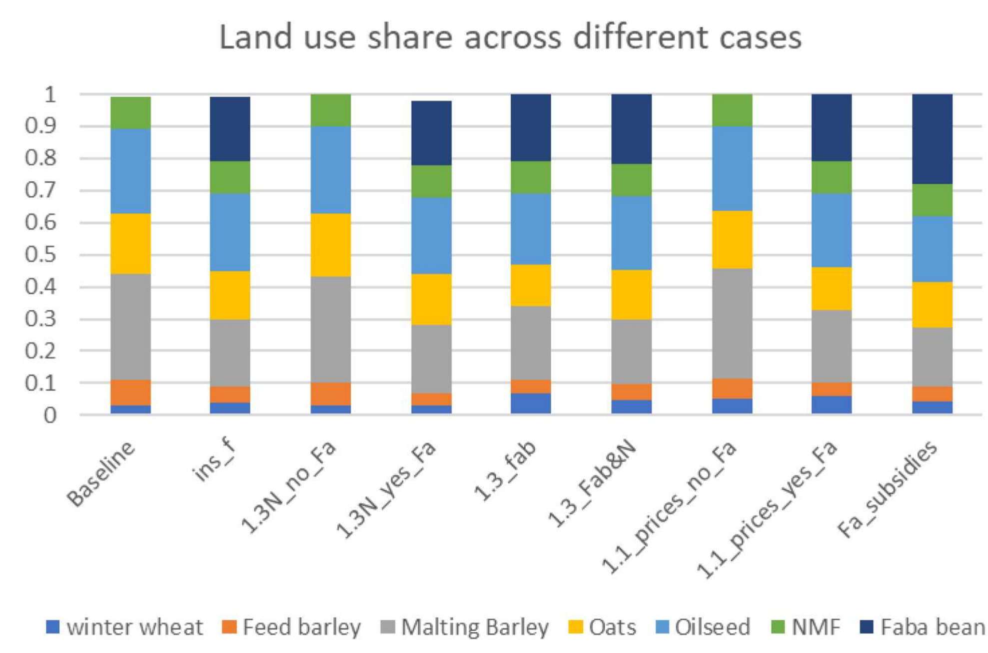

Figure 1. Share of mean allocated land for 30 years, across all scenarios. (1) baseline, (2) ins_f = insert faba beans; (3) 1.3N_no_Fa = increase in N fertilizer price by 30% with no faba beans; (4) 1.3N_yes_Fa = increase in N fertilizer price by 30% including faba beans; (5) 1.3_fab = 30% increase in the price of faba beans by 30%; (6) 1.3_Fab&N = increase of faba beans and N fertilizer prices by 30%; (7) 1.1_prices_no_Fa = 10% increase in crop prices without faba beans; (8) 1.1_prices_yes_Fa = 10% increase in crop prices with faba beans; (9) Fa_subsidies = increase of faba bean subsidies by €100/ha.

scenarios. The results show that the introduction of faba beans to the model (**ins_f**) leads to a decrease in land use share of feed and malting barley in comparison with the baseline while the allocated area on winter wheat is slightly increased. The reallocation of land, in scenario **ins_f,** from barley and oats to winter wheat and faba beans can be explained by the high pre-crop values between faba beans and winter wheat. Hence winter wheat production is favoured by faba bean introduction, unlike the production of other crops.

Scenario **1.3N_no_Fa** did not significantly affect the land share of crops in comparison with the baseline. Scenario **1.3N_yes_Fa** led to the reallocation of the land mostly from barleys and oats to faba beans, similar to **ins_f**. Reallocation of the land to faba beans was anticipated considering that the relatively low fertilization requirements of faba beans compared to cereals mean that higher nitrogen fertilizer prices would result in only a marginal increase in faba bean production costs. Conversely, reduced nitrogen fertilization, prompted by high fertilizer prices, would significantly impact cereal yields more adversely. Land use is linked to the fertilizer response functions and also to other factors in the model since crop yields are also dependent on pre-crop values which are different between crops, as well as on liming and fungicide use. Hence, due to the complexity of DEMCROP, changes in one input price do not lead to equivalent changes in the areas of all crops in the results.

Scenario **1.3_fab,** where only prices of faba beans increase by 30%, did not, however, significantly increase the land share of faba beans compared to the other scenarios. The area under faba beans is almost the same in all scenarios, mostly because faba beans should not be cultivated on the same field parcel more often than once per 4–5 years, to avoid significant crop losses due to pests and diseases (The Finnish Cereal Committee [VYR], 2022b). Hence the land-use share of faba beans is close to 20% in all scenarios. Interestingly, the area allocated for winter wheat more than doubles from the Baseline level if N fertilizer prices increase by 30% and faba beans can be cultivated. This, again, is a clear implication of the good pre-crop values between winter wheat and faba beans. DEMCROP aims to identify the most optimal pre-crop combinations (such as faba beans-winter wheat) while also optimizing the use of inputs considering crop responses and thus simulates decisions of profit maximizer farmers.

In scenario **1.1_prices_no_Fa** only malting barley had the highest land share among all scenarios. Thus, an increase in crop prices by 10% does not seem to have a significant effect on land allocation without faba beans. This is because a uniform increase of 10% in the prices of all crops implies an increase in the area under the relatively highly profitable crops, e.g. malting barley and winter wheat. In the scenario with 10% higher prices of all crops but including faba beans (**1.1_prices_yes_Fa**) land-use results are comparable to scenario **1.3_fab**. Cultivated areas of feed barley, oats and oilseeds reduced and gave an area for winter wheat, malting barley and faba beans in scenario **1.1_prices_yes_Fa,** compared to scenario **ins_f**. Results in scenario **Fa_subsidies** are comparable to **1.1_prices_yes_Fa** scenario with cultivated areas of malting barley, oats and oilseeds being reduced while the areas for faba beans being increased compared to **ins_f.**

A combination of scenarios **1.1_prices_yes_Fa** and **1.3_fab** was also examined**.** For example, an increase in crop prices by 10, 20, 30 and 40% and a simultaneous increase in N fertilizer price by 30% was examined. The results showed that land allocated to cereals (malting and feed barley as well as winter wheat) was slightly increased at the expense of faba beans and other crops, while the rest of the land remained almost unchanged. For example, in the most extreme case, an increase of all crop prices by 40% and a 30% increase in fertilizer price, land share changed by 2%, −3% and 5% for winter wheat, feed barley and malting barley, respectively, and very slightly for oilseeds and oats, compared to **1.3N_yes_Fa** (30% increase in N fertilizer price with faba beans in the model).

Table 4 presents the average annual volume of N fertilizer applied on each crop across all scenarios in comparison with average annual crop yields. The model estimates endogenously the optimum level of yields and N fertilization considering the costs of inputs (N fertilizer and fungicide use per crop, liming per field parcel) and their yield effects to maximize the farmer's profit. Results showed that introducing faba beans to the baseline (***ins_f***) could lead to an increase in yields specifically of winter wheat, barley and oats in addition to increasing crop diversity. Fertilizer use results are in line with land use share results in Figure 1. For example, the introduction of faba beans (**ins_f**) led to the reallocation of land from most cereals to faba beans; therefore, N fertilizer requirements were reduced and because faba beans require less N fertilizer the overall amount was reduced.

Table 4. Average annual N fertilizer (kg/ha) use and crop yields (ton/ha) over 30 years.

	Winter wheat		Feed barley		Malting Barley		Oats		Oilseed		Faba bean		
	N kg	Yield	N	Yield	N	Yield	N	Yield	N	Yield	N	Yield	Tot N
Baseline	159	5.80	98	4.70	95	4.39	98	4.84	92	1.55	NA	NA	542
ins_f	142	6.03	89	4.89	90	4.74	80	4.94	93	1.60	30	1.57	524
1.3N_no_Fa	136	5.63	79	4.51	80	4.25	85	4.68	69	1.44	NA	NA	449
1.3N_yes_Fa	106	5.86	78	4.75	78	4.47	66	4.78	70	1.48	30	1.55	428
1.3_fab	146	6.07	89	4.89	93	4.68	82	4.94	93	1.61	30	1.59	533
1.3_Fab&N	116	5.87	73	4.78	79	4.51	70	4.77	71	1.51	30	1.55	439
1.1_prices_no_Fa	168	5.58	104	4.79	101	4.51	103	4.90	99	1.58	NA	NA	575
1.1_prices_yes_Fa	151	6.17	89	5.05	99	4.79	89	5.04	100	1.64	30	1.53	558
Fa_subsidies	141	6.15	80	4.96	90	4.78	78	4.95	96	1.66	30	1.24	515

(1) baseline, (2) ins_f = insert faba beans; (3) 1.3N_no_Fa = increase in N fertilizer price by 30% with no faba beans; (4) 1.3N_yes_Fa = increase in N fertilizer price by 30% including faba beans; (5) 1.3_fab = 30% increase in the price of faba beans by 30%; (6) 1.3_Fab&N = increase of faba beans and N fertilizer prices by 30%; (7) 1.1_prices_no_Fa = 10% increase in crop prices without faba beans; (8) 1.1_prices_yes_Fa = 10% increase in crop prices with faba beans; (9) Fa_subsidies = increase of faba bean subsidies by €100/ha.

As expected, an increase in N fertilizer price by 30% (**1.3N_yes_Fa, 1.3_Fab&N**) led to a reduced overall amount of fertilizer use compared to the baseline, particularly in the scenarios with faba beans. Although yield changes between different scenarios are not very large, crop yields tend to slightly increase when faba beans are grown while fertilizer use is decreased. This means reduced dependence on chemical N fertilizer. Per hectare yields of all cereals and oilseeds were slightly increased in all scenarios examined compared to the baseline, except for **1.3N_no_Fa**. In the case of **1.3N_yes_Fa**, all crops showed higher yields than **1.3N_no_Fa** despite the increase in N prices, and almost the same yields compared to the baseline. The highest use of N fertilizer was found in scenario **1.1_prices_no_Fa** which was anticipated considering that part of land was reallocated from feed barley and oats to winter wheat which is high in N fertilizer requirements. Scenarios **1.3_fab** and **Fa_subsidies** showed similar results, with overall N fertilizer volume decreasing slightly compared with the baseline.

Table 5 presents the annual average total farm (100 ha) crop production volumes over 30 years, expressed as production in tons per year. Results showed that in the scenarios with faba beans cultivated the overall average production of cereals is smaller than in the scenarios without faba beans mainly because land is being reallocated to grow faba beans. The harvested average volumes (Table 5) are still reasonable considering the logistics costs which can be minimized if full or almost full truck loads (30–50 tons/truck, depending on the size of a truck) of each crop can be collected from a farm. Hence the crop rotation and land use plans derived are feasible on typical 100 ha-sized cereal farms in southwest Finland.

Figure 2 suggest that in every scenario that faba beans are introduced they tend to replace mainly malting barley and oilseeds, while winter wheat areas tend to be increased. Feed barley parcels were also reduced in the presence of faba beans and were generally replaced by faba beans and oats. Overall, crop rotation patterns do not change very

Table 5. Results on average annual total crop production volumes in tons per farm, assuming a farm size of 100 ha.

	Winter wheat	Feed barley	Malting Barley	Oats	Oilseed	Faba bean
Baseline	19.4	37.7	144.9	91.9	41.4	NA
ins_f	24.1	26.1	101.1	75.7	37.9	31.9
1.3N_no_Fa	16.9	31.6	143.2	92.0	38.5	NA
1.3N_yes_Fa	25.4	20.6	92.4	78.0	36.0	31.0
1.3_fab	42.5	21.2	102.9	67.5	36.0	32.8
1.3_Fab&N	27.4	23.9	90.2	74.7	34.7	33.6
1.1_prices_no_Fa	30.0	30.4	154.8	88.2	41.6	NA
1.1_prices_yes_Fa	37.0	20.2	108.7	67.2	37.7	32.2
Fa_subsidies	26.6	23.2	87.7	69.4	34.3	43.7

(1) baseline, (2) ins_f = insert faba beans; (3) 1.3N_no_Fa = increase in N fertilizer price by 30% with no faba beans; (4) 1.3N_yes_Fa = increase in N fertilizer price by 30% including faba beans; (5) 1.3_fab = 30% increase in the price of faba beans by 30%; (6) 1.3_Fab&N = increase of faba beans and N fertilizer prices by 30%; (7) 1.1_prices_no_Fa = 10% increase in crop prices without faba beans; (8) 1.1_prices_yes_Fa = 10% increase in crop prices with faba beans; (9) Fa_subsidies = increase of faba bean subsidies by €100/ha.

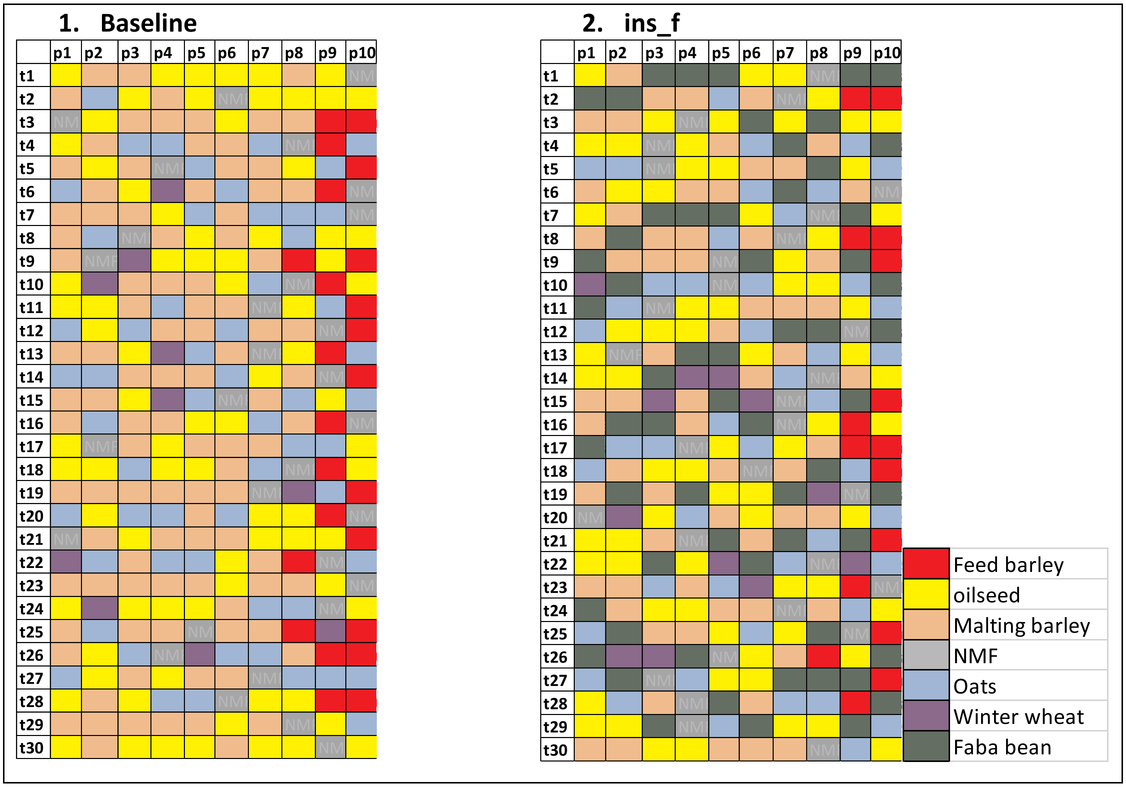

Figure 2. Optimal crop rotations, across all scenarios. (1) baseline, (2) ins_f = insert faba beans; (3) 1.3N_no_Fa = increase in N fertilizer price by 30% with no faba beans; (4) 1.3N_yes_Fa = increase in N fertilizer price by 30% including faba beans; (5) 1.3_fab = 30% increase in the price of faba beans by 30%; (6)1.3_Fab&N = increase of faba beans and N fertilizer prices by 30%; 7) 1.1_prices_no_Fa = 10% increase in crop prices without faba beans; (7) 1.1_prices_yes_Fa = 10% increase in crop prices with faba beans. Table rows t1-t30 indicate years and columns p1-p10 different field parcels. Different colours indicate different crops.

significantly among scenarios due to the introduction of faba beans since the overall area of faba beans remains less than 20% (due to the recommendation which says that faba beans should be cultivated in the same field parcel only once per 4–5 years). NMF parcels rarely appear before faba beans in two consecutive years due to the very low pre-crop value when faba beans are the subsequent crop (Table 1). For the same reason but because of a high positive pre-crop effect, NMF is almost always observed before oilseed and winter wheat. Feed barley is cultivated in the most distant field parcels because feed barley has lower logistic costs than the more valuable crops.

The use of fungicides was slightly reduced due to legume introduction since faba beans replaced some barley and wheat for which fungicides are used in Finland. However, since the use of fungicides is relatively small and inexpensive, reducing it has little economic or environmental consequences. Still, this responds to the EU-level targets of reducing chemical crop protection (Europa, 2022).

4. Discussion

Cultivation of faba beans improved the farm economy in Southwest Finland in almost all the studied scenarios to some extent. Hence faba beans can be considered a profitable activity even if assuming baseline prices and subsidies. This result, which has not always been reported in other studies, comes from the systematic consideration of pre-crop effects between all crops cultivated in a long-term dynamic setting at a farm with 10 field parcels which provide flexibility on crop rotation optimization.

The results suggest that farm profits increased significantly and even more than 10% over the entire 30-

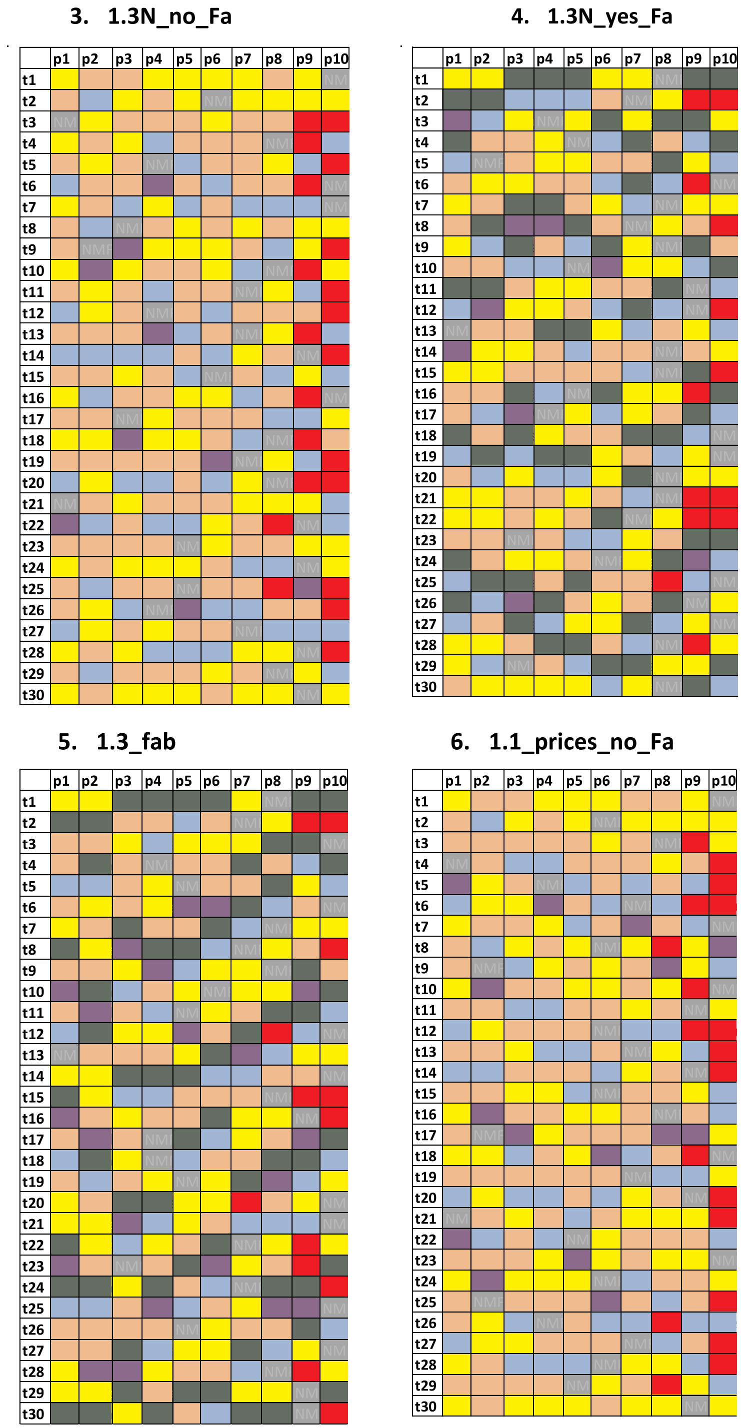

Figure 2. Continued.

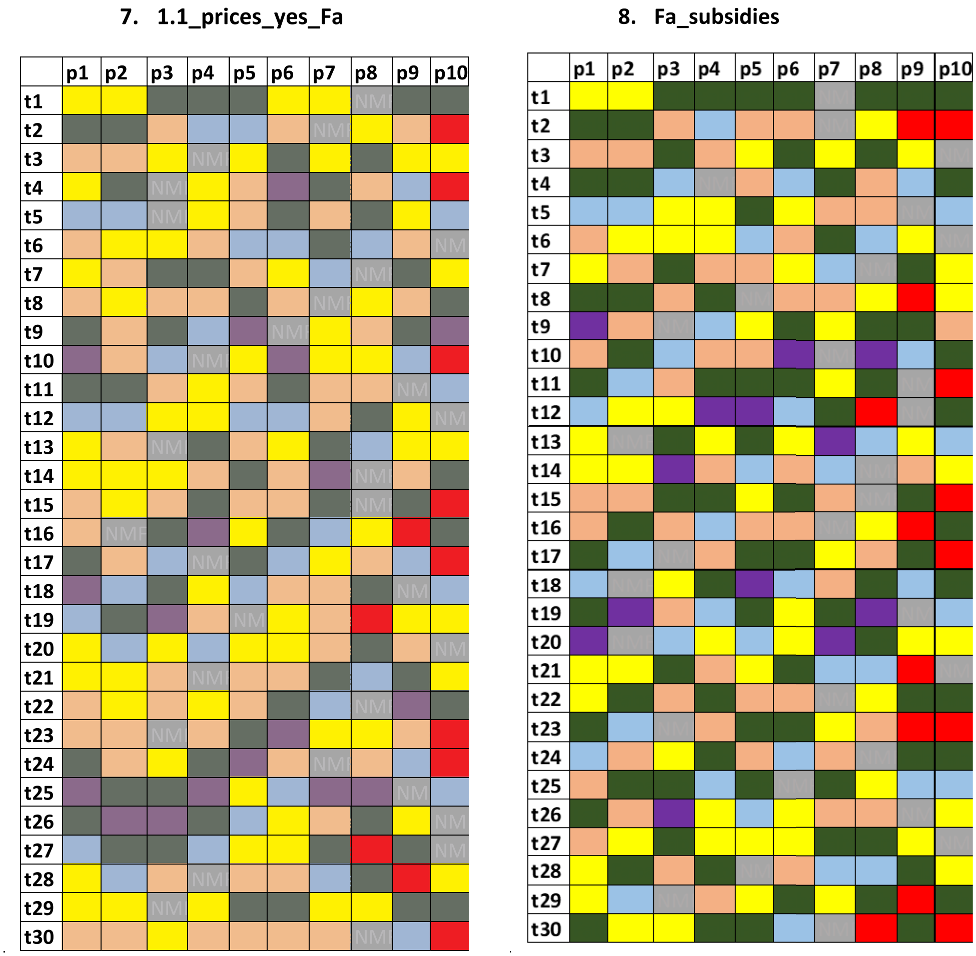

Figure 2 *Continued*

year time horizon considered in scenarios where either faba bean or N fertilizer prices, or both faba bean and N fertilizer prices were increased by 30%. The results on N fertilizer use show that cultivating grain legumes such as faba beans reduces dependence on fossil inputs such as chemical N fertilizers and at the same time improves the farm economy. Uncertainty is inherent in the agricultural sector. As such, farmers face increasing pressure on their income due to extreme weather conditions and high price volatility, therefore making farmers more hesitant about making long-term investments. In this analysis, uncertainty is not taken explicitly into consideration; therefore, the NPV effects assume that farmers are not risk-averse. The positive pre-crop effects of faba bean on the yield of subsequent crops according to field experiments (Angus et al., 2015; McEwen et al., 1990) and on-farm data (Peltonen-Sainio et al., 2019) and their rational utilization across the field parcels of farm explain the improved farm economy in this assessment.

Increased cultivation of grain legumes, even up to 20–25% of the land area of a farm diversifies land use and may reduce the production of crops like malting barley, oats and feed barley, thus reducing risks for productivity caused by monotonous cereal sequencing (Peltonen-Sainio & Jauhiainen, 2019). Despite positive legacy effects of grain legumes on cereal yields, the overall on-farm production volume of cereals may decrease moderately due to lower cereal area. This however requires a stronger and stable demand for grain legumes. According to Cortignani and Dono (2020), increased legume production reduced the quantity of other main crops and thus caused some economic losses for their value chains. The findings of this study confirm that production of some cereals at the farm level may decrease (malting barley), and some increase (winter wheat) due to the introduction of grain legumes despite the increased yields of cereals due to positive pre-crop yield effects of legumes. However, this study focused on farm level and did not consider value chain level effects and further research is needed on the value chain level economic effects of grain legumes. These results point to a more diversified agroecosystem thanks to diversified crop rotations, which in the long term would indirectly enhance the associated diversity of wild flora, wild fauna and soil microbes (Venter et al., 2016) that may affect the sustainability of agricultural systems. The results further suggest that a potential uniform increase in all crop prices might imply increasing fertilization and make cereal crops such as malting barley or bread wheat even more competitive, while faba beans may not be among the most profitable crops, at least if the cultivation of faba beans is not somehow incentivized by other means.

These findings are in accordance with the outcomes of rotation-specific gross margin calculations conducted by Preissel et al. (2015), who showed that pre-crop effects (such as the reduced need for nitrogen fertilizer, crop protection or tillage) lead to clear but relatively small gains (typically 0–200 €/ha) in terms of gross margins for a farmer. Gross margin gains of less than €100 per ha per year can be considered minor, but it is still a positive change for a farmer. Preissel et al. (2015) noted that the farm-level gross margin implications are sensitive to assumed pre-crop effects. The contribution of this study is the use of empirically estimated legacy effects – that have been realized on the farms of the study region and consistently estimated for various preceding crop – following crop combinations – in a dynamic optimization framework which considers pre-crop effects between all crop combinations in rotations. This means that the dynamic optimization framework recognizes the full potential of the pre-crop effects between all crops and plans the field parcel-specific crop rotations at farm scale. The results show positive economic gains of introducing grain legumes even assuming historical prices, and significant (>10%) farm economic gains if future N fertilizer or grain legume prices are high. Hence, compared with other studies, this study shows, based on rigorous dynamic optimization, good productivity and economic value potential for introducing grain legumes.

The results of this study highlight that farmers and society may gain more if crop production decisions are made based on entire multi-year crop rotations and not based on the cultivation of individual crops in a short-run setting. Results of this study are also likely more convincing for the farmers because the data on legacy effects originates from farmers' fields (Peltonen-Sainio et al., 2019), i.e. from actual production situations, and not from field experiments that might give too optimistic results compared to the conditions in a farm.

The legume-based rotations have also positive long-term impacts e.g. on soil health and functionality (Aschi et al., 2017; Chahal et al., 2021), biodiversity (Everwand et al., 2017), greenhouse gas emissions due to reduced mineral N fertilization (Köpke & Nemecek, 2010) and thus for viability and societal reputation of farming (Ditzler et al., 2021). Increasing the land allocated for grain legumes could potentially lead to indirect energy savings from fertilizers, reductions in greenhouse gas emissions, global warming, ozone formation, acidification and ecotoxicity (Köpke & Nemecek, 2010). This study is based on pre-crop values estimated using a relatively limited number of years (Peltonen-Sainio et al., 2019) and did not cover long-term implications of soil health and biodiversity that might occur in the studied 30 years. If such implications were known and could be quantified they could be considered using the modelling approach of this study. Some environmental valuation studies suggest that consumers appreciate such long-term environmental gains, even significantly in financial terms (Latvala et al., 2021). Some limitations of this approach are worth mentioning. Cultivation of faba beans and other legumes, in general, comes with some drawbacks, such as yield risks due to diseases (Stoddard et al., 2010) and frosts, heat and droughts (Alharbi & Adhikari, 2020). For example, fungal diseases can severely damage faba bean crops, especially in wet weather conditions, which is a significant risk for farmers. The main three pathogens affecting faba beans globally are ascochyta blight, chocolate spot and rust (Stoddard et al., 2010; Torres et al., 2006). These risks were not explicitly covered in this study though the relatively low initial long-term average yield estimate of faba beans (2.1 tons/ha) includes their occasional very low yields. It was assumed in this study that following recommendations for keeping a 4–5-year break in cultivating grain legumes at the same field parcel would largely eliminate severe pest and disease losses of faba beans.

Future research could include improvements in the productivity and resilience of faba beans through the development of drought-resistant new cultivars (Muktadir et al., 2020), or using irrigation systems during the dry summer months, which could mitigate economic risks although irrigation requires some investment costs. Further research is needed on the value chain level economic effects of grain legumes which has not been accounted for in this study.

Long-term impacts of legumes on soil and the resulting positive effects on crop yields were not considered in this study due to lack of data, but only short-run pre-crop effects between crops were considered. Hence, there is a need for more empirical studies to estimate the long-term legacy effects of grain legumes to account for improved soil status and crop yields in the long run (e.g. 15–30 years) and not only improved yields or avoided yield losses of monoculture in the short run (1–2 years).

The most recent CAP reform post-2020 (European Commission, 2022c) proposes a new set of objectives upon which member states will develop their national strategic plans. The results of this study could encourage Finnish policy-makers, as well as farmers and agricultural advisors, to introduce or promote the cultivation of faba beans in cereal farms. Regional or global economic crises may affect adversely the supply of energy and fertilizers. New strategies have to be developed to become less dependent on chemical fertilizers. Replacing imported livestock feed, e.g. soybean meal for pigs and poultry animals, with domestic legumes, would improve, for example, Finland's self-sufficiency in terms of protein fodder. The current study shows that legumes can be already competitive crops to be produced on a market basis, especially if N fertilization prices are high. However, high prices of all crops, especially those of cereals, may reduce the relative competitiveness of legumes. Hence, from a policy perspective, there could be some support policies for legumes (e.g. per-hectare payments for legumes, income support, etc.) aimed at keeping legumes competitive in such situations. Primarily, however, there is a need for R&D work for improved crop protection and irrigation (little used in field crop production in Finland) to prevent yield losses e.g. during drought periods. Both public policy-makers and the food industry purchasing legumes from farmers could also implement policies to reward farmers for some ecosystem services not priced at the markets (e.g. biodiversity).

5. Conclusions

This study applied empirically estimated pre-crop values, estimated from a large dataset in the study region of southwest Finland, in a dynamic optimization framework to investigate the long-term farm-level profitability and production effects of increasing the share of grain legumes in crop rotations. Unlike in previous studies, the dynamic optimization framework applied in this study recognized the full potential of the pre-crop effects between all crops at different field parcels and considered logistic costs. The results show positive economic gains of introducing grain legumes even assuming historical prices and significant (>10%) farm economic gains if future N fertilizer or grain legume prices are high. Including faba beans in crop rotations and utilizing pre-crop effects between crops consistently over several years, even decades, may give Finnish farmers higher NPVs (Net Present Values) and reduce the use of fewer chemical fertilizers. Farmers should be made more aware of the pre-crop effects and benefits of legumes in crop rotations. Besides, faba beans and in general legume-based rotations have positive long-term implications on soil quality and biodiversity (Everwand et al., 2017) and thus future viability and societal reputation of farming.

The potential for reduced chemical nitrogen fertilizer use and positive yield effects due to the pre-crop effect of legumes is lost if considering only short-run perspective, which often leads to the dominance of cereals in land use. Finland, as well as many other countries, has to develop new strategies to become less dependent on chemical fertilizers due to e.g. crises with implied high prices of nitrogen fertilizers and their limited availability.

In terms of policy implications, the results of the present study suggest that faba beans are already profitable and competitive crops at the farm level due to their positive pre-crop values. However, more research is required on the development of drought-resistant new cultivars, to improve crop protection and irrigation to prevent yield losses e.g. during drought periods which have already caused losses for farmers cultivating legumes. Further research is also needed on the value chain level economy of grain legumes. There could be also some stronger support policies for legumes such as per-hectare payments for legumes, crop insurance, income support, etc., aimed at keeping legumes competitive or reducing economic losses in adverse weather or market situations. Positive effects of legumes on biodiversity and climate (reduced chemical nitrogen fertilizer, improved soil structure) can be considered positive externalities little encouraged by agricultural policy.

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Appendix

The effect of nitrogen fertilization on crop yields is formulated using nitrogen response equations. Either Mitscherlich (Spring and winter wheat, feed and malting barley, oats) or quadratic (oilseed) form is used for different crops. Faba bean was assumed to be fertilized with a fixed amount of 30 kg/ha (The Finnish Cereal Committee [VYR], 2018).

Quadratic:

$$Q_i = \hat{Y}_i - \frac{\hat{N}_i}{2}\left(\theta_i + \frac{p_N}{p_i}\right) + \theta_i(\mathrm{N}_{itp} + F) - \frac{1}{2\hat{N}i}\left(\theta_i + \frac{p_N}{p_i}\right)(\mathrm{N}_{itp} + F)^2 \qquad (A1)$$

Mitscherlich:

$$M_i = \left(\hat{Y}_i + \frac{p_N}{p_i + \beta_i} - \frac{p_N e^{-\beta_i}\hat{N}_i}{p_i + \beta_i}\right)e^{-\beta_i}(\mathrm{N}_{itp} + F) \qquad (A2)$$

where Q_i and M_i are the yields of crop i after responses on fertilization in quadratic and Mitscherlich forms. $\hat{Y}_i$ is the baseline yield level based on statistics and $\hat{N}_i$ the baseline fertilization amounts for crop i. p_N and p_i refer to prices of nitrogen fertilization and crop $_i$, respectively. N_{itp} is the optimized fertilization amounts and F is the impact of faba beans on nitrogen levels.

Table A1. Parameter values for nitrogen response functions Source: Purola et al. (2018).

Crop	θ	β	$\hat{Y}$	$\hat{N}$
Winter wheat	–	0.0105	4385	140
Feed barley	–	0.0168	3848	90
Malting barley	–	0.0168	3851	90
Oats	–	0.0197	3893	90
Oilseed	9.82	–	1654	100