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Profitability of intercropping legumes with cereals: A farm-level analysis

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ABSTRACT

The benefits of grain legume and cereal intercropping, such as increased yield stability, resource efficiency, weed suppression, improved diversity of agricultural landscapes compared to monoculture systems have been extensively studied. Despite these benefits, the adoption of intercropping remains limited in Europe, including Finland, primarily due to socio-economic factors and perceived challenges. This research aims to fill the gap in understanding the farm-level economic implications of adopting oat-pea intercropping in Finnish agriculture. Using a dynamic optimization model, the study evaluates the profitability of oat-pea intercropping, considering dynamic factors such as crop yields, land utilization, and crop rotation, under different scenarios. Results showed that intercropping increases farmer's net present value (NPV) by reducing costs associated with nitrogen fertilization and increasing yields of various crops. When faba beans and peas are included as sole crops in the cropping system, profits increase by 37 %, driven by faba bean prices and positive yield effects on the following crops, i.e. pre-crop effects. Even with increased labor costs, including intercrops in crop rotations improves farm economy. More specifically, intercropping becomes unprofitable to be included in the crop rotation if labor costs increase by 2.6 times (442 €/ha). Increasing intercrops' price will lead to an increase in profits from 12 % to 32 %. Supportive policies, like enhancing agricultural extension services to train farmers in intercropping, could accelerate its adoption. Additionally, developing the market for pea-oat intercropping can promote wider acceptance by building strong connections between farmers, processors, and retailers.

1. Introduction

Sustainable development of agriculture has been at the core of the agricultural policy agenda in Europe in the last decades. Agricultural diversification is considered one of the most promising approaches and top priorities to achieve this goal [1,2]. The benefits of integrating legume crops into the cropping system have been analyzed and reported by numerous studies (e.g. Ref. [3–6]), and one way to achieve this is by using legumes as intercrops [7].

Intercropping means the simultaneous cultivation of at least two crops in the same field [8], although not necessarily sowing or harvesting them at the same time. Although intercropping has been a common agricultural practice for ages, agricultural intensification of the last decades replaced intercropping with monocultures [9]. Legumes are being successfully used in intercropping because they fix atmospheric nitrogen (N) through symbiosis with rhizobia in their root system. Hence, cereals being competitive in N uptake, can benefit from the natural N supply released by the roots of legumes ([10]; Hauggaard-Nielsen, Ambus and Jensen, 2003; [11]). As a result, grain legumes can replace and decrease the need for mineral N fertilizers, reduce N leaching into the environment [12,13] and increase energy efficiency. For example, in the EU, the production of fertilizers is the largest energy consuming activity in agriculture [14]. Furthermore, intercropping grain legumes with cereals or other non-legumes can generate beneficial biological interactions between the crops that can result, for example, in enhanced yields, improved climate resilience and stability of production, more efficient use of available resources, alleviation of weed infestation and overall improved plant health [15]. Recent meta-analyses confirmed these benefits [7,16].

The legume production area in Europe is still negligible, less than 3 % of the arable area [17], indicating farmers' persistent reluctance to grow legumes [18]. In northern Europe, grain legumes such as peas (*Lathyrus oleraceus* Lam.) and faba beans (*Vicia faba* L.) have been historically cultivated [19]. Recently, the cultivation area of grain legumes has increased in Finland but has fluctuated ([20], 2024). The harvested area of peas has seen a steep upward trend, being 6200 ha in 2010 and reaching 43,900 ha in 2023 [21]. The area of cultivated faba beans increased from 9000 ha to 18,000 ha 2010–2020 but decreased

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continuously since 2020 to 9000 ha in 2023 and to 6000 ha 2024 in Finland. Average harvested yields of faba beans have decreased from the level of 2500 kg/ha 2016 to less than 2000 kg/ha in recent years [21]. Unfavourable weather conditions for faba beans, such as droughts, which faba beans hardly tolerate, have probably influenced reduced yields and cultivated areas in recent years.

The agricultural land use of grain legumes in general, in Finland varies depending on the region and growing conditions with the highest being in the southwestern parts of Finland (VYR, 2022a), where growing conditions are most favorable. However, cultivating peas and oats (*Avena sativa* L.) as an intercrop is less demanding in terms of soils and climate conditions and thus more common in the middle and northern parts of the country than cultivating grain legumes as a single crop (Peltonen-Sainio et al. , 2024). Since 2020, more than 40,000 ha of 'mixed cereals' have been cultivated in Finland, mainly used for animal feed directly at livestock farms. This implies limited markets and poor opportunities to sell the crop harvest at a good and competitive price [22]. Some part of this area is probably oat-pea intercropping. Unfortunately, the available statistical data does not show the actual areas or yields of cereals-peas intercropping.

Due to climate change, Finland is expected to experience warmer and longer growing seasons [23] reduced and more sporadic snow cover time [24], higher precipitation [25], and increasing weather variability and extremes such as strong winds, heavy rains, and warm spells [26]. Cereals, which are the main crops cultivated for feed and food in Finland, are expected to be especially vulnerable to these changes. For example, spring cereals are mostly sensitive to drought and elevated temperatures, rapeseeds to pests and elevated temperatures, while forage and winter crops are vulnerable to mild-to-cold shifts over winter causing overwintering damage [27]. Intercropping has the potential to enhance climate resilience by optimizing the use of plant resources such as space, nutrients, and water, while also alleviating the risks of insect, pathogen, and weed infestations. These combined effects may lead to increased profitability for farmers, although intercropping, as well as other diversification measures, may require more complex management, specialized machinery and greater labor input ([28]; Zabala et al., 2023).

Cereal-legume intercropping may face challenges [13,29–31]. For example, Mamine and Farés (2020) gave a thorough overview of the main factors and obstacles of the wheat (*Triticum aestivum* L.) and pea intercrops in Europe, especially by highlighting fewer options for chemical crop protection. Furthermore, intercropping may challenge harvesting, grain separation and use [32–34]. Thereby, adoption of intercropping may require greater expertise of crop species when grown together and increase expenses. Additionally, yield quality may be lower due to species (pathogens, pests, etc.) cross-contamination and potential damage during harvesting and separation processes [35]. Overall, uncertainty of costs in intercropping requires further analysis.

Socio-economic research related to the adoption of intercropping with grain legumes in Europe, and Finland in particular, is scarce. The lack of research regarding the profitability of different crop mixtures has been highlighted in the scientific literature review by Rosa-Schleich et al. [36]. The profitability of the pea–wheat intercrop was investigated by Pelzer et al. [37] in France, who found that the average gross margin of the pea–wheat intercrop with or without nitrogen fertilisation was higher than the average gross margins of the pea and wheat sole crops with or without nitrogen fertilization. Most recently, the socio-economic factors affecting the adoption of intercropping were studied by Fares and Mamine [34] who found that potential barriers for adoption are market access, public subsidies, lack of technical advice and extension, and issues related to storage and collection. A few other studies focused on farmers' perceptions on intercropping (Lemken et al., 2017), as well as the motivation and barriers to adopt [38,39]. While numerous studies have highlighted the significant ecological advantages of intercropping [15,40,41], only a few have examined the economic benefits [42] derived from this practice. This study, therefore, aims to fill this gap in the literature.

The main research question of this study is how adopting oat-pea intercropping by Finnish farmers affects farm-level economics, when considering implications on crop yields, land utilization, and crop rotation over the long term. Additionally, the study seeks to investigate the profitability of cultivating grain legumes intercropped with oats under varying prices of intercrops, increased costs due to labor input and considering the possibility of adoption of faba beans and peas as a single crop. The analysis considers pre-crop effects of crop rotations explicitly and examines the impact of integrating grain legumes, both as monocrops and intercropping, into the cropping system of a typical cereals-producing farm in southwest Finland over a 30-year period, reflecting the duration of a typical farming career. This farm level analysis investigates the relative competitiveness of oats and peas intercropping and faba beans or peas as a single crop at the farm level. Building on limited prior research, this study investigates under which scenarios intercropping oats and peas is a profitable option for a farmer, and what the production, land use, and income implications are.

2. Material and methods

2.1. Study area

This study focuses on the province of Southwest Finland, recognized as one of the most significant agricultural regions in the country. In 2022, the average useable agricultural area per farm in Southwest Finland was 65 ha. Approximately 55 % of the farms in the region primarily cultivate cereals, while horticulture farms account for 7 %, and other crop farms (not primarily producing cereals) represent 20 %. Cattle farming is carried out on around 5 % of the farms, with only 3 % specializing in dairy production (OFS, 2022). The region also produces significant quantities of pig or poultry meat, with 6 % of farms engaged in this sector. Pig and poultry farms have traditionally relied on imported protein feeds, particularly soy [*Glycine* max (L.) Merr.], as domestic protein crops have been less prominent. There is, however, an increasing trend that Finnish meat processing companies aim to replace imported soya with domestic protein feeds especially in pork production (HKScan 2017, Atria 2022). This offers opportunities for the increasing use of grain legume mixtures as animal feed. Currently, turnip (*Brassica rapa* L.) and grasslands, oilseed rape (*B. napus* L.), sugar beet (*Beta vulgaris* var. *altissima*), potato (*Solanum tuberosum* L.), and other crop areas are relatively small, while spring cereals like barley (*Hordeum vulgare* L.), oats, and wheat cover roughly 70 % of agricultural land. Southwest Finland offers ample opportunities for diverse crop selection and land utilization [20].

2.2. DEMCROP model

In DEMCROP (Dynamic Economic Model of Crop Rotations and Farm Management) [43–45], dynamic optimization is utilized to integrate crop production and farm economics with diverse technical data on input use and response functions. These include the cereals' and oilseeds' crop yield response to N fertilizer levels, as well as the yield effects of liming and fungicide treatments. Parameters utilized in the model, such as crop yields, variable costs, subsidies, and crop prices, are usually derived from official statistics or empirical estimations.

The model implementation accounts for the dynamic effects of crop rotation across ten field parcels annually over a span of 30 years, incorporating the usage of fertilizers and fungicides per crop, as well as liming per field parcel. Accounting for profit discounting, the model serves as a comprehensive tool to assess the potential contributions of pea-oat intercrops alone and in combination with legume single cropping to productivity, land use, production, and profits at a typical cereal-producing farm. Previously, DEMCROP has been utilized for cereal-producing farms in Finland [43–46], and for a dairy case farm [47], but intercropping, an important option especially when considering adaptation to climate change and sustainable farming, has not so far been included in applications of the model. Below, we briefly outline the intercropping model developed during this study.

The model assumes that the farmer aims to maximize profits, by choosing among six potential crops, taking into account their respective input requirements. Additionally, the farmer may opt to set aside the parcel as fallow or designate it as a nature-managed field (NMF) eligible to specific agri-environmental payments. The sum of set-aside and NMF land was constrained to 25 % of a farmer's land, with the requirement to cultivate the rest of the land in order to receive CAP payments [48–50]. 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 [49].

Net present value is maximized with 6 % interest rate over 30-year time horizon which approximately reflects a farming career. The interest rate (discount factor) was set to 6 % because it has been estimated that Finnish stock markets have yielded 7 % annual return for invested capital, on average, during the last 100 years [51]. However, it's noted that farmers, as small-scale private investors, encounter certain transaction costs. Denoting the interest rate with ŗ and the discount factor with b = 1/(1+r), the optimization problem is as follows (equations (1)–(4)):

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

subject to

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

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

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

where p_i is the price of crop i, Y_{ti} the yield of crop i at time t, S_i is the agricultural subsidies for crop i, C_{tpi} 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. N_{tp}., F_{tp}, and L_{tp} denote N fertilizer use, fungicide use, and liming at parcel p at time t with, respectively, and $C_{L,}$ C_F and C_N denote the respective cost functions. Finally, V_{itp} and G_p denote the variable and logistic costs.

Statistical yields for crop i are denoted with $\widehat{Y}_i$,while α_i is used as the crop-specific effects of N use (N), liming (L) and fungicide (F) on yield, on parcel p at time t, β_{ij} is the pre-crop value of crop j on crop i, γ_i are the yield losses due to monoculture, and p_N is the price of N fertilizer. The model estimates endogenously the optimum level of yields and N fertilization for cereals and oilseeds considering the costs of inputs (N fertiliser and fungicide use per crop, liming per field parcel) and their yield effects in order to maximize farmer's profit. The carry-over effect of additional N due to legumes for the subsequent crops is included in the pre-crop effects and it is not additionally considered.

The impact of nitrogen fertilization on crop yields is determined using N response equations. For different crops, either the Mitscherlich form (applied to spring and winter wheat, feed and malting barley, and oats) or the quadratic form (used for oilseed) is utilized. It is assumed that faba beans, peas and pea-oat intercrops containing two amounts of oat, either 7.5 % or 15 % in the seed mixture are fertilized with a constant amount of 30 kg/ha [52], 30 kg/ha, and 34 kh/ha and 39 kg/ha (expert knowledge).

The functions for calculating the crop yield effects of N use, liming, and fungicide use are presented in equations (5) and (6). The optimization problem described in equations (1)–(6) was using the CONOPT3 solver of the general algebraic modelling system (GAMS) software (GAMS, 2021).

Quadratic:

$$Q_i = \widehat{Y}_i - \frac{\widehat{N}_i}{2}\left(\theta_i + \frac{p_N}{p_i}\right) + \theta_i(N_{itp}+F) - \frac{1}{2\widehat{N}i}\left(\theta_i + \frac{p_N}{p_i}\right)(N_{itp}+F)^2 \tag{5}$$

Mitscherlich:

$$M_i = \left(\widehat{Y}_i + \frac{p_N}{p_i+\beta_i} - \frac{p_N e^{-\beta_i}\widehat{N}_i}{p_i+\beta_i}\right)e^{-\beta_i}(N_{itp}+F) \tag{6}$$

where Q_i and M_i are the yields of crop i after responses on fertilization in quadratic and mitscherlich forms. $\widehat{Y}_i$ is the baseline yield level based on statistics and $\widehat{N}_i$ 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 the impact of faba beans, peas and intercrops on N levels.

The model encompasses various production activities, including the management of a specific piece of farmland, which consists of ten parcels of equal size (parcels 1–10) within the farm. Parcel 1 is situated closest to the farm centre, while parcel 10 is the farthest away. The distances from the parcels to the farm centre are evenly distributed, ranging from 0 to 7 km, with a mean (driving) distance of 3.5 km. Such a dispersed field parcel structure is typical in the region, as also elsewhere in Finland. Topography, suitable soils and watercourses, as well as ownership of farmland result in varying distances from farm centre to field parcels.

Currently, a strong recommendation advises against cultivating oilseeds or grain legumes on the same field parcel more often than once per 4–5 years, to avoid significant crop losses due to pests and diseases [53]. Hence, these crops were combined with a large yield penalty due to sequential monocropping over years, and this yield penalty was inherited even after 4 years if oilseeds are cultivated again in the same field parcels. The yield penalties for oilseeds [43] and grain legumes in the DEMCROP model were determined in consultation with experts in crop protection and crop science.

2.3. Input data

In this study, DEMCROP model utilized historical data for the years 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 (cereals, grain legumes) are collected from the official farm statistics [21] for Southwest Finland. The yields for pea-oat intercrops in Southwest Finland were derived from Ref. [54] who conducted field experiments in southwest Finland experimental station in Mietoinen (60°37′47.0''N; 21°51′30.0''E; elev. 13 m). Cereal crop prices were taken from the official farm statistics (2022), while producer prices for grain legumes were taken from Ref. [55]. The price of pea-oats intercrops was assumed to be the same as the price of peas due to the lack of data related to intercrop market prices.

The mean variable costs associated with crops including costs related to seeds, fertilizers, liming materials, crop protection chemicals, machinery, infrastructure, transportation costs, and other variable expenditures were derived from a recent version of a dynamic regional sector model of Finnish agriculture (DREMFIA) [56,57] which utilizes

Table 1
Parameter values for nitrogen response functions.

Crop	θ	$\beta\bullet$	$\widehat{Y}$	$\widehat{N}$
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

Source [44].

Table 2
Annual average per ha input data for Southwest Finland used in the numerical analysis.

Crops	Yields[1], $\hat{Y}$ (kg/ha) 2010-2020	Subsidies[2], S_i (€/ha) 2023	Prices[3], P_i (€/kg) 2017-2020	Variable costs[4], V_i (€/ha) 2023	Optimal pH[4]	Fungal disease losses[4] (%)	Initial N use requirements (kg/ha)
Spring Wheat	2851	468.2	0.185	801	6.5	5.85	110
Winter Wheat	4386	468.2	0.185	777	6.5	5.85	140
Feed barley	3848	468.2	0.148	753	6.1	6.35	90
Malting barley	3851	468.2	0.169	778	6.5	6.35	90
Oats	3893	468.2	0.171	801	6.1	0	90
Oilseed	1654	588.2	0.393	707	6.1	0	100
Setaside	–	468.2	–	296	–	–	0
NMF	–	533.2	–	296	–	–	0
Peas-Oats 15 %	3994	588.2	0.201	771	6.5	0	39
Peas-Oats 7.5 %	2830	588.2	0.201	771	6.5	0	34.5
Faba bean	2140	588.2	0.230	771	6.5	0	30
Peas	2488	679.2	0.201	821	6.5	0	30

NMF: Nature managed field
Peas-Oats 15 %, Peas-Oats 7.5 %: pea-oat intercrops containing 15 % and 7.5 % respectively of oats in the seed mixture.
[1] Finnish Food Authority (2023)
[2] Finnish Food Authority (2024)
[3] Finnish Food Authority (2022)
[4] DREMFIA, Lehtonen and Rämö (2022)

annually validated input prices and approximations of the average input use per crop in each region. A farmer was assumed to receive all basic farm subsidies, as well as the basic agri-environmental subsidies. Subsidy data were derived from the Finnish Food Authority [58]. Most agri-environmental subsidies were considered, but the ones with specific requirements and commitments (e.g. balanced nutrients, control drainage, green manure lawns, etc.) were excluded from the model because they vary greatly across farms and their economic significance and production implications are minor on cereals farms [59]. Labour use per ha was obtained from Palva [60]. Cost per hour of labour (appr. 15 €/hour) was derived from the national level FADN system [61].

Pre-crop value is a measure used to determine the legacy effects of crop sequencing, i.e., the relative benefits of a previous crop for a subsequent crop in a rotation. The legacy effects include all possible legacy effects, e.g. increased or decreased soil N available for the next crops, or reduced pest and disease pressure, from earlier crops to subsequent crops in the rotation. When compared to monocultural crop sequencing, this is frequently stated as a larger yield or biomass in the case of positive pre-crop value. On the other hand, yield loss can also occur if the pre-crop value is negative, which indicates that the previous crop and the subsequent crop are incompatible in some way [62].

The pre-crop effects used in the current study (Table 3) were obtained from Peltonen-Sainio et al. [63] (Tables 1–3) who applied a large dataset of pre-crop and subsequent crop combinations using two-year Sentinel-2 satellite images and the derived mean values from the Normalized Difference Vegetation Index (NDVI) in Finland. For example, assuming that spring wheat (row 1) is cultivated after spring wheat (column 1) there is zero pre-crop effect, while if winter wheat is cultivated after spring wheat a 1.25 % increase on spring wheat yields was observed in farmers' fields compared to a case with monotonous wheat sequencing. In general, the pre-crop values associated with intercropping in Finland are not yet largely studied. Furthermore, the legacy effects may range a lot due to widely varying composition of the intercrops used by farmers. Therefore, since the legacy effects of intercropping on cereals and vice versa are only available for certain crops, it was assumed in this study that these combinations of cereals and intercrops are representative for the analyzed case.

2.4. Scenarios

The economically optimal farm management for a typical Finnish cereal farm was examined over 30 years in ten different scenarios. The

Table 3
Pre-crop values for each crop combination, based on Peltonen-Sainio et al. [63], presented as %-change in comparison to the monoculture, i.e. the same crop. 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 spring wheat is repeated in the field parcel. Crops in the first column are the subsequent crops, while crops in the first row are the previous crops.

	SWheat	WWheat	FBarley	MBarley	Oats	Oilseed	setaside	NMF	Fababean	Peas	peas-oat 7.5	peas-oat 15
SWheat	0.00	3.00	5.31	6.80	1.33	7.72	4.40	0.50	7.80	8.40	0.00	0.00
WWheat	1.25	0.00	6.10	6.10	4.85	8.75	3.28	9.40	9.55	8.85	0.00	0.00
FBarley	−0.23	1.28	0.00	0.00	−0.18	3.90	−3.47	−3.55	4.37	3.18	−3.89	−3.89
MBarley	−0.23	1.28	0.00	0.00	−0.18	3.90	−3.47	−3.55	4.37	3.18	−3.89	−3.89
Oats	2.20	2.95	4.88	4.88	0.00	4.31	−1.75	−2.23	7.90	0.97	0.38	0.38
Oilseed	4.38	5.20	6.40	6.40	3.80	0.00	4.85	9.45	9.05	8.00	0.00	0.00
setaside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NMF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fababean	1.60	5.30	5.20	5.20	−3.00	1.83	1.25	−5.90	0.00	0.00	0.00	0.00
Peas	8.30	6.25	9.40	9.40	14.60	6.08	6.28	−8.55	0.00	0.00	0.00	0.00
peas-oat 7.5 %	0.00	0.00	−8.25	−8.25	−3.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00
peas-oat 15 %	0.00	0.00	−8.25	−8.25	−3.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00

NMF: Nature managed field
Peas-Oats 15 %: pea-oat intercrops containing 15 % of oats in the seed mixture.
Peas-Oats 7.5 %: pea-oat intercrops containing 7.5 % of oats in the seed mixture.

baseline or business as usual scenario represents the currently typical cropping system in Southwest Finland with cereals (winter wheat, spring barley, spring oats), oilseeds, nature management fields and (grass-covered) set aside, while grain legumes are not commonly cultivated. The first scenario (**Insert_interc**) assumes that intercropping is introduced to the crop rotation of a typical cereal farm defined in the baseline. The objective of this scenario is to analyze the optimal allocation of land for pea-oat intercrops containing two amounts of oat, either 7.5 % or 15 % in the seed mixture. The seed mixture was decided as an appropriate mixture to prevent lodging of the crop without compromising pea yields and ensuring protein payment for the pea crop which in 2002, required that pea intercrops should include a companion less than 15 % in the seed mixture [64].

Intercropping systems have several challenges that are usually linked to labor intensity affected by weed control, harvesting, and grain separation activities. In Finland, the majority of mixtures are used as animal feed, therefore, in most cases no separation of grains is needed. In an attempt to capture the potentially increased labor costs due to intercropping, the third (**interc_labor_85**) and fourth (**interc_labor_170**) scenarios assume that the labor costs of intercropping increase by 50 % and 100 %, respectively the amount of labor cost assumed in the baseline. For example, scenario **interc_labor_85** considers that labor costs increase by €85/ha annually and **interc_labor_170** considers €170/ha increase. Scenario **interc_labor_cut** determined the labor cost threshold at which the intercrop becomes unprofitable to enter crop rotation. The objective of identifying this critical point is to gain insight into the economic viability of the intercropping system under different labor cost scenarios.

The following scenarios, **inter_price1.1**, **inter_price1.2**, **inter_price1.4**, assume an increase in the price of the pea-oat mixture by 10 %, 20 %, and 40 % respectively, compared to the baseline. These scenarios aim to conduct a sensitivity analysis for the pea-oat mixture price, as the actual market price of a legume-cereal intercropping is not accurately known due to the rarity of mixtures in the market. It is a common practice, among the minority of farms which cultivate oat-pea intercrops, to keep these mixtures on the farm as feed for their livestock. Since the value of legume-cereals intercrop as a feed may vary, it is reasonable to consider different price levels.

The last two scenarios, **inter_lab85_leg** and **inter_lab170_leg**, are similar to scenarios interc_labor_85 and interc_labor_170, respectively. The main difference is the inclusion of faba bean and pea as single crops in the model. This addition allows for the evaluation of the relative contributions of legumes intercropping and single cropping options, and the evaluation if potential economic losses from intercropping can be mitigated through increased cultivation of grain legumes.

3. Results

The maximized net present value (NPV) for the baseline scenario with no intercropping or single cropping of grain legumes amounted to €31,253 per 10 ha over a 30-year period. This translates to an annual average of €10,040 per 100 ha, relatively close to the average farm income of cereal farms (average size appr. 70 ha 2022) in the study region during the period of 2000–2021, which was €9400 per farm (Luke, 2023).

The incorporation of intercops into the cropping system (Insert_interc scenario) increased farmer's NPV by 10 % (Fig. 1). This increase in profits was expected due to the reduced costs associated with N fertilization. Evidently, the increase in profits (37 %) when peas and faba beans are also included is noteworthy. The high increase in profits is driven by the prices of legumes and their high, positive pre-crop effects.

A potential increase in intercrop labor costs by €85 per ha (interc_labor_85) compared to the baseline led to an increase in NPV by 4 % due to the introduction of intercropping, while an increase in labor costs by €170 per hectare still led to a 2 % increase in NPV (interc_labor_170). However, if legumes were also included in the cropping system, despite an increase in intercrop labor by €170, the increase in NPV due to introducing intercropping would be much higher, at 23 %. The model indicates that an increase in intercrop labor costs by 2.6 times (442 €/ha) would be required to exclude intercropping from the crop rotation completely (interc_labor_cut).

Assuming an increase in intercrop prices by 10 %, 20 %, and 40 % would result in respective increases in NPV due to the introduction of intercropping by 16 %, 19 %, and 32 % compared to the baseline. This is notable, especially considering that the market would likely demand higher prices because of the higher quality of grain resulting from

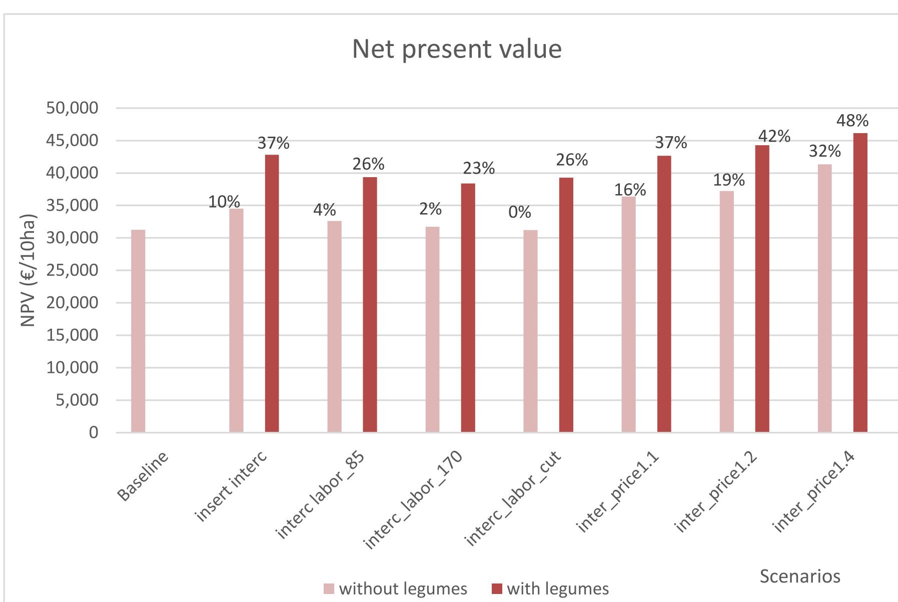

Fig. 1. Net Present Values (euro per 10 ha) over 30 years across all scenarios and the percentage change between each scenario and the baseline.
1) Baseline; 2) Insert_interc = insert intercrops; 3) interc_labor_85 = increase labor costs for intercrops by €85; 4) interc_labor_170 = increase labor costs for intercrops by €170; 5) interc_labor_cut = the cutoff point at which the intercrop becomes unprofitable; 6) inter_price1.1 = increase in intercrop price by 10 %; 7) inter_price1.2 = increase in intercrop price by 20 %, 8) inter_price1.4 = increase in intercrop price by 40 %.

increased protein content.

The reported NPVs are driven by the land use changes resulting from the introduction of intercrops and legumes. Fig. 2 depicts the average optimal land use share for each crop over the 30-year period across all scenarios. In the baseline scenario, on average, winter wheat (20 %), malting barley (20 %), oats (5 %), oilseeds (30 %) and NMF (25 %) constitute the land use in rotations over a 30-year period. The incorporation of intercrops in the cropping system (Insert_interc) resulted in the reallocation of half of the winter wheat land use share and almost half of the barley land use share, to intercrops, while the land use share of oats increased. This could be explained given the positive intercrop legacy effects when oats are the subsequent crop (0.38 %) (Table 3) in contrast to the negative legacy effects when barley is the subsequent crops (−3.89 %). However, when intercrops are the subsequent crop both oats and barley have a negative pre-crop effect which is higher in barley's case.

In scenarios interc_labor_85 and interc_labor_170, intercrops became less profitable leading to a small share of land being shifted back to barley, and oilseed. Increasing intercrop price by 10 % (inter_price1.1) compared to scenario *insert_interc* slightly increased intercrop land use, while a 40 % increase (inter_price1.4) resulted in a 7 % increase in land use for intercrops. Comparing the scenarios interc_labor_85 and inter_lab85_leg, the incorporation of peas and faba beans as sole crops led to the reallocation of land use from cereals to legumes because they were more profitable.

Incorporating intercrops into the cropping system (Insert_interc) leads to a slight increase in the yields of wheat, barley, and oilseeds, while slightly reducing the amount of applied N fertilizer for wheat and oats (Table 4). However, N fertilizer use per crop production was reduced in *Insert_interc* scenario for all crops (Table 5). The most significant reduction in fertilizer application was observed in oats (Table 4). The crop rotation outcomes (Fig. 3.2) indicate that in scenario *Insert_interc* the model favors the sequence of oats succeeding intercrops, utilising the positive effects of intercrops as preceding crops.

An increase in intercrop labor costs (*interc_labor_85*) resulted in minor changes compared with *Insert_interc* scenario, maintaining increased yields across almost all crops compared to the baseline scenario (Table 4). Further increase in intercrop labor costs (*interc_labor_170*) led to further reduction in intercrop land share and consequently to slight increase in N fertiliser utilized by crops. It is noteworthy that baseline labor costs for intercrops would need to increase by 260 % for them to no longer be optimal for inclusion in crop rotation (*interc_labor_cut*). This result suggests that an increase in intercrop variable costs to the extent that they become entirely unprofitable is quite high, hence, possibly less likely to occur.

A sensitivity analysis of intercrop prices (inter_price1.1, inter_price1.2, inter_price1.4) did not show any significant changes in either the fertilization amounts, or the intercrop yields compared with the scenario *insert_interc*. Evidently, the increase in intercrop price only affected the land use compared with scenario *insert_interc,* especially in the case of a 20 % increase (inter_price1.2).

The scenario *inter_lab80_leg* showed that incorporating faba beans and peas into the crop rotation resulted in a noteworthy increase in the yield of almost all crops and a reduction in fertilizer usage because replacing part of the cereals requiring high N fertilization by less fertilized legumes implies reduced N fertilization at a farm. Despite an €80 increase in intercrop labor costs, there was no significant impact on intercrop production, underscoring the added value of integrating faba beans and peas into the cropping system. In the scenario with higher labor costs (inter_lab170_leg), incorporating faba beans led to greater yields compared to scenarios where faba beans were not included. The total amount of N fertilizer used was slightly increased, which is anticipated due to the cultivation of cereals (winter wheat) crops.

The optimal crop sequence (Fig. 3) is naturally affected by the pre-crop values applied (Table 3). For example, winter wheat usually follows barley and NMF (Fig. 3.1). Oilseeds as following crop benefits from almost all cereal crops considering the high pre-crop values. In scenario *Insert_interc* it is apparent that intercrops replaced wheat and barley on some parcels (Fig. 3.2). Similarly, barley is almost never followed by intercrops due to the significantly low pre-crop values, while wheat often follows peas and faba beans due to the very high pre-crop values (8.85 % and 9.44 %, respectively).

Overall, crop rotation patterns do not change very significantly among scenarios. Intercrops rarely appear on the same parcel two consecutive years due to high yield loss due to diseases. For the same reason grain legumes and intercrops were assigned quite high monoculture loss penalty in the model.

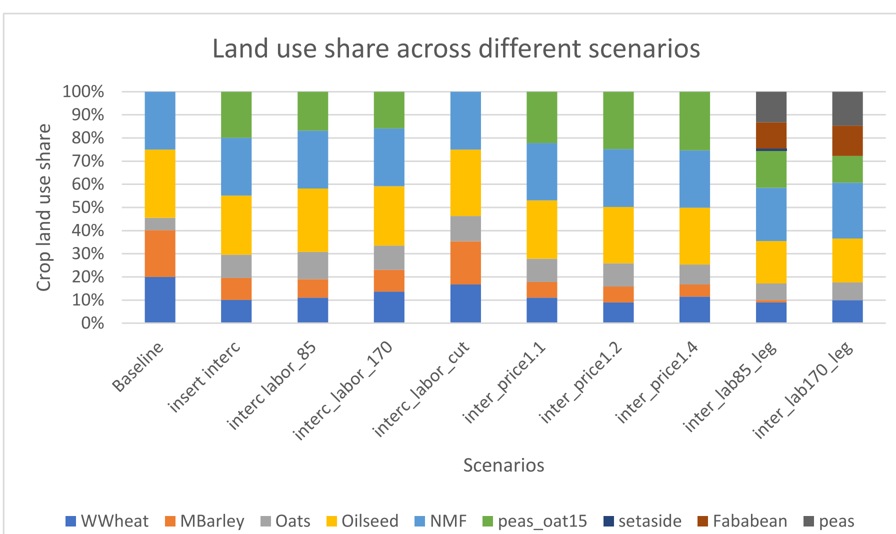

Fig. 2. Share of mean allocated land for a 30-year period, across all scenarios.
1)Baseline; 2) Insert_interc = insert intercrops; 3) interc_labor_85 = increase labor costs for intercrops by €85; 4)interc_labor_170 = increase labor costs for intercrops by €170; 5) interc_labor_cut = the cutoff point at which the intercrop becomes unprofitable; 6) inter_price1.1 = increase in intercrop price by 10 %; 7) inter_price1.2 = increase in intercrop price by 20 %, 8) inter_price1.4 = increase in intercrop price by 40 %; 9) inter_lab85_leg = increase labor costs for intercrops by €85/ha including legumes; 10) inter_lab170_leg = increase labor costs for intercrops by €170/ha including legumes. Peas-Oats 15 %: pea-oat intercrops containing 15 % of oats in the seed mixture.

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

	Winter wheat		Malting barley		Oats		Oilseed		Peas-oat15		Faba bean		Peas		
	N	Yield	N	Yield	N	Yield	N	Yield	N	Yield	N	Yield	N	Yield	Tot N
Baseline	146	4.94	82	3.70	93	4.31	81	1.35	–	–	–	–	–	–	403
Insert_interc	140	5.00	86	4.01	68	4.06	84	1.45	34	2.55	–	–	–	–	411
interc labor_85	144	5.08	85	3.92	69	4.07	84	1.44	35	2.67	–	–	–	–	417
interc_labor_170	147	5.07	77	3.55	66	4.09	84	1.43	38	3.10	–	–	–	–	411
interc_labor_cut	148	5.01	82	3.67	93	4.32	84	1.41	–	–	–	–	–	–	406
inter_price1.1	144	5.06	86	3.95	64	3.93	84	1.45	36	2.53	–	–	–	–	413
inter_price1.2	143	5.00	86	3.99	64	3.90	80	1.41	36	2.45	–	–	–	–	409
inter_price1.4	138	4.96	79	3.69	66	4.15	78	1.36	38	2.63	–	–	–	–	399
inter_lab85_leg	132	5.20	78	4.35	68	4.10	78	1.60	38	3.08	30	3.43	26	1.87	448
inter_lab170_leg	128	5.22	–	–	70	4.41	85	1.65	32	2.62	30	3.47	28	1.97	373

1)Baseline; 2) Insert_interc = insert intercrops; 3) interc_labor_85 = increase labor costs for intercrops by €85; 4) interc_labor_170 = increase labor costs for intercrops by €170; 5) interc_labor_cut = the cutoff point at which the intercrop becomes unprofitable; 6) inter_price1.1 = increase in intercrop price by 10 %; 7) inter_price1.2 = increase in intercrop price by 20 %, 8) inter_price1.4 = increase in intercrop price by 40 %; 9) inter_lab85_leg = increase labor costs for intercrops by €85 including legumes; 10) inter_lab170_leg = increase labor costs for intercrops by €170 including legumes.

Table 5
Average annual N fertiliser (kg) per crop production (ton) over thirty years.

	WWheat	MBarley	Oats	Oilseed	peas_oat15	Fababean	peas	tot N
	N kg/t	N kg/t	N kg/t	N kg/t	N kg/t	N kg/t	N kg/t	kg/t
Baseline	30	22	22	60	–	–	–	134
insert interc	28	21	17	58	13	–	–	137
interc labor_85	28	22	17	58	13	–	–	138
interc_labor_170	29	22	16	58	12	–	–	137
interc_labor_cut	30	22	22	59	–	–	–	133
inter_price1.1	28	22	16	58	14	–	–	138
inter_price1.2	29	21	16	57	15	–	–	138
inter_price1.4	28	21	16	57	15	–	–	137
inter_lab85_Faba	25	18	17	48	12	9	14	143
inter_lab170_Faba	25	–	16	52	12	8	14	127

1)Baseline; 2) Insert_interc = insert intercrops; 3) interc_labor_85 = increase labor costs for intercrops by €85; 4) interc_labor_170 = increase labor costs for intercrops by €170; 5) interc_labor_cut = the cutoff point at which the intercrop becomes unprofitable; 6) inter_price1.1 = increase in intercrop price by 10 %; 7) inter_price1.2 = increase in intercrop price by 20 %, 8) inter_price1.4 = increase in intercrop price by 40 %; 9) inter_lab85_leg = increase labor costs for intercrops by €85 including legumes; 10) inter_lab170_leg = increase labor costs for intercrops by €170 including legumes.

4. Discussion

This study focused on a topical issue of intercropping as a means to improve profitability and sustainability of farming in Finland. While mixtures are commonly used in grasslands in the northern agriculture [65], they are less frequently used in arable crops. To support the transition to more sustainable farming [66], it is important to understand the potential economic benefits of intercropping. Highlighting these benefits can make the adoption of intercropping practices more appealing to farmers and encourage them to search for management solutions to potential barriers for adoption. The simulation results if this study indicate that despite an increase in labor costs associated with intercropping, the introduction of cereals-legumes intercropping led to an increase in Net Present Value (NPV). This increase is attributed to the efficient utilization of resources and higher yields compared to sole crops of oats and peas (Table 2).

Notably, the model would necessitate a 260 % increase in intercrop labor costs to entirely exclude them from the crop rotation. This scenario, *interc_labor_cut*, highlights that intercrop labor costs need to be significantly high for them to become suboptimal to cultivate. A farmer could offset intercropping labor costs by cultivating grain legumes as sole crops, because they are very profitable. Through crop diversity the farmer becomes more resilient to price fluctuations, changes in market demand for a certain crop, as well as weather variability.

Incorporating intercropping into the cropping system, as demonstrated in the Insert_interc scenario, reduced slightly the N input per crop production for all crops. This reduction is appealing to farmers because it allows them to decrease production costs and reduce dependence on external inputs. Reduced N fertilizer use through intercropping can also bring additional positive sustainability impacts to society, such as decreased N leaching into waterways, reduced GHG emissions, and lower energy consumption [67]. However, farmers face a number of obstacles such as the investment costs associated with purchasing compatible cultivars of peas and oats for intercropping, as well as additional costs associated with sowing, harvesting, sorting and storage of the mixture [34]. Sorting, however, may not be necessary if the mixture is to be used as animal feed [31], e.g., in pig farms. Although intercropping systems have been known and performed for decades, farmers would still benefit from precise instructions for use of intercrops, market acceptance of intercrop yields and development of mixture products.

An important result of this study is that if cereal farmers add faba beans and peas more often also as sole crops in their rotations, this could significantly increase their economic gains. This potential for increased profitability is contingent on factors such as crop yield risks of legumes as sole crops compared to the yield risks of intercropped legumes, soil suitability, farming system, farm type, and favorable market access for peas and faba beans. Another important result is that oat-pea intercropping provides significant economic gains as well, even in the case of higher variable costs such as labour. Oat-pea intercropping, already cultivated in low land areas in many parts of the country, is more likely to be feasible for farms throughout the country when compared to faba beans which is more demanding in terms of soil, crop protection and water availability.

Pig and poultry farms, in Finland, have traditionally relied on imported protein feeds, particularly soya, as domestic protein crops have

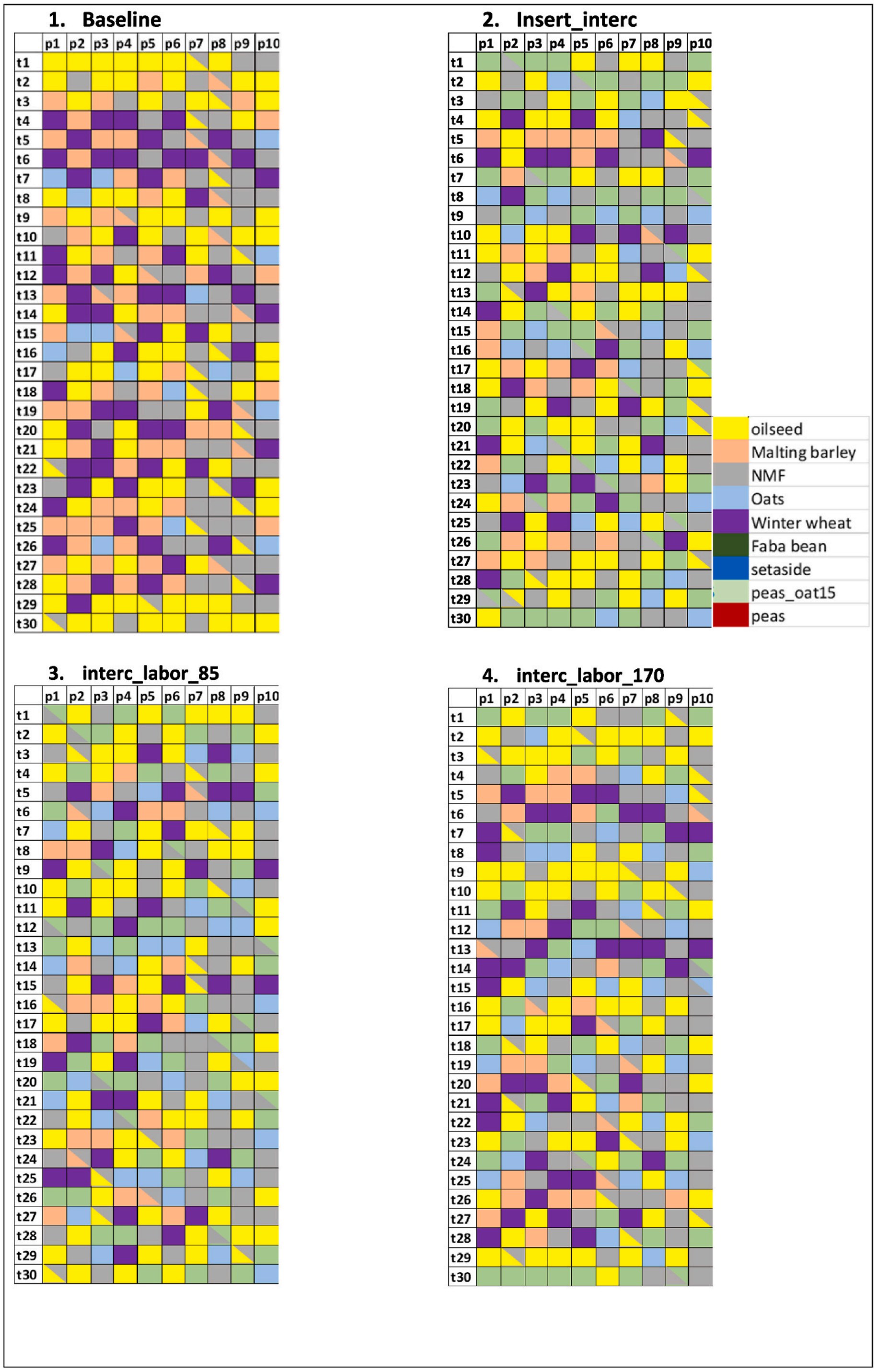

Fig. 3. Optimal crop rotations on 10 parcels, *p*, for 30 years, *t*, across all scenarios.
1)Baseline; 2) Insert_interc = insert intercrops; 3) interc_labor_85 = increase labor costs for intercrops by €85; 4) interc_labor_170 = increase labor costs for intercrops by €170; 5) interc_labor_cut = the cutoff point at which the intercrop becomes unprofitable; 6) inter_price1.1 = increase in intercrop price by 10 %; 7) inter_price1.2 = increase in intercrop price by 20 %, 8) inter_price1.4 = increase in intercrop price by 40 %; 9) inter_lab85_leg = increase labor costs for intercrops by €85 including legumes; 10) inter_lab170_leg = increase labor costs for intercrops by €170 including legumes.

been less prominent. Therefore, including cereal-grain legume intercropping as well as legumes as sole crops could reduce farmers' dependence on imported protein feeds. Several adoption incentives for farmers identified by Fares and Mamine [34] include market incentives as they may increase the value of the cereal-legume mix quality.

The findings of the current study showed that increasing intercrops' price could lead to an increase in profits from 12 % to 32 % which is consistent with the findings of Fares and Mamine [34]. Moreover, peas cultivated as sole crops exhibit high variation in yield and quality at high latitudes, with both abiotic and biotic constraints negatively impacting yield stability (Peltonen-Sanio et al., 2017). Hence, intercropping with cereals is often a feasible strategy to enhance yield stability in peas and reduce yield risks by preventing lodging [64,68] and reducing pest and disease outbreaks [69]. This is especially true when the cultivation areas

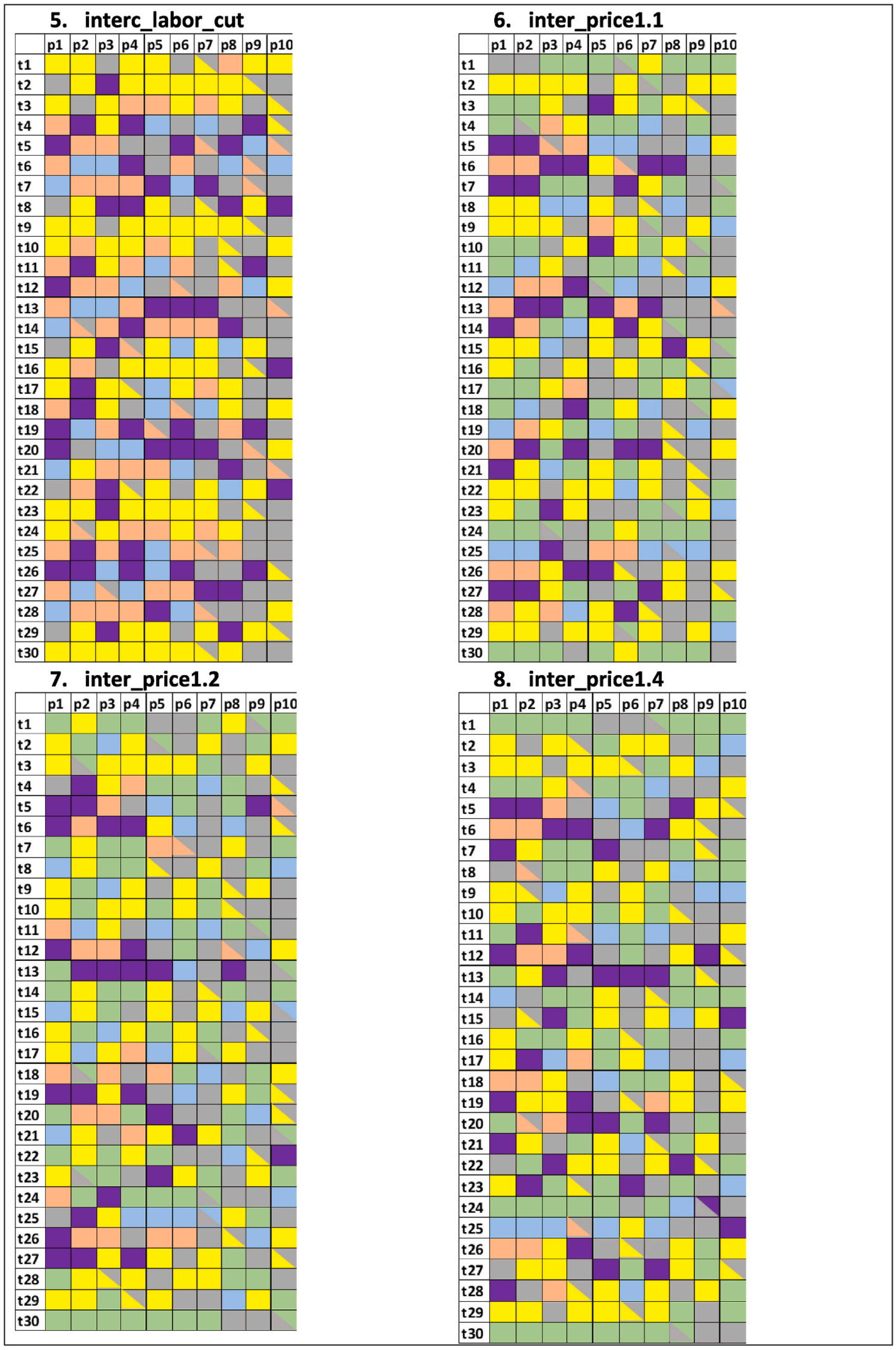

Fig. 3. (*continued*).

of peas are substantial in a particular production region [70].

5. Conclusions

A dynamic optimization model was used to analyze the long-term economic benefits and production effects of introducing pea-oat intercropping in cereal crop rotations at the farm level. The results indicate that intercropping increases farmer's NPV by reducing costs associated with N fertilization and increasing yields of various crops. Including faba beans and peas as sole crops raises profits by 37 %, driven by favorable faba bean prices and positive legume pre-crop effects. Despite higher labor costs, intercrops remain economically viable to be included in crop rotation.

Intercropping reduces the need for N fertilizer while increasing yields for wheat, barley, and oilseeds. Higher intercrop prices, driven by increased protein content and improved grain quality, further enhance profitability and incentivize their adoption by farmers. Regarding land allocation, intercropping leads to various changes in land use allocation. Winter wheat and barley land use shares are reallocated to intercrops, with oats' land use share increasing due to positive intercrop legacy effects. Overall, integrating intercropping, and legumes as a single crop, into the crop rotation has the potential to increase farmer profitability, cropping diversity and optimize land use, while also reducing fertilizer application and enhancing crop yields and yield stability. Intercropping is thus a suitable mean for sustainable farming also in northern conditions.

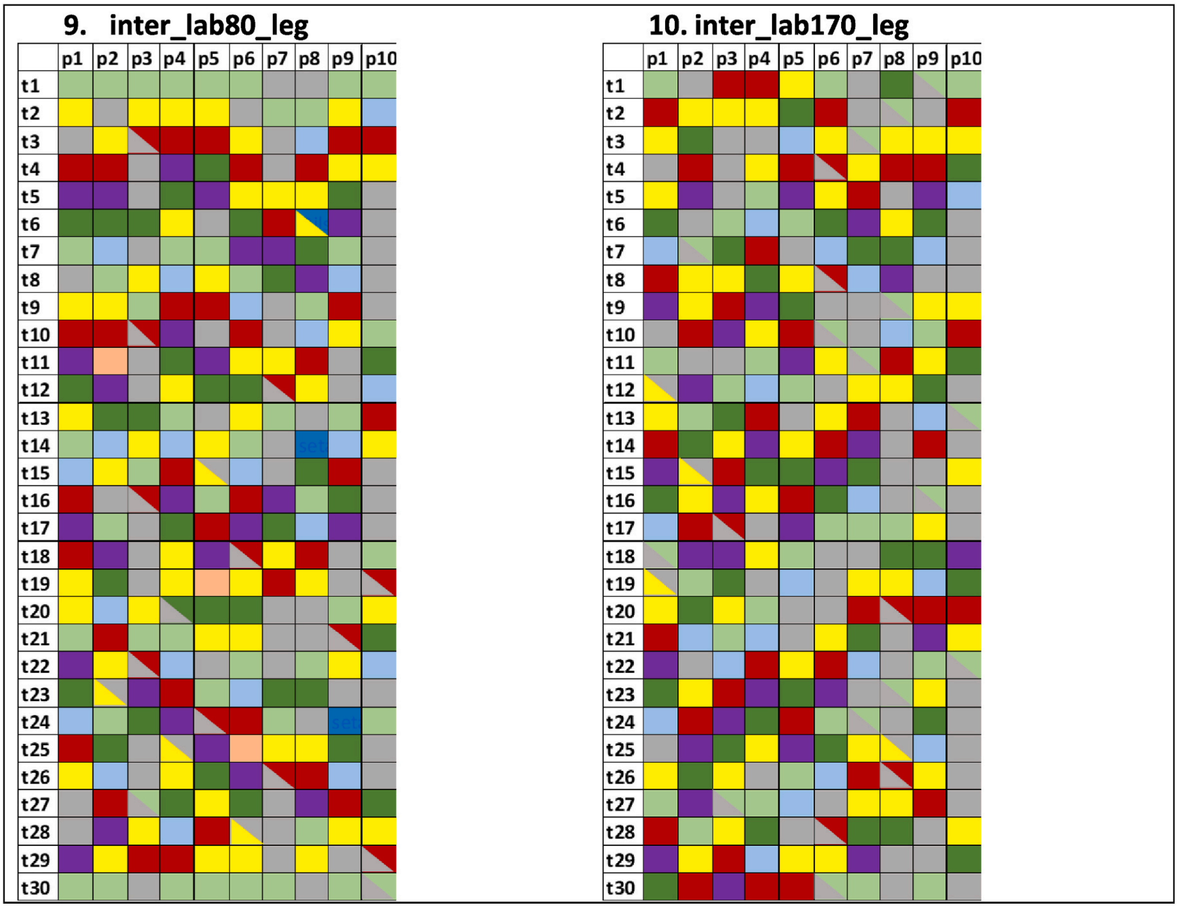

Fig. 3. (*continued*).

The adoption of intercropping practices might be accelerated through supportive policies, such as strengthen agricultural extension services to provide training and technical support to farmers on intercropping techniques. Developing the market for pea-oat intercropping could also contribute to the wider acceptance of intercropping by facilitating connections between farmers, processors, and retailers to create a robust supply chain for intercropped products.

It is worth noting some limitations of this approach based on optimization modelling of a study farm. The current implementation does not account for the long-term impacts of intercrops on soil and the consequent positive effects on crop yields [71] due to lack of sufficient data from the local conditions. The focus was solely on short-term yield effects between crops based on satellite data [62]. Based on this limitation, future research could focus on quantifying long-term soil and yield specific effects considering that the dynamic optimization approach applied utilizes long-term farm level management and economic impacts. Reliable analysis would require additional empirical research to estimate the long-term legacy effects of cereal-grain legumes intercrops, considering improved soil status and crop yields over extended periods, such as 15–30 years.

Another limitation is the absence of data related to the accurate costs of harvesting, sorting and storing of mixtures from intercropping as well as the market price of mix yields. This limitation was partly handled within this study with the sensitivity assessments that covered different cost levels for intercropping. Future research could focus on additional field experiments and data collection, which would improve the accuracy of the economic analysis.

CRediT authorship contribution statement

Domna Tzemi: Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Pirjo Peltonen-Sainio:** Writing – review & editing, Resources. **Taru Palosuo:** Writing – review & editing, Funding acquisition. **Janne Rämö:** Writing – review & editing, Methodology, Data curation. **Heikki Lehtonen:** Writing – review & editing, Supervision, Methodology, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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