AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2024) 33: 268–279

https://doi.org/10.23986/afsci.145642

Trade-offs between carbon conservation and profitability in crop cultivation: unlocking potential through diversifying crop allocations regionally

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Adjusting crop rotation is a key agricultural strategy to boost variable profit, enhance soil fertility, adapt to climate change, and mitigate farming risks. The aim of this paper is to assess the opportunities for simultaneously enhancing carbon balance and variable profit of crop cultivation through altering the allocation of crop use in regional scale. Using a numerical optimization model for mineral soils in southern Finland, results show that careful diversifying of crop cultivation can enhance both carbon balance and profit compared to current allocation. Including the life-cycle carbon footprint of nitrogen fertilizers further increases potential gains. Variable profit can rise by 75–207 € ha^{-1} $year^{-1}$, while carbon balance improves by 70–336 kg C ha^{-1} $year^{-1}$, depending on the weighting of economic and climate outcomes. Changes can be made without significantly increasing fixed costs of cultivation. Optimal strategies include reducing spring crops and fodder grass while increasing nitrogen-fixing grasses and high-profit crops like clover grass, green manure, potato, and sugar beet. Sensitivity analysis highlighted the importance of higher yields for enhanced outcomes, emphasizing the need to enhance forage grass, clover grass, and green manure yields for carbon balance and forage grass, potato, sugar beet, and spring crop yields for increased variable profit. Investments in infrastructure, marketing, and innovative food products are essential to promote local crop diversity and incentivize farmers to utilize and test new crops on a farm.

Key words: diversifying crop production, crop rotations, linear programming, optimization, regional analysis

Introduction

Yield-related uncertainties of farming are expected to increase due to climate change (Rötter et al. 2012). In the northern latitudes, the growing season will be longer and temperatures higher. Periods of droughts and extreme rains will be more common, and they may occur at unexpected times of the year. Also, pest damages and plant diseases will likely to be more common. These developments may lead to either decreasing or increasing yields (Anderson et al. 2020, Marini et al. 2020).

Crop rotation is a traditional agronomic practice, where plants are repeated on the field after one another (Dury et al. 2011). The applied crop rotations also determine the shares of different crops out of the total arable land at landscape and regional levels. Careful planning of crop rotations can create multiple benefits including improved soil fertility (Volsi et al. 2022), fewer yield related risks (Angus et al. 2015) and reduced fertilizer usage (Rodriguez et al. 2021). Altering crop rotations is one of the main tools to adjust and to enhance local food production in the changing climate (Degani et al. 2019). Changes in crop rotations can be also one tool to either reduce the greenhouse gas emission of agriculture or to enhance accumulation of carbon in agricultural soil and thus contribute to the mitigation of climate change (Garbelini et al. 2022, Liu et al. 2022).

Fertilizers are estimated to contribute to 38% of agricultural greenhouse gas emissions (IPCC 2006), including nitrous oxide (N_2O), which is a potent greenhouse gas, approximately 273 times stronger than carbon dioxide (CO_2) (IPCC 2021). Artificial nitrogen fertilizer manufacturing causes life cycle emissions via energy intensive manufacturing process (Soumare et al. 2020), and after its application on to the fields soil N_2O -emissions increase (Chen et al. 2008). Earlier studies (Hasler et al. 2015) have shown that optimizing fertilizer use may decrease the climate impact of cultivation by up to 20% when compared to the worst alternative practices. It has also been shown that by diversifying cultivation with nitrogen fixing legumes (Rodriguez et al. 2021) artificial nitrogen fertilization usage can be reduced, decreasing field management related greenhouse gas emissions (Ito et al. 2018).

Received 13 May 2024 / Accepted 5 December 2024
The Scientific Agricultural Society of Finland

Several field-level simulation studies have demonstrated how carefully diversified crop rotations, adapted to changes in environmental factors or economic conditions, can significantly increase profitability compared to conventional crop rotations. Hunt et al. (2020) showed that diversified crop rotations from conventional 2- year corn-soybean to 4-year corn-soybean-oat/alfalfa-alfalfa systems enhanced profitability via increased crop yields by 4 to 30% due to decreased occurrence of crop diseases. Jalli et al. (2021) showed that diversification from monoculture to a 4-year rotation increased spring wheat yields by 30% (no-tillage) or 13% (ploughing) and decreased leaf blotch disease by 20%, decreasing production risk and environment related uncertainties, especially if rotations included cereals, oil-seeds, and legumes. Smith et al. (2018) studied 14 cropping systems over five years, which revealed that diversified crop rotations were in minimum as profitable as monoculture farming due to reduced herbicide usage. Profitability between the two was also dependent on location and varying weather conditions rather than the field management system. Global meta-analysis by Sánchez et al. (2022) revealed via hundreds of field simulations that despite the increased variable costs, diversified crop rotations were more profitable in comparison to simplified systems with only less than three species in a farm's rotation. Variable profit increased especially if high-value crops were added into the rotation, even if it would have affected original crop's yields negatively.

Several previous studies have explored the potential for carbon conservation through alterations in crop rotations. Heikkinen et al. (2022) found perennial-dominated and grass-lining rotations sequestrated 128–241 kg C ha^{-1} yr^{-1} more C into the soil in comparison with monoculture and annual crop-dominated rotations due to reduced soil management and increased C input to the soil. In addition to increased variable profit Hunt et al. (2020) found that diversification reduced life cycle greenhouse gas emissions by 42 to 57 % mainly because of reduced nitrogen fertilization requirements. King and Blesh (2018) found that including cover crops and perennial crops into rotations increased soil organic C input by up to 42% via an average of 168 cropping systems. Also, West and Post (2002) found rotation diversification within no-till systems sequestered in average of 200±120 kg C ha^{-1} yr^{-1} more annually into the soil in comparison to monoculture based on global database consisting of 276 paired treatments. The reason for increased soil organic C was not specified in the study, but reduced soil erosion and increased residue input via diversification was discussed. Lötjönen and Ollikainen (2017) found via 5-year analytical rotation optimization model, that crop rotations with legumes were always more beneficial in comparison to spring crop monoculture farming since variable profit increased from 262–358 € ha^{-1} yr^{-1} to 260–536 € ha^{-1} yr^{-1} due to increased yields and decreased fertilization requirements, while assuming that legumes had efficient prices. Simultaneously with increased variable profit, optimal crop rotation reduced carbon (C) emissions by 192–214 kg C ha^{-1} yr^{-1} more than monoculture farming, mainly due to decreased fertilizer use.

Previous studies have demonstrated that careful planning of crop rotations holds significant potential for increasing variable profit on a farm while simultaneously reducing the climate impact of cultivation. However, despite extensive research on alternative rotations at the field level, a comprehensive understanding of sustainable land division at larger spatial areas and regionally remains unclear. Regional assessments would assist farmers and policymakers in making informed decisions about ecologically and economically viable crop choices. This involves aligning with regional market demands while considering the climate impact of arable allocations on a regional scale.

The objective of this study is to calculate potential improvements in carbon balance and variable profit by altering crop allocations at a regional level. We developed an optimization model for comparing and identifying efficient crop allocations in mineral soils in southern Finland. The model balances the two objectives: contribution of crop cultivation on mitigation of climate change including carbon sequestration in agricultural soil and greenhouse gas emissions from nitrogen fertilizer and farmers' private variable profit. As far as we know, the potential benefits of modified crop rotations haven't been simultaneously studied at regional levels in Northern Europe with a focus on optimizing both economic and climate outcomes of crop cultivation.

Materials and methods

Model for balancing variable profit and climate impacts of crop cultivation

The management problem is formulated from the point of view of a social planner. The management problem is a multi-objective linear programming problem optimizing the allocation (%) of arable land x_n across n= 1…12 crop categories (Table 1). The objective is to maximize the weighted sum of annual average variable profit P (€ ha^{-1} yr^{-1}) and annual change in soil carbon stock (kg C ha^{-1} yr^{-1}) of agricultural fields at the case study area:

Table 1. Crop category specific parameters. C balance represented does not include the life cycle emissions of inorganic N fertilizers.

Plant (n)	Market price, (p_n € kg^{-1})	Baseline yield, y_n (kg^{-1} ha^{-1})[5]	Subsidies, s_n(€/ha^{-1} yr^{-1})[6]	Other variable costs, V_n(€ ha^{-1} yr^{-1})[4]	Fertilization, l_n(kg N ha^{-1})[4]	C balance, C_n(kg C ha^{-1} yr^{-1})	Nitrogen balance, N_{soil}(kg N ha^{-1})
Spring crops	0.22[1]	3600	450	748	90	-439	-63
Spring rape	0.47[1]	1300	570	660	90	-471	-53
Winter wheat	0.22[1]	4400	450	772	90	-147	-74
Rye	0.20[1]	3900	450	759	90	-21	-53
Winter rape	0.47[1]	1700	570	605	90	136	-70
Broad bean/ Pea	0.28[2]	2500	570	745	50	-372	35
Potato/ Sugar beet	0.20[1]	32600	400	1177	90	-509	-96
Cumin	0.91[3]	900	556	497	90	513	-25
Green manure[4]	[4]	6000	485	120	0	693	182
Clover grass	0.12[4]	8000	450	380	0	964	25
Fodder grass	0.12[4]	10000	450	1007	190	160	-14
Nature management field[7]	[4]	6000	470	120	0	731	94

[1]Average price data in AB-subsidy zone (Statistics Finland 2023b); [2]Finnish retailer in Agriculture (Hankkija 2023); [3](National Land Survey of Finland 2021); [4]Green manure and nature management field prices are according to Mattila and Rajala (2023) and clover grass and forage grass prices are according to National Land Survey of Finland (2022); [5]Yield per crop data is based on average regional yield data (Statistics Finland 2023b) and green manure, clover grass and nature management field yields are based on Mattila and Rajala (2024); [6]Subsidies (€ ha^{-1} yr^{-1}) include the basic subsidy and high latitude subsidy which are the same for all crops, special crop subsidies which are for spring and winter rapes, potato/sugar beet and broad bean/pea, and finally environment and eco subsidies which vary slightly among the crops. (Finnish Food Authority 2023); [7]Nature management field category was formed by combining profit data linked to green manure alongside specific subsidies for Nature management field. Additionally, data on C and nitrogen balance from clover grass was included, excluding considerations related to harvest and manure.

$$\max_{\{x_1,\ldots,x_n\}} z = \alpha P + (1-\alpha)C \tag{1}$$

Parameter α describes the relative weight of two objectives. Average variable profit and carbon accumulation in soil are:

$$P = \sum_{n=1}^{n} x_n P_n \tag{2}$$

$$C = \sum_{n=1}^{n} x_n C_n \tag{3}$$

Upper and lower bounds determined for each crop category reflect the ranges of outcomes that would not require major structural changes in Finnish agriculture and food sector:

$$B_n^l < x_n < B_n^u \tag{4}$$

A constraint is set to safeguard that all land is allocated between the available crop categories:

$$\sum_{n=1}^{12} x_n = 1 \tag{5}$$

Variable profit per crop (€ ha^{-1} yr^{-1}) is defined:

$$P_n = y_n p_n + s_n - c\left(l_n - N_{soil,n}\right) - V_n \tag{6}$$

where y_n denotes average yield per crop (kg ha^{-1}), p_n is crop market price (€ kg^{-1}), s_n is lump-sum agricultural support (€ ha^{-1} yr^{-1}), c is the cost of nitrogen fertilizer (€ kg^{-1} N), l_n is the crop-specific fertilizer requirement (kg N/ha^{-1}), $N_{soil,n}$ denotes the nitrogen surplus in soil (+/- kg N ha^{-1}) and V_n (€ ha^{-1} yr^{-1}) consists other variable costs (€ ha^{-1} yr^{-1}) of crop cultivation. Nitrogen balance $N_{soil,n}$ is determined by:

$$N_{soil,n} = N_{in\,n} - N_{off\,n} + f_n N_{off\,n} \delta(1-\gamma) \quad (7)$$

A portion of the nitrogen remains in the soil and plant residues, and part is removed by crop removal. N balance (kg N ha^{-1}) consists of N intake $N_{in\,n}$ from crops, lost N $N_{off\,n}$ and N intake from manure. N-fixing plants can create a positive N balance while other crops form a negative balance. A proportion δ of yield returns as N and a proportion γ of yield is lost during storage. Parameter f_n (%) describes the amount used as animal feed from the yield. N input from manure accounts for a 10 % loss during storage and assumes that 70 % of the remaining yield is returned as N to the field. However, factors such as the specific method of manure application are not incorporated into these calculations.

The computations are repeated for two options: option 1 considers the carbon balance of soil only, while option 2 accounts for both changes in the carbon stock in soil and the greenhouse gas emission from production and application of nitrogen fertilizer.

Variable costs per crop (€ ha^{-1} yr^{-1}) consists of costs of seeds a_n, lime application b_n, pesticides c_n, tractor work d_n, freight and storage e_n and drying h_n:

$$V_n = a_n + b_n + c_n + d_n + e_n + h_n \quad (8)$$

Fixed costs associated with machinery and farm infrastructure are not accounted for in the computation as they do not have impact on optimal solutions.

Soil C balance is dependent on the balance between the soil respiration and the biomass C input to soil. Adding plant residue and manure into the fields can enhance soil C contents while soil and plant respiration let CO_2 back into the atmosphere. Average soil C balance function per crop (kg C ha^{-1} yr^{-1}) accumulates according to the equation:

$$C_n = y_n\left(F_{p,n} + F_{m,n}\right) - L + (\varepsilon + \lambda)(N_{soil,n} - l) \quad (9)$$

Equation (9) is defined by plant specific C intakes from plant residues $F_{p,n}$ and manure $F_{m,n}$, which both increase among field productivity y_n (kg ha^{-1}), and C loss via soil respiration L.

N fertilizer life cycle emissions consider carbon emissions from manufacturing ε (C kg/N kg) and nitrous oxide emissions per added N fertilizer on the field λ (C kg/N kg). Fertilization requirement l is affected by N balance $N_{soil,n}$ (+/- kg N ha^{-1} yr^{-1}). When N balance is positive, less fertilization is needed for the next period leading to lower emissions. The assumption is a simplification, since some part of N in the soil may be lost after harvest during autumn, winter, and spring before the next sowing due to leaching and runoff influenced by factors such as rainfall, temperature, and soil structure.

C input from plant leftovers $F_{p,n}$ (kg C ha^{-1} yr^{-1}) is described as function:

$$F_{p,n} = \mu h_n k_n \quad (10)$$

Plant residues left on the field will partly turn into soil organic matter and be restored as soil organic C, while some of the residues will be released into the atmosphere. Function (10) is affected by humification coefficient h_n (%) which reflects crop decomposition rate. Value μ (%) stands for C content in crop residues and value k_n (%) is an expansion factor which converts crop roots input to soil C. C input from manure $F_{m,n}$ (kg C ha^{-1} yr^{-1}) considers function:

$$F_{m,n} = f_n(1 - d_n)\mu H(1 - \gamma) \quad (11)$$

Parameter f_n (%) describes the crop yield used as animal feed, d_n (%) the digestibility per plant in an animal's stomach (i.e., how much is respired), μ (%) for manure humification, and γ (%) yield lost during storage. Bare land soil respiration L (kg C ha^{-1} yr^{-1}) is based on soil quality parameters:

$$L = \beta \times \theta \times \rho \times \vartheta \times \tau \times \varphi \times \sigma \quad (12)$$

Soil respiration is caused by cellular respiration process, caused by organisms' biological activity depending on soil C storage size and clay content. Soil respiration is assumed to be the same for all crops, in addition to conventional ploughing. Function (12) considers proportion of organic soil β (%) (moldability), C content in organic matter θ (%), decomposition rate ρ (%), soil volume ϑ (m^3), density τ (tn/m^3), and the soil's humus degradation rate φ (%). Clay content is explained via clay correction factor σ (%) which is explained by soil clay content.

Data

The description of farm variable profit and carbon flows in (6)–(12) are based on crop rotation calculator developed by (Mattila and Rajala 2024) for farmers allowing them to simulate the economic and environmental consequences of alternative crop rotations. In this study, we extend their model to study crop allocations at a regional level. The case study area is the former AB subsidy area, now designated as support area III, and encompasses approximately 70.5% of Finland's cultivated land (Statistics Finland 2024). This area excludes the regions of South Savo, North Savo, North Karelia, Central Ostrobothnia, Lapland, Kainuu, and Northern Ostrobothnia (Ministry of Economic affairs and Employment of Finland 2024).

In this region the lump-sum agricultural support for crop cultivation in arable lands is the same, for more details see Finnish Food Authority (2023). We account only for the mineral arable lands in the subsidy zone which includes around 900 000 ha. We exclude areas that are currently under green fallow and perennial grasses (grasses older than 5 years) and smaller crop categories including vegetables and garden plants. Dry hay, fodder grass, silage, pasture, and mixed grain were combined into forage grass crop category.

Crop-specific parameters for variable profit and C balance are described in Tables 1 and 2. Other variable costs V_n, fertilization levels per crop I_n (kg N ha^{-1}), and nitrogen balance $F_{m,n}$ are directly from Mattila and Rajala (2023) and are detailed in appendixes 1 and 2. All crops in the model were assumed to be cultivated by conventional methodologies regarding ploughing, seeding, pest control and application of N fertilizer. For the calculations, only clover grass and forage grass were considered for animal feed contributing to C input as manure denoted as .

Table 2. Other parameters

Parameter meaning	Symbol and unit	Value	Data source
Feed returns as nitrogen[1,2]	%	70	Mattila and Rajala 2023
Yield used as animal feed[1,2]	%	80*	
Manure humification[1]	%	30	
Clay correction factor	%	30	Xu et al. 2015
Soil volume	m^3	2000	Heinonsalo et al. 2020
Soil density[1]	tn/m^3	1.2	Mattila and Rajala 2023, for comparison Heinonsalo et al. 2020 use 1.3
Decomposition rate	%	1	Akujärvi et al. 2014
Yield lost during storage[1,2]	%	10	Luostarinen et al. 2017
Digestibility[1,2]	%	70*	
C content of plant leftovers[3]	%	45	Statistics Finland 2023a
C content in organic matter[1]	%	58	
Organic soil[1,4]	%	6	Lemola et al. 2018
Humus degradation rate[1,5]	%	1	Akujärvi et al. 2014
C emissions per produced fertilizer[6]	kg C kg^{-1} N	1.06	Yara 2020, IPCC 2006
Nitrous oxide emissions per added fertilizer[7]	λ kg C kg^{-1} N	1.17	IPCC 2006, IPCC 2021
Fertilization cost inc. delivery[8]	€ kg^{-1} N	2.2	Maatalouskauppa Iso-Karhu 2023

[1]Values are according to Mattila and Rajala (2024) crop rotation calculator's approximations. Clay content used is 30 %. Clay correlation factor is 100% when clay content reaches 20 %, which is a simplification and can have an impact on the result. [2]Approximates related to N intake from manure gets values only among clover grass and forage grass in this study. A significant part of spring crops cultivated in Finland is also utilized as feed, but that is not considered. [3]45 % is assumed for all crops based on Finland greenhouse gas inventory. [4]In South Finland (subsidy area AB), 85 % of arable soils are estimated to a moldability below 11.9 % (Lemola et al. 2018). We approximated an average moldability of 6%. [5]Indicating, approximately 1 % of the soil's humus content is degraded each year in Finland. [6]Industrial Haber–Bosch process is used in nitrogen fertilizer manufacturing to combine atmospheric nitrogen (N_2) with hydrogen (H_2), which requires vast amounts of fossil fuels (Soumare et al. 2020). Equation (11) estimates C emissions from increased or decreased N fertilization use (kg C ha^{-1} yr^{-1}). Multiplier 3.9 (kg CO2-eq kg^{-1} N fertilizer) can be used to estimate CO_2-emissions per produced amount in Finnish production based on a manufacturer's available data (Yara 2020). Emission in C (kg) is gained by dividing kg CO2-eq. with 3.67, based on the atom and molecule densities (IPCC 2021). Multipliers divided round up to 1.0636 (kg C kg^{-1} N). [7]1 % N_2O-N-emission is assumed per kg N fertilizer (IPCC 2006). Multiplier 44/28 is used to gain N_2O-emissions. This is multiplied by 273 to gain kg CO2 eq. kg^{-1} N_2O (IPCC 2021). C balance kg C kg^{-1} N_2O is gained by multiplier 3.67. [8]N fertilization cost is based on product YaraBela, which N content is 27%. *Same values for forage grass and clover grass.

The upper and lower bounds for crop categories (see Table 3) were based on climate scenarios for the agricultural sector (Lehtonen et al. 2020) and Finland's self-sufficiency targets (Natural Resources Institute Finland 2023), which served as a starting point for expert analysis. To refine these bounds, we consulted two experts in agriculture and rural business, who provided insights to define practical cultivation limits within the current economic context in southern Finland. Their insights contributed to defining feasible ranges for crop categories by focusing on the current available economic and logistical constraints. For this analysis, minimum and maximum shares of arable land under each crop category were defined such that it would not require major structural changes in agricultural production and infrastructure or disrupt the national food supply chain. Consequently, the model primarily yields boundary solutions, reflecting feasible ranges rather than precise, flexible responses to shifting market conditions. Interior solutions, which could offer more nuanced predictions, would require data on the price elasticity of demand. However, such data was not available. Future research might address this limitation by incorporating demand elasticity, enabling a more dynamic response to changing market signals.

Table 3. Current allocation of crops in the study area, and the lower and upper bounds by crop categories. Upper and lower bounds describe the potential maximum and minimum surface areas (%) in the current economic environment in southern Finland.

Plant (n)	Current allocation (%/100)[1]	Lower bound (%/100)[2]	Upper bound (%/100)[2]
Spring crops	0.516	0.34	0.80
Spring rape	0.021	0.02	0.05
Winter wheat	0.057	0	0.13
Rye	0.022	0	0.03
Winter rape	0.000	0	0.04
Broad bean/ Pea	0.035	0	0.09
Potato/ Sugar beet	0.017	0.007	0.023
Cumin	0.009	0	0.012
Green manure[3]	0.007	0	0.15
Clover grass	0.008	0	0.07
Fodder grass	0.227	0.05	0.25
Nature management field[3]	0.081	0	0.15

[1]Statistics Finland data (2023) based on AB subsidy zone areas (Finnish Food Authority 2023). [2]Based on expert analysis (ProAgria, June and October 2023), climate scenarios for agriculture sector (Lehtonen et al. 2020) and Finland's self-sufficiency rates (Natural Resources Institute Finland 2023). [3]Green manure and nature management field combined cannot form together more than 25 % of cultivated fields due to subsidy restrictions (Finnish Food Authority 2023).

Results

The average hectare-wise carbon balance and the profit under current allocation of arable land across crops in the study area are –79 kg C ha^{-1} yr^{-1} and 396 € ha^{-1} yr^{-1} (Fig. 1). A negative carbon balance indicates that arable fields are a source of greenhouse gas emissions. When the greenhouse gas emissions of nitrogen fertilization are accounted in the computation, the net impact of crop cultivation on climate change mitigation is currently clearly negative –154 kg C ha^{-1} yr^{-1} (Fig. 2). Negative N balance has also an effect on the profit which for option 2 is less than for option 1 being 322 € ha^{-1} yr^{-1}. Negative carbon balance is consequence of popularity of spring crops that are currently cultivated at 52 % of the arable fields in the case study area.

Optimizing crop allocations for different weights for variable profit and carbon balance resulted in optimal solutions that are characterized by production possibility frontier in Figures 1 and 2. The results imply that there are opportunities for improving both variable profit and the carbon balance of agriculture by adjusting crop cultivation on a regional scale. The potential increase in variable profit is 75–207 € ha^{-1} yr^{-1} and the potential improvements in carbon balance are in the range 70–336 kg C ha^{-1} yr^{-1} depending on the weight associated for economic and climate outcomes.

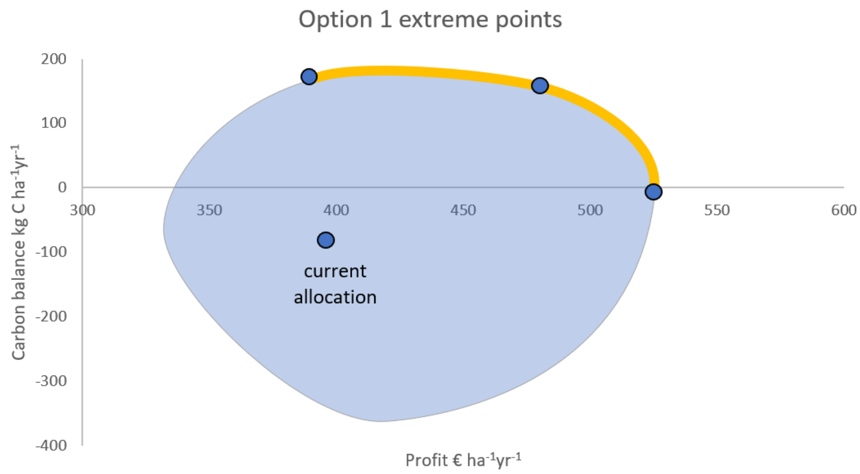

Fig. 1. Production possibility frontier, range of feasible solutions and variable profit and carbon balance under current crop allocation in the study area for option 1. The three marked points on the frontier represent optimal solutions for three problem formulations (a) C balance is emphasized over profit, (b) variable profit and carbon balance are weighed equally and (3) margin profit is emphasized over C balance.

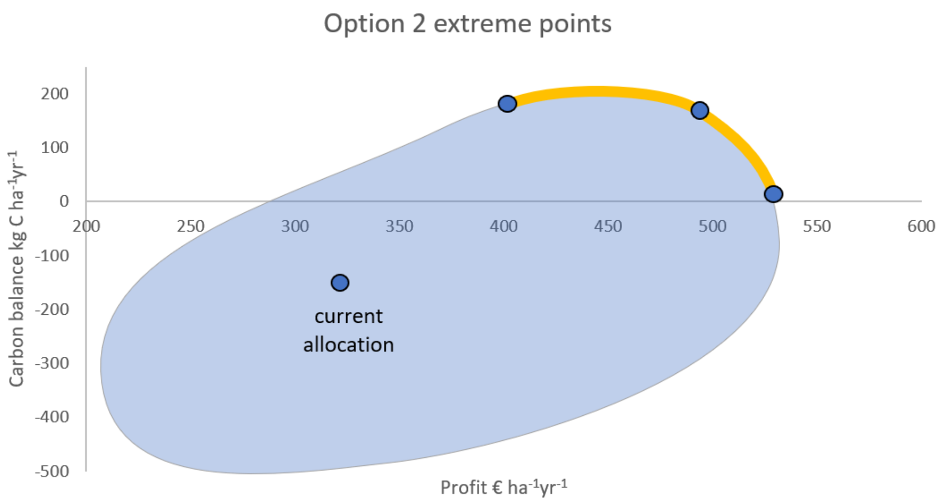

Fig. 2. Production possibilities frontier, range of feasible solutions and current variable profit and carbon balance for extended problem formulation (option 2) that includes the carbon emissions from fertilizer use.

Optimization suggested a need for diversified land allocation, especially within grass categories (see Table 4 for the distribution of crop categories). Currently, two dominant crop categories in Finland are spring crops and forage grass. In optimal solutions spring crops allocation decreased to the lowest bound due to lower variable profit and carbon balance in comparison to other crop categories. Economically optimal solutions emphasizing farmer variable profit are characterized by increased share of potato/ sugar beet, cumin, winter rape and broad bean/ pea, and winter wheat of arable land.

Table 4. Allocation of agricultural land among the 12 crop categories

	Spring crops	Spring rape	Winter wheat	Rye	Winter rape	Broad bean/ Pea	Potato/ Sugar beet	Cumin	Green manure	Clover grass	Fodder grass	Nature management field
1	51.6 %	2.1 %	5.7 %	2.2 %	0.0 %	3.5 %	1.7 %	0.9 %	0.7 %	0.8 %	22.7 %	8.1 %
2	34.0 %	2.0 %	2.1 %	3.0 %	0.0 %	0.0 %	0.7 %	1.2 %	12.5 %	7.0 %	25.0 %	12.5 %
3	34.0 %	2.0 %	0.0 %	0.0 %	3.5 %	0.0 %	2.3 %	1.2 %	12.5 %	7.0 %	25.0 %	12.5 %
4	34.0 %	2.0 %	0.0 %	0.0 %	0.0 %	3.5 %	2.3 %	1.2 %	12.5 %	7.0 %	25.0 %	12.5 %
5	34.0 %	2.0 %	13.0 %	0.0 %	4.0 %	9.0 %	2.3 %	1.2 %	12.5 %	7.0 %	5.0 %	10.0 %
6	34.0 %	2.0 %	10.5 %	0.0 %	4.0 %	9.0 %	2.3 %	1.2 %	12.5 %	7.0 %	5.0 %	12.5 %

1 = Current allocation; 2 = Optimal solution: maximized carbon balance; 3 = Optimal solution: C balance and variable profit are weighed equally (option 1); 4 = Optimal solution: C balance and variable profit are weighed equally (option 2); 5 = Optimal solution: maximized variable profit (option 1); 6 = Optimal solution: maximized variable profit (option 2)

In all optimal solutions, grass allocation — encompassing green manure, clover grass, forage grass, and nature management field — increased compared to the current allocation. The allocation of land for grasses increased as the weight assigned to climate impacts in the optimization process rose. While green manure and nature management fields do contribute to income, their favorable status is attributed to positive climate impacts, low variable costs, and relatively high subsidies. Allocation of land for clover grass hits the upper bound in all optimal solutions due to mutual positive impacts on economic and climate outcomes. Clover grass is a crop that does not require fertilization, and the yield can be harvested for feed and for sale. Forage grass allocation hits the upper bound in most optimal solutions due to high C balance and bounds set for other grasses.

We conducted a sensitivity analysis by first doubling the upper bounds for each crop (except for spring crops), one at a time. The analysis, while giving equal emphasis on both objectives, indicates that expanding the area for green manure and clover grass, would result in a substantial positive additive impact on the carbon balance while also having a relatively strong positive impact on profit. This effect is particularly notable in option 2 when accounting for the lifecycle carbon emissions of fertilizer. Expanding the upper bounds for potato and sugar beet areas had the most substantial adverse effect on the C balance. However, the C balance changed only a little (+4 or –6 kg C ha^{-1} yr^{-1}) while still having a strong positive impact on variable profit (126 or 111 € ha^{-1} yr^{-1}). This result can be attributed to the negative C balance of potatoes and sugar beets, coupled with their relatively high variable profit compared to other crops. In the analysis spring crop area was always at the minimum since its mutual enhancements for variable profit and C balance are lower in comparison to other crops.

We also performed a sensitivity analysis by examining the impact of a 20% yield increase. Analysis with equal emphasis on both objectives and uniform 20 % increase in yield led to significant increases in both C balance: 344 (+186 kg C yr^{-1}) and 352 kg C ha^{-1} yr^{-1} (+185 kg C yr^{-1}) increases for options 1 and 2, respectively, and increased variable profit by 186 € ha^{-1} yr^{-1}. Specifically, raising yields of forage grass, clover grass, and green manure would result in a significant increase in the C balance, while increasing yields of forage grass, potatoes, sugar beets, and spring crops would boost variable profit.

Discussion

This paper examines the trade-offs between farmers' private profits and the climate impacts of crop cultivation. Using a multi-objective optimization model, we calculated efficient crop allocation strategies for arable mineral soils in southern Finland under the current economic landscape, aiming to increase soil carbon sequestration, reduce greenhouse gas emissions from nitrogen fertilizers, and enhance profits by adjusting crop allocations. Our results suggest that slight adjustments in crop allocations in southern Finland can simultaneously improve economic and climate outcomes. Compared to current, the optimal solution, while giving equal weight to both goals from social planner's perspective, increased carbon balance by 236 or 321 kg C ha^{-1} yr^{-1} (options 1 and 2, respectively) and raised average profits by 84 or 173 € ha^{-1} yr^{-1} (options 1 and 2, respectively). These results assume that the changes in crop allocations can be reached through feasible adjustments to crop rotations and without substantial increases in fixed costs of cultivation.

Our results align with earlier research regarding the gains for both objectives although there are slight differences regarding the methodologies and limitations. West and Post (2002) found that rotation diversification increased carbon input into the soil, however they considered no-till systems whereas we assumed conventional ploughing. On a farm level optimization, Lötjönen and Ollikainen (2017) also found mutual improvements for climate and profits due to reduced fertilization use, including a few spring crop options and two legume options for the rotations. Also, Hunt et al. (2020) calculated that crop diversification decreases cropping systems life cycle greenhouse gas emissions due to reduced N fertilization requirements, but they did not include soil carbon stock changes in the calculations.

We found that improvements in carbon balance and profits were attained by diversifying grass allocation to high profit grasses (from fodder grass to other) and decreasing spring crop allocation by adding higher-profit crops' allocation. Similar observations regarding field use have been shown by Heikkinen et al. (2022) who found perennial-dominated and grass-lining rotations sequestrate more carbon into the soil in comparison with monoculture or annual crop-dominated rotations. King and Blesh (2018) estimated on a farm level that including cover crops and perennial crops into rotations increase soil organic carbon input. They included perennial crops only up to 30%, which is probably why our results gained better enhancements (our upper bound for perennial crops was 58.2% including all grasses and cumin).

In addition to adding grass allocation in southern Finland, our results promote adding higher profit crops into rotations. Sánchez et al. (2022) have estimated that incorporating high-profit crops will likely increase farm's profits even if the change would decrease the original crop's yields. On the other hand, diversifying carefully can also lead to increasing yields (Hunt et al. 2020, Jalli et al. 2021). We demonstrated via sensitivity analysis that theoretical yield increases of 20% would have major impacts on carbon balance and profits. In our calculations, the carbon balance was also particularly sensitive to higher grass yields and allocations, given their high carbon balance. Profits, on the other hand, were notably increased with higher yields of potato and sugar beet, clover grass and spring crops.

The main goal of our study was to understand how, and to what extent, monetary and climate benefits can be improved by adjusting the allocation of different crops at the regional level. However, we made several simplifying assumptions, which could be relaxed in future research by improvements and extensions to the model presented in this study. Firstly, we assumed uniform soil type in the study area, while there are wide variation of soil qualities and microclimates between the fields parcels in the study area. Moreover, not all crop rotations are feasible in all soil types and farms.

Second, adjusting crop selection on a farm may require investments in machinery or training, leading to additional costs not considered in this study. If additional investments are needed, potential gains in profits and carbon balance likely reduce. Larger farms are generally better positioned to diversify due to economies of scale, while smaller farms may struggle to cultivate a range of crops. Farm characteristics such as production type, size, and market orientation also influence rotation choices. For example, diversified rotations may be more feasible in poultry-farming areas than in regions dominated by dairy farms (Peltonen-Sainio et al. 2020). Key barriers to diversification include limited experience with alternative crops, lack of research-based best practices, access to appropriate machinery, and demand for less common crops. Farmers have also noted that inconsistent policies can hinder diversification (Rodriguez et al. 2021). Additionally, many farmers are risk-averse, favoring traditional methods over new ones, particularly when the economic benefits of diversification appear modest (Purola and Lehtonen 2020).

Third, the management problem is formulated as a static linear programming problem, which neglects any non-linearities in cost or yield functions. As a result, the optimal solutions generally align with either the lower or upper bounds for decision variables. Farmers have a practical interest in increasing soil carbon to maximize long-term profits, but such an analysis would require a dynamic model, which was beyond our scope. Instead, we assessed changes in average soil carbon and profit per hectare to estimate potential gains achievable through minor adjustments in crop production shares, focusing solely on these two objectives.

The modeling can be refined to produce more detailed results. For instance, computations could be expanded to cover various soil types and geographical regions, along with more specific crop categories or including discrete set of conventional crop rotations. This would yield more accurate estimates of the average carbon balance in mineral agricultural lands at the regional level. Additionally, incorporating other agricultural practices as decision variables, such as soil tillage (Jalli et al. 2021) or pre-crop effects, may further enhance climate impact outcomes. Also, more specific N balance estimations could be considered, since some part of N in the soil may be lost due to leaching and runoff influenced by factors such as rainfall, temperature, and soil structure (an average 15–18 kg N ha^{-1} loss was reported due leaching on Finnish soils (Salo et al. 2013). Furthermore, including carbon inputs from manure derived from diverse feed crops, in addition to fodder grasses and clover grass, could significantly augment carbon contributions to the fields. Also, a dynamic model incorporating market prices from the EU ETS and analyzing carbon retention at the field level could enhance future research beyond this study's static approach.

As a result of these assumptions, the numerical results on efficiency gains from optimized crop allocations may be over or underestimations. In addition, we recognize that the carbon stock of agricultural soils can't be increased infinitely. Recent research on Finnish agricultural fields estimates that the national soil surface is already rich in carbon. However, the intensively cultivated high clay soils in Southern and Southwestern Finland were found to have great potential in increasing surface soil carbon content (Soinne et al. 2023).

To conclude, this study demonstrates that carefully planned crop diversification can improve profitability and climate benefits of crop cultivation. A critical question for policy makers is to incentivize and make amendments in soil carbon economically feasible for farmers. EU agricultural policies are increasingly incentivizing climate-friendly practices, including subsidies for grass crops that promote soil health and diversity. Additionally, fostering local diversification with profitable crops will require new incentives, such as improved access to information on diverse crop rotation benefits and planning, reliable and predictable market signals, private sector support, and risk mitigation tools.

Acknowledgments

This research is one outcome of the HiiletIn project, funded by the Ministry of Agriculture and Forestry of Finland through the Catch the Carbon research and innovation programme. We extend our gratitude to Tuomas Mattila for providing valuable advice and feedback on an earlier version of the paper, and to Jukka Rajala for offering helpful comments regarding reservations and interpretations. Special thanks to Sari Peltonen, Juha Sohlo, and Marja Suutarila at ProAgria for their consultation and providing opportunities to present the results of this research to specialists and farmers. We also appreciate the support and important feedback from the audience of events in which earlier version of this work was presented.

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Appendix

Appendix 1. Variable costs (€ ha^{-1} yr^{-1}) itemized per plant according to crop rotation calculator by Mattila and Rajala (2024)

Plant (n)	seeds [1]	application of lime	pesticides	tractor work [2]	freight and storage [3]	drying [3]
Spring crops	70	20	60	180	53	53
Spring rape	6	20	90	200	23	23
Winter wheat	70	20	60	180	60	60
Rye	66	20	40	200	53	53
Winter rape	6	20	40	180	30	30
Broad bean/ Pea	114	20	90	200	90	45
Potato/ Sugar beet	300	20	200	180		180
Cumin	10	20	90	60	8	12
Green manure	60	0	0	60		
Clover grass	30	0	40	200	110	
Hey meadow	30	20	20	200	110	
Nature management field	60	0	0	60		

[1] Seed price is calculated according to crop market price (Table 1) + 100 € multiplied with assumed seed amount % tn^{-1} for all but grasses and potato/sugar beet categories. [2] Assumed working hours per plant multiplied with 20 € h^{-1} hourly wage. [3] Yield (kg ha^{-1}) multiplied with plant-based factor.

Appendix 2. Nitrogen intake, respiration and from manure, kg N ha^{-1} (Mattila and Rajala 2024)

Plant	Nitrogen lost via harvest[1]	Nitrogen intake via plant[2]	Nitrogen from manure[3]	Artificial nitrogen spread	Humification coefficient, (%)	Expansion factor, (%)
Spring crops	56	–	–	90	0.22	1.04
Spring rape	29	–	–	90	0.21	3.60
Winter wheat	76	–	–	90	0.21	1.57
Rye	59	–	–	90	0.23	1.87
Winter rape	91	–	–	90	0.21	3.60
Broad bean/ Pea	116	154	–	50	0.19	1.35
Potato/ Sugar beet	85	–	–	90	0.18	0.12
Cumin	23	–	–	90	0.32	12.50
Green manure	–	182	–	0	0.27	1.97
Clover grass	184	124	184*0.8*0.7*0.9=93	0	0.35	1.17
Hey meadow	114	43	114*0.8*0.7*0.9=57	190	0.34	0.82
Nature management field	–	124	–	0	0.30	2.50

[1] Yield (Table 1) multiplied with assumed nitrogen content (%). [2] Nitrogen lost via harvest affected by yield used for feed (80 %), nitrogen content of manure (70%) and yield lost during storage (10%)