



Economic optimization of sustainable soil management: a Dutch case study

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Abstract

Soil quality is pivotal for crop productivity and the environmental quality of agricultural ecosystems. Achieving sufficient yearly income and long-term farm continuity are key goals for farmers, making sustainable soil management an economic challenge. Existing bio-economic models often inadequately address soil quality. In this study, we apply the novel FARManalytics model, which integrates chemical, physical, and biological indicators of soil quality indicator, quantitative rules on how these indicators respond to farmers' production management over time, and an economic calculation framework that accurately calculates the contribution of production management decisions towards farm income. This is the first study applying this model on existing arable farms. FARManalytics optimizes crop rotation design, cover crops, manure and fertilizer application and crop residue management. Nine Dutch arable farms were analyzed with a high variation in farm size, soil type, and cultivated crops. First, we assessed farm differences in soil quality and farm economics. Second, we optimized production management to maximize farm income while meeting soil quality targets using farm-specific scenarios. Third, we explored the impact of recent policy measures to preserve water quality and to increase the contribution of local protein production. The results show that the case farms already perform well regarding soil quality, with 75% of the soil quality indicators above critical levels. The main soil quality bottlenecks are subsoil compaction and soil organic matter input. We show that even in front-runner farms, bio-economic modeling with FARManalytics substantially improves economic performance while increasing soil quality. We found that farm income could be increased by up to €704 ha⁻¹ year⁻¹ while meeting soil quality targets. Additionally, we show that to anticipate on stricter water quality regulation and market shift for protein crops, FARManalytics is able to provide alternative production management strategies that ensure the highest farm income while preserving soil quality for a set of heterogeneous farms.

Keywords Soil quality · Sustainable soil management · Farm economics · Scenario analysis · Mixed-Integer Linear Programming

1 Introduction

Soil quality is a major determinant of crop productivity, farm resilience, and environmental quality of agricultural ecosystems (Karlen et al. 1997; Kumar and Karthika 2020; Stevens 2018). Current unsustainable farming practices threaten soil quality worldwide (Koch et al. 2013). Subsoil compaction caused by heavy field traffic, loss of soil organic matter, acidification, decline of biodiversity, nutrient losses, and erosion are examples of such threats (Kumar and Karthika 2020; McBratney et al. 2014; Ros et al. 2022; Yang et al. 2020). Deteriorated chemical, physical, and biological soil functions will likely have an adverse impact on crop production in the long term. Changes in the climate, like increased occurrence of droughts and floods, and a growing world

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population may further add to these threats at global and regional levels, making it more challenging to achieve food security (Amundson et al. 2015; McBratney et al. 2014; Wall and Smit 2005).

Sustainable soil management has to overcome these threats by meeting present productivity needs without compromising soil quality for future generations (adapted from Smith and Powlson 2007). Various studies have shown that good soil management practices can boost soil quality and mitigate the adverse impact of agriculture on the environment. Examples include practices to increase soil organic matter (SOM), to minimize synthetic inputs, to reduce soil disturbance, to keep soil covered, and to diversify crops and crop rotations (Adetunji et al. 2020; Castellazzi et al. 2008; Silva et al. 2021). Given the long history of efforts to embed improved soil management measures into mainstream agriculture, there are abundant studies that deal with barriers that limit the adoption of sustainable soil management in agriculture. Currently, the implementation of sustainable soil management is not evident due to the following six key limiting factors.

- (1) Insufficient insights into the relationship between soil quality and farmers' production management, namely the complete set of physical and non-physical inputs made by the farmer (Brady et al. 2015; Kik 2021a). For example, soil compaction from field traffic is difficult to measure (Rücknagel et al. 2015) and its impact on crop yield and quality is not always clear.
- (2) Interactions among soil quality indicators (Bouma 2014; Stevens 2018). Trade-offs exist where improvement of one soil quality indicator might come at the expense of another. For example, cover crops have a beneficial impact on soil structure, SOM, and reduce nitrate leaching, but they might serve as a host crop for plant-parasitic nematodes, thereby reducing crop yield (Adetunji et al. 2020; Puissant et al. 2021).
- (3) Trade-offs between long-term soil quality (> 10 years) and annual farm income (Bos et al. 2017; Kik 2021a; Stevens 2022). Pressure on short-term profit resulting from current narrow crop margins makes it difficult to invest in long-term soil quality, in particular when farmers do not own the fields they cultivate (Stevens 2022). Potential gains from increased soil quality are uncertain and typically manifest in the long term. For example, a higher organic matter input from compost, crop residue incorporation, or cover crops will increase SOM, but it is costly in the short term (Kik et al. 2024).
- (4) Trade-offs between agricultural productivity and environmental quality (O'Sullivan et al. 2018; Schulte et al. 2014; Stevens 2018). Optimizing soil quality for agricultural productivity might come at the expense of environmental quality. For example, an economically optimal crop nitrogen (N) fertilization level might come at the cost of high N-losses to the environment (Silva et al. 2021).
- (5) Proper implementation of sustainable soil management strongly depends on the initial soil quality and current production management. Therefore, production management decisions must be tailored at farm level to effectively achieve soil quality targets (Young et al. 2021). If these target values are not defined and the impact of production management is highly site-dependent, general implementation is undesirable (Hannula et al. 2021). For example, the impact of carbon sequestration strongly depends on the current carbon saturation level of the soil (Lessmann et al. 2022; Moinet et al. 2023).
- (6) Lock-in, being defined as "a self-reinforcing mechanism that reproduces the status quo and impedes change" (Weituschat et al. 2022). Farmers' decisions are driven by a wide range of factors including technical developments, policies, and economic context. These factors can interact to create a cognitive lock-in, in which current production management is maintained (Weituschat et al. 2022).

At the farm-level, achieving a sufficient yearly income and long-term continuity of the farm are prime goals for farmers (Kay et al. 2012). Regarding these goals, the implementation of sustainable soil management can be considered an economic problem. Considering sustainable soil management as a socio-economic problem, the challenge is to implement the right production management decisions at the farm-level that ensure (1) profit for a sufficient yearly farm income and (2) long-term preservation of soil quality. Such a challenge is typically addressed via bio-economic modeling, which is among the most popular farming system redesign methods (Janssen & van Ittersum 2007). Integrative bio-economic models evaluate trade-offs and synergies between different farm management strategies, but most of these models only make tenuous references to soil quality (Schreefel 2022). Examples of such studies can be found in Bos et al. (2017), Dogliotti et al. (2005), and Mandryk et al. (2014). According to Schreefel (2022), models that focus on the assessment of soil quality and its multifunctionality largely lack integration of the environmental impact and socio-economic impact at farm level. They therefore integrated the Soil Navigator soil assessment model (Debeljak 2019) into the FARMdesign bio-economic farm model (Groot et al. 2012), thereby optimizing the multifunctionality of soil using nutrient flows and soil organic matter as soil quality indicators. The Soil Navigator uses qualitative decision rules to assess the effects of management on soil functions. However, making the right production management decisions at farm level requires quantitative relationships

between management and soil quality to ensure sufficient farm profit and preservation of soil quality. Therefore, our aim is to build on Schreefel (2022) approach by using the FARManalytics bio-economic modeling approach developed by Kik et al. (2024)

The aim of this study is to optimize production management on representative Dutch arable farms to maximize farm profit while increasing long-term soil quality. We define three sub-objectives:

1. Describe nine existing farms in the Netherlands and calculate the impact of their current production management on soil quality and farm economics.
2. Optimize production management on these farms using different scenarios to achieve highest profit while increasing soil quality
3. Explore alternative production management on these farms for (1) policy scenarios implementing stricter water quality regulations, and (2) field beans as an alternative crop.

We selected the Netherlands as a case study region (Fig. 1). The Netherlands is a suitable case study region to evaluate potential sustainable farm management strategies because of its high demand for agricultural products and its intensive land use due to high land prices. We assume the farmer to be the primary actor and decision-maker with regard to sustainable soil management (Kik 2021b). Moreover, we assume farmers to be financially rational decision-makers. In this study, we focus solely on agricultural productivity and do not consider other ecosystem services as a potential additional source of farm income.

Fig. 1 Soil management on a Dutch arable farm (picture: Maarten Kik)



2 Methods

2.1 Model description FARManalytics

FARManalytics is a bio-economic modeling approach that allows to analyze and optimize farmers' production management to maximize farm profit while preserving or increasing soil quality. Production management decisions included crop rotation, cover crops, manure, fertilizer, and crop residue management. Definitions and illustrations of these decisions can be found in Appendix 1. For an extensive description of the model, we refer to Kik et al. (2024). The two main inputs of FARManalytics are a soil quality indicator set (Soil quality) and an economic calculation framework (Farm economics). The key features of FARManalytics are explained in the "FARManalytics" section.

2.1.1 Soil quality

The soil quality indicator set consists of 15 chemical, physical, and biological indicators based on studies by de Haan et al. (2021) and Ros et al. (2022). Examples of these indicators are phosphorous (P) availability, soil organic matter (SOM), subsoil compaction vulnerability, and plant parasitic nematodes. Indicators and their respective target ranges are used to assess soil quality at a specific location at a certain point in time. Based on the indicators, constraints set requirements on farmers' production management to ensure the indicators stay in or move towards the target range. For example, if the indicator potassium (K) availability is below the minimum target, the constraint K fertilization advice is formulated in such a way that the K availability moves

towards the target range. If K availability is within the target range, K fertilization is formulated in such a way that the K availability remains in the target range. To apply the constraints, quantitative rules on the impact of production management decisions on soil quality were developed. These entail for example the K content of fertilizers and K removal via harvested crops in order to calculate the K fertilization advice.

2.1.2 Farm economics

The economic calculation framework calculates the contribution of production management decisions to farm income. The indicator for farm income is profit, which is the gross income minus all costs, including opportunity costs for own labor and capital (Kay et al. 2012). Farm profit is calculated as the sum of profit generated through crops and selling crop residues minus costs for cover crops, manure, and fertilizer. Farm overhead costs are neglected, the calculated profit therefore is a profit on crop enterprise, being the total profit on farm level excluding costs that cannot be attributed to the considered production management decisions. The calculation framework uses Activity-Based-Costing to accurately attribute fixed costs towards the respective production management decisions (Drury 2008).

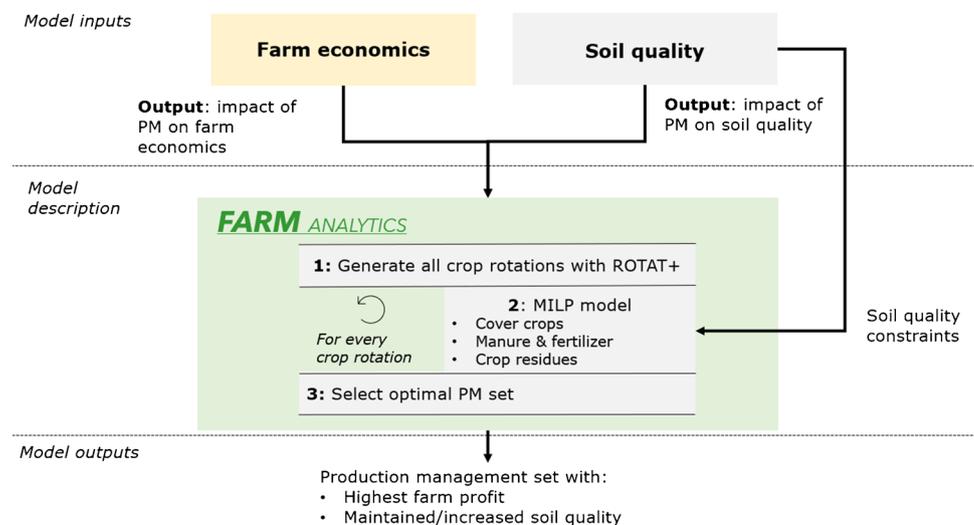
2.1.3 FARManalytics

FARManalytics is a bio-economic model with the scope at farm level. At farm level, farms are assumed to be homogeneous in their soil type and production management. The temporal scale is the time length of a crop rotation, typically 8 to 12 years. Within this time, we assume production management (PM) to be static. Input prices and

output prices, i.e., crop prices are assumed static. Yields are determined using a target-oriented approach, which implies that yields are static and do not respond to changes in soil quality or production management (van Ittersum and Rabbinge 1997). Figure 2 presents a conceptual outline of the FARManalytics model.

FARManalytics consists of two modules: PM calculator and PM optimizer. In the PM calculator, the production management decisions for crop rotation, cover crops, manure and fertilizer application, and crop residue management are fixed inputs. The PM calculator allows to gain insight into whether current production management keeps soil quality indicators in their target range. The PM optimizer is an optimization model that selects the most appropriate production management fulfilling the soil quality constraints (Soil quality) while generating highest farm profit (Farm economics). Figure 2 presents an outline of the PM optimizer module. The first process in the PM optimizer is to generate all feasible crop rotations using ROTAT+ (Dogliotti et al. 2003). The input for ROTAT+ is a list with crops and the respective plant and harvest dates, maximum crop frequency, and minimum period of return. The second process is to optimize the selection for cover crops, manure and fertilizer application, and crop residue management within every feasible crop rotation using Mixed-Integer-Linear-Programming. The output from the soil quality indicator set (Soil quality) and farm economics (Farm economics) is used as an input. The result of process two is a collection with all feasible crop rotations with optimized cover crop, manure, fertilizer, and crop residue choices. Process three is to select the best production management set in this collection: the set achieving maximum profit while fulfilling all soil quality constraints.

Fig. 2 Overview of the main inputs (farm economics and soil quality) and conceptual outline of the FARManalytics bio-economic model. The objective of FARManalytics is to optimize farmers' production management (PM) to achieve maximum farm profit while maintaining or increasing soil quality



2.2 Case farms and data collection

The case farms were participating in the “Farmers Network for Soil Sampling” initiated by Wageningen Plant Research. In 2019, nine out of in total 16 farmers in this network responded positively to a call to participate in this study. In 2020, we collected the current production management data on all farms, which is presented in Table 1. Soil samples were obtained from each farm, being available from routine soil sampling events done every 4 years. We also gathered information on current production management decisions, including crop rotations, manure and fertilizer application (type, quantity, timing, and application technology), and types of cover crops. This data was sourced from farm management systems and through semi-structured interviews with the farmers. In 2021, we made an economic analysis based on current production management. Economic data was obtained through structured interviews with the farmers using templates. The templates were completed based on estimations made in consultation with the farmers, as much of the required economic data was not readily available. For the economic data such as costs of inputs, crop prices, and crop yields, we used averages from 2019, 2020, and 2021. Following completion of the analysis, the results were reviewed with the farmers in a semi-structured format. By combining soil sample data with current production management information, we identified soil quality limitations and challenges. Again, the results were shared and discussed with farmers in a semi-structured interview. In 2023, we presented the FARManalytics scenario results to the farmers. In an unstructured interview, we also asked for their input on a scenario addressing a specific challenge on their farm.

2.3 Scenarios

We defined four farm-level scenarios to study the impact on soil quality and farm economics ([Farm scenarios](#)). Subsequently, we study the impact of two policy developments on soil quality and farm economics ([Stricter water quality regulations](#) and [Field beans as part of protein transition](#) sections).

2.3.1 Farm scenarios

The selected farm scenarios consist of a baseline scenario, a soil quality tactical scenario, and soil quality strategic scenario, which were the same for all farms. The farm strategic scenario consists of a farm-specific challenge. The precise definition of the farm scenarios is as follows:

- **Baseline:** Continuation of current production management during one complete rotation. Calculated with the FARManalytics module PM calculator.
- **Soil quality tactical:** Maximize farm profit with soil quality constraints applied. Calculated with the FARManalytics module PM optimizer. Decision variables are cover crops, manure, fertilizer, and crop residue management because these are typical production management choices that can be changed in the tactical dimension.
- **Soil quality strategic:** Additional decision variable compared to “soil quality tactical” is crop rotation.
- **Farm strategic:** Maximize farm profit with soil quality constraints applied for a farm-specific challenge. Decision variables are equal to the “soil quality strategic” scenario. Inputs and constraint settings were made in consultation with the farmers. Table 2 details the farm-specific challenges for each farm.

2.3.2 Stricter water quality regulations

The first policy scenario is the stricter water quality scenario. In it, we explore the impact of two recent policy measures aimed at improving surface and ground water quality in agricultural ecosystems in the Netherlands. We only chose to implement this scenario on the farms *S*, *CR*, *S-CR*, *L*, and *CSW-1* because these farms represent different soil types and are considerably different in their current production management. The studied policy measures are as follows: (1) the Dutch 7th Nitrate Directive Action Program, which intends to achieve the objectives formulated in the European Union (EU) Nitrate Directive; and (2) the EU Derogation Grant for 2023–2025, which includes a gradual phasing out of the exemption for the Netherlands to use more animal manure than 170 kg N ha⁻¹. Both policy measures have been implemented because the current water quality is below the standard defined in the EU Water Framework Directive, despite efforts made in the past to achieve this objective. The combined measures specified in the 7th Action Nitrate Directive Program and the EU Derogation Grant have a major impact on farmers’ production management and subsequently profit. Changes to the current production management might be required to comply with legislation, especially for farms on sandy and loess soil. Various measures will be implemented gradually, with full implementation by 2027. For this scenario, we selected the full implementation outlined for 2027 because farmers will ultimately have to comply with these requirements. Table 3 presents the exact measures implemented in the water quality scenario.

In the water quality scenario, we used crop rotation, cover crops, manure, fertilizer, and crop residue management as decision variables. The measures resulting from stricter

Table 1 Farm characteristics and current production management decisions for nine arable case study farms from the Netherlands. Detailed manure applications can be found in Appendixes 2 and 4. Crop acronyms: CA carrots, GB green beans, GC grass seed, KC corn (kernel), PE peas, SC silage corn, S seed onions, SP seed potato, SB sugar beets, SP spring barley, SPI spinach, STP starch potato, WB winter barley, WP ware potato, WW winter wheat. Cover crop mixes: Mix 1 A. Strigosa, vetch, clover, white radish; Mix 2 A. Strigosa, flax, vetch, clover, peas; Mix 3 oats, Vetch, Phacelia; Mix 4 = Oats, yellow mustard; Mix 5 = clover, vetch, flax, sorghum, peas

Nr.	1	2	3	4	5	6	7	8	9
Farm	Sand	Sand-river clay	Loess	Clay organic	Clay nord	Clay river	Clay polders	Clay southwest 1	Clay southwest 2
Acronym	S	S-CR	L	CO	CN	CR	CP	CSW1	CSW2
General characteristics									
Soil type	Sand	Sand/river clay	Loess	Sea clay	Sea clay	River clay	Sea clay	Sea clay	Sea clay
Farm type	Conventional	Conventional	Conventional	Organic	Conventional	Conventional	Conventional	Conventional	Conventional
Tillage system	Plowing/spading	Non-inversion tillage	Non-inversion tillage	Non-inversion tillage	Plowing/subsoiling	Plowing/subsoiling	Plowing/subsoiling	Non-inversion tillage	Non-inversion tillage
Size	Large	Middle	Middle	Middle	Middle	Middle	Small	Middle	Middle
Crop rotation									
Crop rotation	STP-SPB-SB-SP-SC-SB-	WP-SB-KC-WW	WP-SO-SB-WW-WP-SPB	GC-CA-WB-SPI	SP-WW-WB	WP-WW-SB-WW-	SP-SB-GS-SO	WP-WW-SO-WW-WP-WW-	WP-WW-SB-WW-SP-WW
Crop rotation (continued)	STP-SC-SB-SP-SC-SPB	WP-KC-KC-WW	SB-WW-WP-SO-SB-WW	GC-SO-PE-GB	WW	WP-WW-SO-WW	SP-SB-WW-TU	GS-PE-WP-WW-SB-SC	SO-WW-WP-WW-CA-WW
Cover crops	SPB: winter radish SC: rye	WW: white radish KC -> KC: Avena Strigosa	WW: yellow mustard SPB: yellow mustard	GC: rye WB/SPI/PE: mix 3 SO: mix 4	WW -> SB: mix 1 WW/WB -> SP: mix 2	WW: yellow mustard	SO: yellow mustard WW: grass TU: mix 5	WW: mix 2 PE: mix 2 GS: GS	WW: mix 3
Manure	Cattle slurry Pig slurry Green compost	Cattle slurry	Pig slurry Cattle slurry	Goat solid manure (organic) Vinasse potassium	Cattle slurry (solid fraction) Protamylasse	Pig slurry Champost	Champost	Pig slurry Cattle slurry	Cattle slurry Cattle solid manure
Liming	Yes		Yes			Yes	Yes		
Crop residue management	SPB: keep	WW: keep	WW: keep SPB: keep	WB: sell	WW: sell WB: sell	WW: sell	GS: keep WW: sell	WW: keep GS: sell	WW: keep
Fertilizer (kg N/P/K ha ⁻¹)	54-3-20	71-0-0	99-0-67	0-0-0	108-20-58	108-0-74	93-8-9	84-6-33	118-0-61

Table 2 Challenges to be modeled with bio-economic modeling approach FARManalytics in the farm strategic scenarios, which include a farm-specific challenge to maximize profit while preserving or increasing soil quality

Nr.	Farm	Farm challenge
1	Sand	(1) Optimize crop rotation with 1:3 break crops (2) Ware potatoes as alternative for starch potatoes
2	River clay-sand	Explore potential of land exchange with dairy farmers: Grow grass/silage corn in return for potato land at dairy farm
3	Loess	Optimize position of onions in rotation
4	Clay organic	Explore potential of cut-and-carry fertilizers: spread cut grass clover
5	River clay	Maximize farm income without potatoes in crop rotation
6	Clay nord	P and K fertilization from manure
7	Clay polders	Explore potential of land exchange with dairy farmers: Grow grass/silage corn in return for potato land at dairy farm
8	Clay Southwest 1	Optimize crop rotation with celeriac as an alternative crop for seed onions
9	Clay Southwest 2	Optimize crop rotation by increasing the share of sugar beets

Table 3 Measures resulting from the 7th Action Nitrate Directive Program (ND) and Derogation Grant 2023–2025 (DER) and their implications on farmers' production management. ¹Break crops are crops with an expected positive impact on soil quality and water quality. A list of break crops is available from RVO (2022). ²Catch crops are cover crops that take up residual N after cultivation of a main crop

to prevent N leaching. A list of allowed catch crops is available from RVO (2023). ³Winter crops are crops that do not require planting a catch crop because they have a low amount of residual N. A list of winter crops is available from RVO (2023). Acronyms: N nitrogen, P phosphorous

Measure	Source	Implementation	Soil types
Break crops	ND	Compulsory break crop ¹ every 3 years at field level	Sand, loess
Catch crops	ND	Recommended catch crop ² after all crops except winter crops ³	Sand, loess
		Discount on N norm if harvest after 1 Oct and no catch crop	All
		Compulsory catch crop after corn	All
P norms	ND	P in compost counts 25% for legal P norm	All
		P in solid manure/champost counts 75% for legal P norm	All
N autumn	ND	After August 1st, not more than 60 kg N-total via slurry	All
Buffer zones	ND/DER	Uncultivated buffer zones next to water streams (implemented as 4% of the total area)	All
Nutrient norms	DER	20% discount on fertilization norms in "nutrient polluted areas" (implemented as 20% discount on total N fertilization)	All

water quality regulations as presented in Table 3 were implemented as additional constraints. A detailed description of the implementation of these constraints in the model can be found in Appendixes 3 and 5.

2.3.3 Field beans as part of protein transition

In this scenario, we explored field beans as an alternative crop to meet the increasing demand for high-quality plant-based protein sources (Augustin and Cole 2022; Ofoedu et al. 2022). Field beans offer advantages over other protein crops like soybeans, peas, lentils, and lupines in the Netherlands. Field beans demonstrate the highest yield potential in the regions' cooler, humid climates (Timmer and Toren 2022). The harvest time of field beans in August or early September fits better compared to the late harvest of soybeans in October. Ongoing research indicates promising

advancements in field bean cultivars, leading to higher yields and improved quality (Augustin and Cole 2022).

Despite current field bean cultivation in the Netherlands (Statistics Netherlands 2020), critical information such as input costs, crop yields, and output prices remains scarce. Field beans exist in two forms: winter field beans (planted in autumn) and spring field beans (planted in spring) (Jensen et al. 2010). Winter beans excel in yield potential but are vulnerable to winter foraging (Van Overveld, Limagrains Netherlands, personal communication, 25 May 2023).

We estimated costs, yields, and prices for field beans as follows. Direct costs, such as seeds and crop protection, were assumed consistent across farms (Roothaert, Limagrains Netherlands, personal communication, 25 May 2023). Field operation costs such as mechanization, energy, and labor were individually calculated for each farm. Yield data was derived from recent trials in the Netherlands (Prins et al.

2018, 2019; Prins and Timmer 2017; Timmer and Toren 2022), with average yields set at 5000 kg ha⁻¹ for spring beans and 7000 kg ha⁻¹ for winter beans. Given the absence of registered field bean prices, we estimated prices based on average feed prices from 2019 to 2022 (Wageningen Livestock Research 2023). Energy and protein content values of field beans were used to calculate an estimated price of 0.32 kg⁻¹. (Limagrains Nederland 2023). Based on the average yield and average price, we calculated a standard revenue. We conducted sensitivity analyses varying from -25 to +50% of standard revenue to assess the viability of field beans in the cropping plan. Given that field beans are leguminous, they require no additional nitrogen fertilization and can supply approximately 75 kg N ha⁻¹ to subsequent crops (Limagrains Nederland 2023).

3 Results

The results are structured as follows: “Farm scenarios” to “Field beans as part of protein transition” sections are structured as follows. First, we discuss the results of the four farm-level scenarios (Impacts of farm scenarios). Next, the results of stricter water regulations and of field beans as an alternative crop are discussed in the “Impact of stricter water quality regulations” and “Impact of stricter water quality regulations” sections, respectively.

3.1 Impacts of farm scenarios

Figure 3 shows the results of the soil quality indicators in the baseline scenario.

Overall, the case farms demonstrate commendable performance, with only a few indicators showing limitations. Moreover, most of these limitations can be addressed through simple and practical production management decisions, such as increasing potassium fertilizer, sulfur fertilizer, or lime application. Figure 3 shows that P input is a limiting factor on multiple farms due to the upper bound P norm being lower than the lower bound P fertilization advise. This implies that farmers cannot apply P according to the agronomic recommendations, because it will exceed the legal norm. All farms exceed the target set by the subsoil compaction index, although farms with a higher share of cereals in the crop rotation (CN, CO, CSWI) come close to the target value. Compared to crops such as potatoes, sugar beets, and seed onions, cereals pose a lower risk on subsoil compaction due to the lower number of crop operations, the smaller harvest volume, and the earlier harvest time. Input of organic matter is a limiting factor primarily due to the required increase in SOM for improving cation exchange capacity on sandy soils (S, S-CR), or due to the reduced slaking vulnerability on loess and clay soil (L, CR, CSWI, CSW2).

Figure 4 shows the current costs and profits for the baseline scenario on all farms.

Figure 4 shows considerable differences in profit between the farms in the baseline scenario. The profit of farm *loess* (L) is €1493 ha⁻¹, whereas this is €79 ha⁻¹ for farm *clay polders* (CP). The differences between these farms are mainly caused by crop profits and land costs. For example, land costs on *clay polders* are €1318 ha⁻¹, while land costs on loess soil are only €557 ha⁻¹. Additional variation in the baseline scenario is caused by differences in costs and profits of cover crops, manure, crop residues, and fertilizers. For example, on-farm *clay rivers* (CR) the total cost of all these production management decisions is €125 ha⁻¹, compared to €612 ha⁻¹ for farm *clay organic* (CO). Figure 4 illustrates that manure can either be a cost or a profit. Because of the high manure surplus in the Netherlands, slurry is often available at a premium. Therefore, farms that mainly apply slurry (S, S-CR, L, CR) show a profit for manure. Manure costs on farm *clay organic* (CO) are high because this farm is required to buy expensive organic manure.

Figure 5 shows the total profit for the baseline, soil quality tactical, soil quality strategic, and farm strategic scenarios. A detailed overview of all production management decisions in all scenarios can be found in Appendixes 2 and 4.

For almost all farms, we observe an increase in profit when production management is optimized, subject to all soil quality constraints. There are substantial differences in the potential of profit increases between farms, varying from € 47 ha⁻¹ for a farm on river clay (CR) up to €704 ha⁻¹ for an extensive farm on clay (CSW2). For most of the farms, switching to other crops in the cropping plan leads to an increase in profit (Fig. 6A). For farms on loess soil (L), the soil quality strategic scenario results in a decline in crop profit, which implies the crop rotation in the baseline scenario does not match the agronomic constraints in the soil quality strategic scenario. The clay farm in the North (CN) and the farm on river clay (CR) already have an optimal crop rotation, as evidenced by the fact that a further increase in profit in the soil quality strategic scenario compared soil quality tactical scenario is not possible.

Aside from cropping plan changes, increases in profit come from (1) reduction in fertilizer costs; (2) increase in profit from crop residues; and (3) lower manure costs. A decrease in fertilizer costs ranging from €19 to €182 ha⁻¹ is possible on all farms, with the exception of farm CO, which does not use synthetic fertilizer. In the soil quality strategic scenario, crop residues (cereal straw) are sold on all farms that do not sell crop residues in the baseline scenario (S, S-CR, L, CO, CSWI, and CSW2). Profit decreases in the soil quality tactical scenario for farm S, because in order to meet the soil quality target, more cover crops have to be grown than in the baseline scenario. However, in the soil quality strategic scenario, profit increases compared to the baseline



Fig. 3 Results of soil quality indicators in the baseline scenario for nine case farms. “x” indicates a lower limit for the indicator. “-” indicates an upper limit for the indicator. Blanks imply that an indicator is not applicable on the soil type. For P, both a lower limit (P advice) and an upper limit (P legal norm) apply. The unit for the indicators

M. chitwoodi, P. penetrans, R. solani, S. sclerotiorum, and V. dahliae is the potential loss in crop revenue (PRL) in € ha⁻¹. Acronyms: N nitrogen, P phosphorous, K potassium, S sulfur, Mg magnesium, CRA crumbling ability, SV slaking vulnerability, WEV wind erosion vulnerability, SCI subsoil compaction index, OM organic matter

scenario: by optimizing the cropping plan with more silage corn instead of starch potatoes, soil quality targets can be met while increasing profit.

Figure 6A and B show how the different production management decisions contribute to a change in profit for the soil quality strategic and farm strategic scenarios compared to the baseline scenario.

Figure 6B shows larger changes in crop profit compared to Fig. 6A, which implies more crop rotation changes in the farm strategic scenario. The changes in costs and profit for crops, manure, fertilizer, and crop residue management in the farm-strategic scenario are similar to the changes in the soil quality strategic scenario. For the farms *sand* (S),

sand-river-clay (S-CR), *loess*, *clay polders* (CP), and *clay southwest 1* (CSW1) the farm strategic scenario resulted in a larger increase in profit than the soil quality strategic scenario. Exchanging land with dairy farmers, which was a challenge studied in the farm strategic scenario for farms on sandy soil and *clay polders* (S, S-CR, CSW1) resulted in a considerable increase in profit compared to the baseline scenario. Switching from low-yielding seed onions to better-yielding plant onions and celeriac on clay farm southwest 1 (CSW1) increased the profit with €250 ha⁻¹ year⁻¹ compared to the baseline scenario. Growing seed onions in the farm strategic scenario on the farm clay nord (CN) only resulted in a minor increase in profit compared

Fig. 4 Profit or costs from current production management decisions (baseline scenario). All components above the x-axis represent profits, all components below represent costs. Farm acronyms: *S* sand, *S-CR* sand river clay, *L* loess, *CO* clay organic, *CN* clay north, *CR* clay river, *CP* clay polders, *CSW 1* clay southwest 1, *CSW-2* clay southwest 2

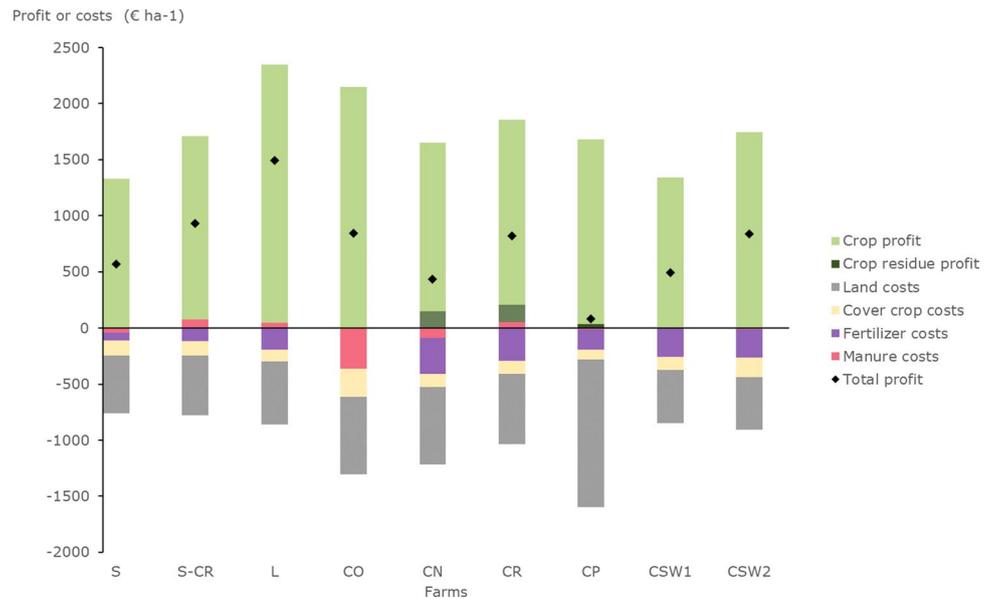
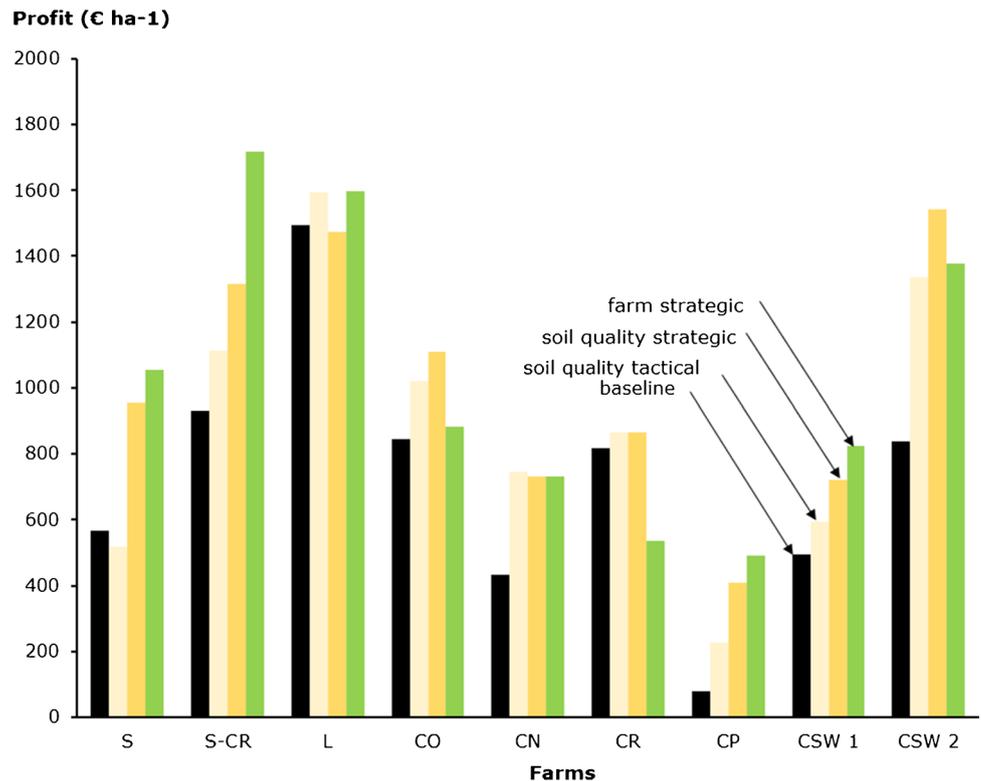


Fig. 5 Profit resulting from optimization of production management with bio-economic model FARManalytics for different scenarios on arable farms in the Netherlands. Farm acronyms: *S* sand, *S-CR* sand river clay, *L* loess, *CO* clay organic, *CN* clay north, *CR* clay river, *CP* clay polders, *CSW 1* clay southwest 1, *CSW-2* clay southwest 2



to the baseline scenario. On farm *CSW2*, a higher share of sugar beets in the rotation, at the expense of the more profitable crops carrots and onions, resulted in lower total profit compared to the soil quality strategic scenario. The implementation of cut-and-carry fertilizer as an alternative for expensive organic solid manure on clay organic (*CO*) resulted in higher costs, decreasing profit compared to the

soil quality strategic scenario. On the farm *clay river (CR)*, the farm strategic scenario centered on potential profit without ware potatoes in the cropping plan due to labor constraints. This resulted in a decrease of profit compared to the baseline and soil quality strategic scenarios, as ware potatoes are profitable for this farm.

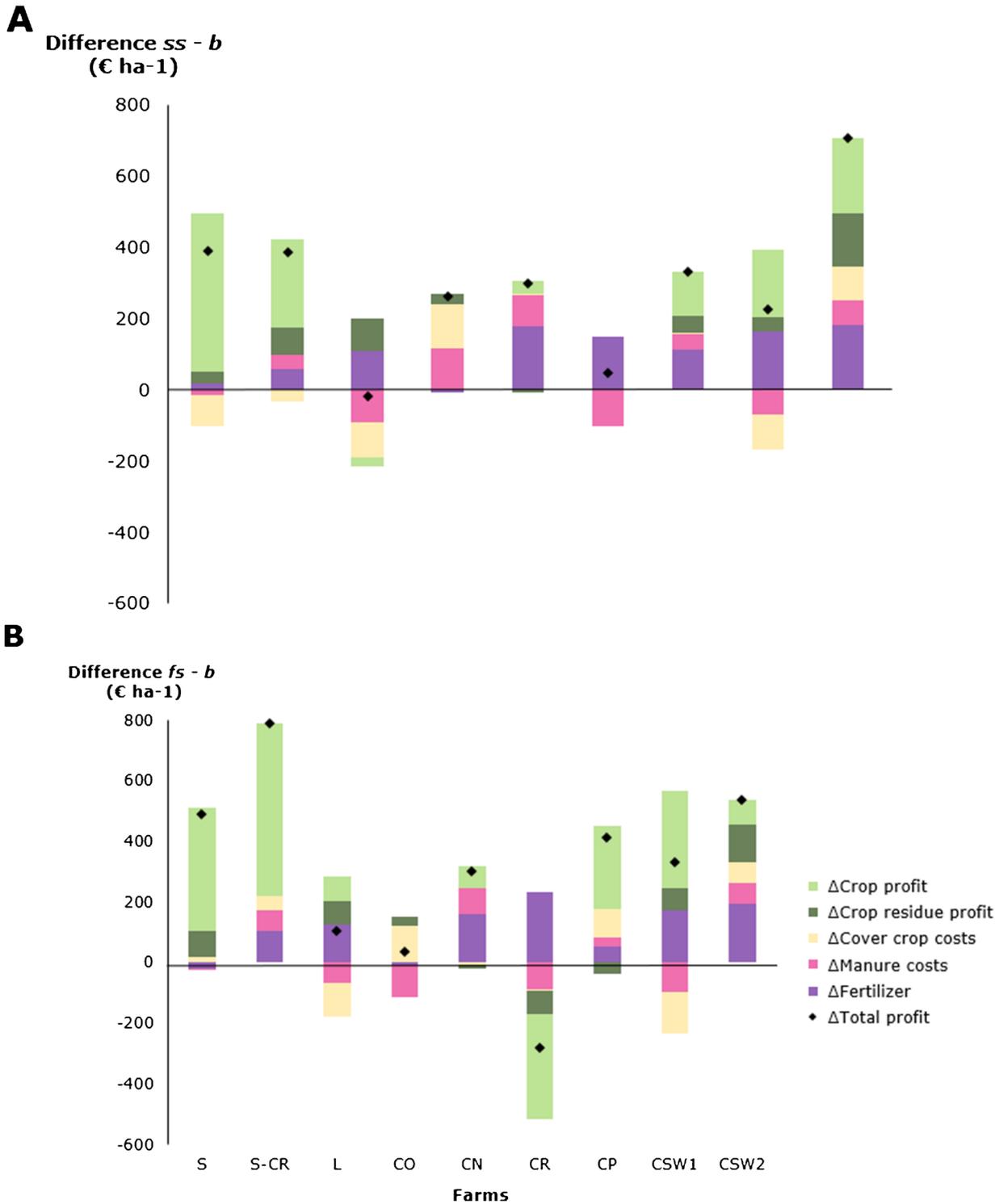


Fig. 6 **A** Change in costs or profit from production management decisions in the soil quality strategic (ss) scenario compared to the baseline scenario (b for nine arable farms in the Netherlands). **B** Change in costs or profit from production management decisions in the farm

strategic (fs) scenario compared to the baseline scenario(b) for nine arable farms in the Netherlands. Farm acronyms: S sand, S-CR sand river clay, L loess, CO clay organic, CN clay north, CR clay river, CP clay polders, CSW 1 clay southwest 1, CSW-2 clay southwest 2

3.2 Impact of stricter water quality regulations

Figure 7 shows the total profit for the scenario where production management is optimized subject to stricter water quality regulations. In addition to the “baseline” results, this figure also presents the outcomes of the “soil quality strategic” scenario, which represents total profit in an optimized situation without stricter water quality regulations.

From Fig. 7 follows that for all farms the implementation of water quality restrictions is feasible but results in a decline in profit compared to the soil quality strategic scenario, a scenario without water quality. However, by optimizing their production management, farms *S*, *CR*, and *CSW2* can increase their total profit compared to the baseline scenario while meeting both soil quality targets and implementing water quality restrictions. Despite the drastic measures (such as compulsory break crops) for the farm on sandy soil (*S*), the farmer can increase profit due to land exchange with dairy farmers. On clay soil (*CR*, *CSW2*), the impact of water quality restrictions is substantially less compared to sand and loess. On farms *S-CR* and *L*, profit decreases compared to the baseline scenario. This implies that despite the optimization of production management, implementation of water quality restrictions goes at the expense of income. Both farms have to comply with all water quality measures (Table 3). Farm *S-CR* has to grow more break crops, which are not very profitable. On farm *L*, the main driver for the loss in profit is the non-cultivated buffer zones.

3.3 Impacts of field beans as part of protein transition

Figure 8 presents the total profit for the field bean scenario and the results of the sensitivity analysis. For comparison, also the results of the baseline and the soil quality strategic scenarios (the optimized scenario without field beans) are included. The production management decisions in the field bean scenario can be found in Appendixes 3 and 5.

Figure 8 follows that based on the current yield and current prices of field beans in the field beans baseline, field beans can be considered a serious alternative crop in the cropping plan of all considered farms since profit increases compared to an optimized scenario without field bean (soil quality strategic scenario). However, if the revenue of field beans decreases with 25%, total profit does not increase compared to the soil quality strategic scenario, which implies that based on that revenue field beans are not an interesting alternative. Based on the sensitivity analysis “fb+25%” and “fb+50%” the share of field beans in the rotation increases on farms *S*, *S-CR*, and *CR*. On farms *S* and *CR*, the crop frequency of field beans approaches the maximum of 0.2. On farms *L* and *CSW2*, the share of field beans remains equal compared to the field bean baseline.

Fig. 7 Total profit for the water quality scenario, a scenario in which production management is optimized subject to policy measures to improve water quality. For comparison, the total profit from the baseline situation and total profit for the soil quality strategic scenario in which production management is optimized without water quality restrictions is included. Farm acronyms: *S* sand, *S-CR* sand river clay, *L* loess, *CO* clay organic, *CN* clay north, *CR* clay river, *CP* clay polders, *CSW 1* clay southwest 1, *CSW-2* clay southwest 2

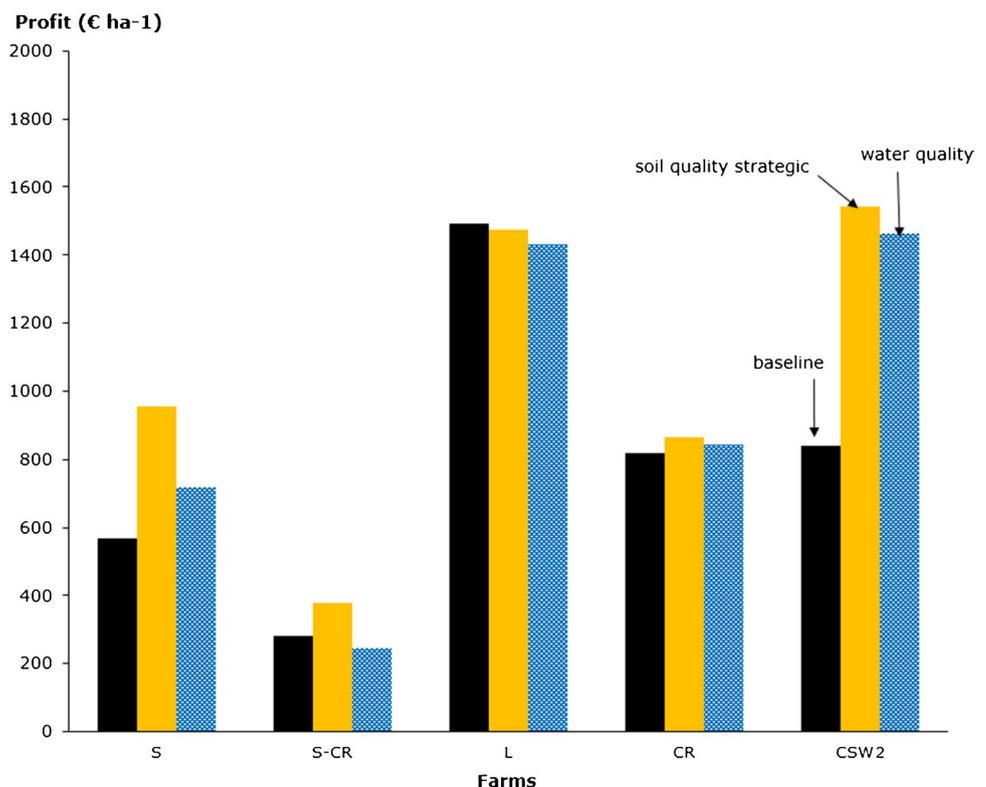
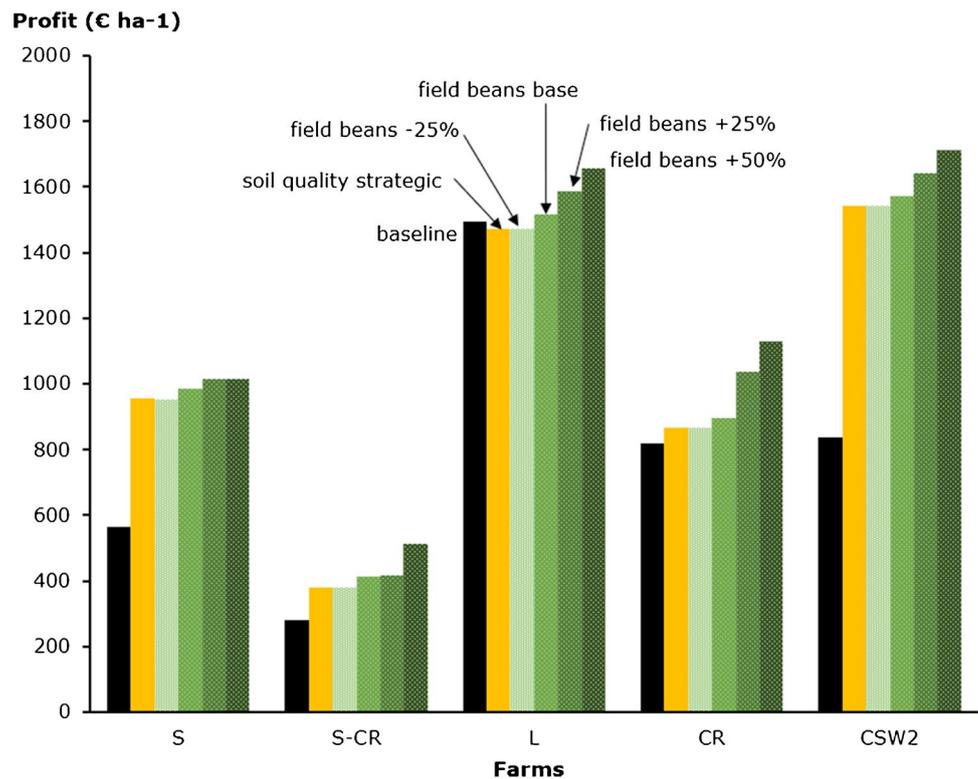


Fig. 8 Profit for scenarios that explore the potential of field beans as an alternative crop on arable farms in the Netherlands. In the field bean base, field beans are added with their crop profit based on their current revenue. fb-25%, fb+25%, and fb+50 are the results of a sensitivity analysis with -25%, +25%, and +50% of the revenue compared to the base. The total profit from the baseline scenario and the soil quality strategic scenario (crop rotation) optimized without field beans) is included for comparison. Farm acronyms: *S* sand, *S-CR* sand river clay, *L* loess, *CO* clay organic, *CN* clay north, *CR* clay river, *CP* clay polders, *CSW 1* clay southwest 1, *CSW-2* clay southwest 2



4 Discussion

4.1 Impact of production management

4.1.1 Soil quality bottlenecks and economic performance in the baseline

The evaluated farms perform relatively well regarding their impact on soil quality: most of the soil quality indicators are above their target. Ros et al. (2022) report similar findings using the Open Soil Index framework across agricultural fields in the Netherlands. Current soil quality bottlenecks are organic matter input, subsoil compaction, and nutrients. Mandryk et al. (2014) found that improving soil organic matter content was one of farmers' most important goals. Van den Akker and Hoogland (2011) confirm subsoil compaction to be a major bottleneck in soil quality in the Netherlands. Finally, Ros et al. (2022) found insufficient sulfur availability in 49% of the Dutch agricultural fields. The baseline shows considerable differences in economic performance between farms, which aligns with farm income monitoring (Wageningen Economic Research 2022). For instance, in 2021, the income gap between the top 20% and bottom 20% of farmers was €74,000.

4.1.2 Improving production management in the tactical dimension

In the soil quality tactical scenario, choices of cover crops, manure, fertilizer, and crop residue management were optimized within the farms' current crop rotations. For seven out of nine farms, farm income increased substantially while achieving all soil quality targets except subsoil compaction. Preferred cover crops are *A. strigosa*, yellow mustard, and winter radish, which fit best in requirements regarding frost vulnerability, regrowth, rooting, and plant-parasitic nematode development. The most preferred manure types are cattle slurry and compost due to their economic value and composition. Cattle slurry, available either free or at a premium, offers high nutrient concentrations per unit of phosphorus (P), while compost supplies organic matter efficiently within P application limits. Solid manure is not preferred due to higher costs and lower nutrient availability. This is contradictory to farmers' perceptions that solid manure is the best type of manure for the soil (Van Eekeren et al. 2009). A general conclusion from literature is that application of any type of manure is beneficial for soil quality compared to no manure being applied, due to the addition of carbon and base cations (Zavattaro et al. 2017). P and potassium (K) fertilizers were phased out. According

to the advice of CBAV (2022), P and K recommendations can be fulfilled with the application of manure and compost alone. This is supported by the findings of de Vries et al. (2023) which demonstrate that manure and compost alone meet these nutrient needs nationally. Synthetic N fertilizer use decreased substantially compared to current practices, aligning with studies by Oenema et al. (2009), Silva et al. (2017), and Silva et al. (2021). A potential solution to more effectively apply N fertilizer might be by implementing best practices from peers (Lamkowsky et al. 2021). Based on Van Der Burgt et al. (2006), the FARManalytics model accounts for all possible sources of N, such as N supplying capacity from the soil, previous crops, and cover crops; this is not always done in practice due to the uncertainty surrounding the magnitude of these sources. Losses like volatilization, leaching, and denitrification during the seasons are partly ignored in FARManalytics; this might lead to an overestimation of plant available N by FARManalytics. On all farms that currently do not sell crop residues, crop residues can be used to generate additional income. Although crop residues have a widely acknowledged beneficial impact on soil quality (Klopp and Blanco-Canqui 2022; Turmel et al. 2015), alternative sources of nutrients and organic matter are widely available at low prices in the form of animal manure.

4.1.3 Improving production management in the strategic dimension

In the soil quality strategic scenario, changes in crop rotation were allowed. For three farms, profit did not increase compared to “soil quality tactical,” which implies that the current crop rotation is already optimal. However, for five out of nine farms, optimizing the crop rotation led to a substantial increase in profit by prioritizing the most profitable crops. Accurate crop profit calculation is crucial for this optimization (Mattetti 2022). For example, seed onions were excluded from the crop rotations on three farms because of their low profitability. In the farm strategic scenario, farm-specific challenges were studied. For three farms, the farm strategic scenario included land exchanges with dairy farmers. The land exchange resulted in even higher income increases compared to the quality strategic scenarios, indicating that land exchange could be a valuable approach to increase profit while achieving soil quality targets. Integrating arable and livestock production through joint land use approaches, such as integrated crop-livestock systems, shows potential benefits for farm income, soil quality, and environmental performance as recognized in the literature (Lemaire et al. 2014; Sekaran 2021).

4.1.4 Impact of stricter water quality regulations

In the water quality scenario, we optimized farmers’ production management with additional restrictions to preserve water quality. Implementation of these restrictions comes at a cost since profit is always higher in a scenario without water quality restrictions (soil quality strategic). However, when compared to the baseline scenario, three out of five farms could increase farm income while meeting soil quality targets and water quality restrictions by optimizing their production management. Belhouchette et al. (2011) studied the impact of implementation of the EU Nitrate Directive on French arable farming and found that farm income was not negatively affected, although substantial changes in production management were required. In contrast, Dellink et al. (2011) state that the economic performance of agriculture will suffer from more stringent water quality regulations.

4.1.5 Impact of field beans as alternative crop

Based on current yields and expected prices, field beans are an interesting alternative crop to replace part of cereals in the crop rotation, as highlighted by Jensen et al. (2010). However, current crop yield and the host status of field beans for soil-borne diseases are a point of concern. Field beans, being leguminous crops, can meet their own N needs and benefit subsequent crops (Ditzler et al. 2021; Jensen et al. 2010; Palmero 2022), and incorporating these benefits is crucial for profitable grain legume cultivation (Preissel et al. 2015). Sensitivity analysis shows that a substantially higher revenue (i.e., 50%) only has a limited impact on the optimal cropping plan. The share of field beans is close to the maximum (i.e., once every 5 years), and despite higher revenues, other crops such as potatoes and onions are more profitable.

4.2 Limitations and opportunities for on-farm decision support

In this section, we discuss the main challenges that need to be addressed before a model like FARManalytics can be applied for on-farm decision support.

4.2.1 Limited number of case farms

Case farms were selected from the Farmers Network for Soil Sampling. Farmers in this network already have a strong interest in sustainable soil management explaining the already good performance of soil quality indicators. Although the number of studied farms is limited, these case farms exhibit substantial diversity in soil type and farm setup, offering a representative overview of arable farms in the Netherlands. The wide variation in soil type

and management styles underscores the need for customized solutions. Despite the network bias and small sample size, this study illustrates the added value of integrated bio-economic modeling of soil quality and farm economics. It suggests that even for front-runners, a substantial increase in farm income seems to be achievable while preserving soil quality. Future research should consider using larger samples of randomly selected farms to enhance generalizability. When extrapolating the findings of this study to arable farming in the Netherlands as a whole, we hypothesize that more intensive farms may face greater challenges in increasing farm income while meeting soil quality targets. Current production management of these intensive farms may push soil quality closer to the limit, leaving less room for improvement.

4.2.2 Spatial variability within farms

Currently, spatial allocation of production management is organized at farm level, assuming homogeneity in soil quality and field characteristics across the entire farm. We justify this decision based on balancing required input, model complexity, and result quality. However, two aspects have critical consequences. First, soil quality can vary substantially within a farm, meaning not every management decision is suitable for every field. For example, a field with low soil organic matter content might require more organic matter input and, hence, other management decisions than a field with high soil organic matter content. This is illustrated by Lessmann et al. (2022) and Moinet et al. (2023) who emphasize the importance of initial soil conditions in carbon sequestration potential. Second, we assume that available farmland can be flexibly allocated to different crops, whereas, in reality, field size and location are key drivers of crop allocation. For example, implementing a 12-year crop rotation on four 10-ha fields implies that every field has to be split into three parts, resulting in 12 fields of 3.33 ha. Castro et al. (2018) and Dury et al. (2012) recognize that many bio-economic farm models fail to sufficiently address spatial issues.

4.2.3 Validation

Output validation and end-user validation are key concepts in model validation (Bockstaller and Girardin 2003). Output validation ensures that model results are realistic and reliable by comparing them with measured data (Groot et al. 2012). End-user validation assesses the usefulness of model results for decision support. (Bockstaller and Girardin 2003). We discussed results in an iterative way with the farmers, which contributed to both output and end-user validation. Farmers perceived the results as useful and confirmed the added value of integral decision support on soil quality. The most

prevalent reasons for not adopting model suggestions concerned risks (e.g., of soil compaction when applying manure in spring) and changing circumstances (e.g., higher prices for crops in recent years than averages used in this study). A more thorough output validation can be achieved by comparing model-predicted soil quality indicators with long-term trial data, such as those described by Korthals et al. (2014) and Schrama et al. (2018). Regarding end-user validation, the current bio-economic modeling approach allows for the economic evaluation of scenarios, which provides decision support for farmers. However, when optimizing their production management, farmers take more economic aspects into account than just average profit, risk, and uncertainty. Therefore, we recommended doing a structured end-user validation in which farmers reflect on solutions provided by the model and indicate their reasons for implementing these suggestions or not.

4.2.4 Resource availability and product market

In our farm-level optimization, factors like market prices, product demand, climate factors, and regional impact are treated as exogenous variables (Dogliotti et al. 2005). However, production management decisions cannot be considered outside of their socio-economic context (Castro and Lechthaler 2022). For example, the preference for cattle slurry and compost in most scenarios assumes their availability and stable pricing despite potential increases in demand. Similarly, in the field beans scenario, we assume a demand based on current yields and expected prices, but the actual existence of this demand remains uncertain.

4.3 Implications

This study shows that management advice derived from the bio-economic modeling of soil quality and farm economics can increase farm income while improving soil quality. We first discuss the implications of our results at the farm level. Second, we outline the implications for policy makers.

4.3.1 Implications at farm-level

Even for the nine farmers who are actively concerned with sustainable soil management, our study indicates substantial potential to increase profit while improving soil quality. These findings suggest that similar results could be achieved for other arable farms in the Netherlands. The results from this study show how FARManalytics can offer alternative production management decisions to adapt to evolving legislations (e.g., water quality) and changes in product demand (e.g., field beans). These developments require a change of current production management and FARManalytics can help to make the right decisions. Ultimately, this ensures

the long-term preservation of soil quality in a financially robust strategy. To yield useful and reliable results, it is crucial to tailor the FARManalytics model to farm-specific conditions, especially when making crop rotation decisions. Given the considerable variation in crop profitability among farms growing the same crop, accurate cost and revenue data are essential inputs for the model. A farmer's expertise remains essential since FARManalytics does not cover crucial aspects like production risk, robustness of choices, spatial allocation of activities, and variation in fields.

4.3.2 Implications for policy makers

Insights from this study offer valuable information for policy makers and illustrate the importance of policy impact analysis. Broader application of the methods used in this study on a larger and less biased sample of farms will provide more insights. This study goes beyond existing studies like those by de Haan et al. (2021) and Ros et al. (2022) by assessing current soil conditions and their relationship with production management. This allows us to predict potential soil quality issues under different combinations of soil conditions and management strategies. For broader implementation, we recommended a thorough validation of the soil quality quantification in FARManalytics. The FARManalytics model can be extended with environmental performance indicators to perform policy impact analyses on policies aiming at improving environmental quality. For example, in the water quality scenario in this study, policy impact analysis would be beneficial for assessing the effects of measures on indicators like nitrate leaching. FARManalytics is also able to calculate economic returns based on production management decisions. Calculating the expected profit change for farmers to reach environmental targets could be useful for policy makers to create financial incentives needed to encourage change in production management.

5 Conclusions

The objective of this study was to optimize production management to achieve maximum profit while increasing long-term soil quality on nine case farms in the Netherlands using the bio-economic model FARManalytics. Nutrient management, subsoil compaction vulnerability, and soil organic matter input are current bottlenecks to soil quality in the Netherlands. In a scenario studying the impact of stricter water quality regulation policies, we found that these policies limit

production management decisions, thereby reducing potential farm income. In a scenario studying the potential of field beans (*Vicia faba*) as an alternative crop, we found that it can potentially replace some cereals and positively contribute to farm income and sustainable soil management. However, field beans cannot yet compete with cash crops like potatoes or onions. Based on these scenarios, we conclude that FARManalytics is able to offer alternative production management strategies to comply with evolving legislation or market shifts tailored at farm level. We show that the novel bio-economic model FARManalytics allows the preservation of soil quality in a financially robust strategy by selecting appropriate production management. Even for front-runners, optimization can increase profit up to €704 ha⁻¹ while meeting soil quality targets, except for subsoil compaction. These findings underpin the added value of integral modeling of soil quality and farm economics with FARManalytics.

Appendix 1: Production management decisions in FARManalytics

Decision	Definition	Example
Crop rotation ¹	The sequence of crops grown on a field	<ul style="list-style-type: none"> • WW-SB-WW-WP • WW-WW-SB-WP
Cover crop ²	A close-growing crop that provides soil protection, seedling protection, and soil improvement between periods of main crop production	<ul style="list-style-type: none"> • Yellow mustard was planted after winter wheat (1-Aug) and terminated before potato planting (1-Apr).
Manure	Organic matter originating from live-stock husbandry or composting	<ul style="list-style-type: none"> • 30-ton ha⁻¹ pig slurry applied 1 Mar • 20-ton ha⁻¹ compost applied 1 Oct
Fertilizer	Application of plant nutrients through natural or synthetically produced fertilizer	<ul style="list-style-type: none"> • 200 kg calcium ammonium nitrate (27% N) application on 1 May
Crop residue management	Decision to sell crop residues to generate revenue or keep them on the field to enhance soil quality	<ul style="list-style-type: none"> • Sell wheat straw • Keep wheat straw and incorporate it into the soil

¹Castellazzi et al. (2008)²Ramesh et al. (2019)

Appendix 2 Production management decisions case farms

See Table 4

Table 4 Farm characteristics and current production management decisions for nine arable case study farms from the Netherlands. For acronyms, see below

Nr.	1	2	3	4	5	6	7	8	9
Farm	Sand	Sand-river clay	Loess	Clay organic	Clay nord	Clay river	Clay polders	Clay southwest 1	Clay southwest 2
Acronym	S	S-CR	L	CO	CN	CR	CP	CSW1	CSW2
General characteristics									
Soil type	Sand	Sand/river clay	Loess	Sea clay	Sea clay	River clay	Sea clay	Sea clay	Sea clay
Farm type	Conventional	Conventional	Conventional	Organic	Conventional	Conventional	Conventional	Conventional	Conventional
Tillage system	Plowing/spading	Non-inversion tillage	Non-inversion tillage	Non-inversion tillage	Plowing/subsoiling	Plowing/subsoiling	Plowing/subsoiling	Non-inversion tillage	Non-inversion tillage
Size	Large	Middle	Middle	Middle	Middle	Middle	Small	Middle	Middle
Crop rotation									
Crop rotation	STP-SPB-SB-SP-SC-SB-	WP-SB-KC-WW	WP-SO-SB-WW-WP-SPB	GC-CA-WB-SPI	SP-WW-WB	WP-WW-SB-WW-	SP-SB-GS-SO	WP-WW-SO-WW-WP-WW-	WP-WW-SB-WW-SP-WW
Crop rotation (continued)	SC-SPB	WP-KC-KC-WW	SB-WW-WP-SO-SB-WW	GC-SO-PE-GB		WP-WW-SO-WW	SP-SB-WW-TU	GS-PE-WP-WW-SB-SC	SO-WW-WP-WW-CA-WW
Cover crops	SPB; winter radish SC: rye	WW; white radish KC-> KC: Avena Strigosa	WW; yellow mustard SPB; yellow mustard	GC: rye WB/SPI/PE: mix 3 SO: mix 4	WW-> SB: mix 1 WW/WB-> SP: mix 2	WW; yellow mustard	SO: yellow mustard WW: grass TU: mix 5	WW: mix 2 PE: mix 2 GS: GS	WW: mix 3
Manure (ton ha ⁻¹)	STP _s : 25 PS SPB _{at} : 35 CS SB _s : 35 CS SB _s : 3 NKM SP _s : 20 CS SP _s : 2 KF SC _s : 40 CS SC (8): 20 GRC	WP _s : 40 CS SB _s : 40 CS KC _s : 40 CS WW _{at} : 30 CS	WP _s : 30 PS WW _s : 40 CS SPB _{at} : 40 CS SC _s : 40 CS	GC(1) _{at} : 20 GSM ₀ CA _{at} : 20 GSM ₀ WB _{at} : 20 GSM ₀ SPL _{at} : 20 GSM ₀ SP _s : 5 VKA GC(5) _{at} : 15 GSM ₀ SO _{at} : 12 GSM ₀ PE _{at} : 20 GSM ₀ GB _{at} : 15 GSM ₀	SP _{at} : 15 CSF WW _s : 20 CS WB _{at} : 3.5 PM	WW _s : 30 PS WW(5) _{at} : 30 CH	GS _{at} : 30 CH SO _s : 22.5 CH TU _{at} : 30 CH	WP(1) _s : 20 PS WW _s : 30 CS WW(2) _{at} : 20 CS WW(4) _{at} : 20 CS WW(9) _{at} : 20 CS GS _{at} : 20 CS SC _s : 30 CS	WW _s : 37.5 CS WW _{at} : 22.5 CSM
Liming (ton ha ⁻¹)	SB _s : 5 BET	WP _{at} : 5 BET	WP _{at} : 5 BET			WP _{at} : 5 BET	SP _{at} : 5 BET		

Table 4 (continued)

Nr.	1	2	3	4	5	6	7	8	9
Farm	Sand	Sand-river clay	Loess	Clay organic	Clay nord	Clay river	Clay polders	Clay southwest 1	Clay southwest 2
Acronym	S	S-CR	L	CO	CN	CR	CP	CSW1	CSW2
Crop residue management	SPB: keep	WW: keep	WW: keep SPB: keep	WB: sell	WW: sell WB: sell	WW: sell	GS: keep WW: sell	WW: keep GS: sell	WW: keep
Fertilizer (kg N/P/K/S/Mg ha ⁻¹) (cluster a)	N: 54 P: 3 K: 20 S: 2 Mg: 3	N: 71 P K S Mg: 5	N: 99 P K: 67 S Mg Manure	N P K S Mg	N: 108 P: 20 K: 58 S: 26 Mg Cover cops	N: 108 P K: 74 S: 31 Mg	N: 93 P: 8 K: 9 S Mg	N: 84 P: 6 K: 33 S: 45 Mg: 6	N: 118 P K: 61 S: 31 Mg: 19
Crops									
CA: Carrots	SC: Silage corn	SPI: Spinach	BET: Betacal	KF: Kali flow	mix 1	DSV Betasola			
GB: Green beans	SO: Seed onions	STP: Starch potato	CH: Champost	NKM: NakaMag	mix 2	DSV Solarigol			
GC: Grass dover	SP: Seed potato	WB: Winter barley	CS: Cattle slurry	PS: Pig slurry	mix 3	Oats/Vetch/ Phacelia			
GS: Grass seed	SB: Sugar beets	WP: Ware potato	CSF: Cattle slurry solid fraction	PM: Protamyl- asse	mix 4	Oats/Yellow mustard			
KC: Corn (kernel)	SPB: Spring barley	WW: Winter wheat	GRC: Green compost	VKA: Vinasse potassium	mix 5	DSV WarmSea- son			
PE: Peas			GSM _o : Goat Solid Manure (organic)						

Table 5 Overview of proposed measures from EU Nitrate Directive (ND) and loss of derogation (DER)

Measure	Source	Implementation	Soil types
Break crops	ND	- Compulsory break crop ¹ every 3 years at field level	Sand, loess
Catch crops	ND	- Recommended catch crop ² after all crops except winter crops ³ - Discount on N norm if harvest after 1 Oct and no catch crop - Compulsory catch crop after corn	Sand, loess All
P norms	ND	- No N fertilization space for cover crops (except non-leguminous cover crops after wheat, grass seed and rapeseed) - P in compost counts 25% for legal P norm - P in solid manure/champost counts 75% for legal P norm	All All
N autumn	ND	- After August 1st, not more than 60 kg N-total via slurry	All
Buffer zones	ND/DER	- Uncultivated buffer zones next to water streams (implemented as 4% of total area)	All
Nutrient norms	DER	- 20% discount on fertilization norms in “nutrient polluted areas” (implemented as 20% discount on total N fertilization)	All

Appendix 3. Model implementation WQ scenario

Model implementation: WQ scenario

The objective of this scenario study is to study the impact of two major changes in agricultural policy and legislation relating to the preservation of water quality. These changes are the results of the implementation of the following:

1. 7th EU Nitrate Directive. Implemented from 1-1-2023 onwards in different phases.
2. Loss of derogation: Implemented from 1-1-2023 onwards in different phases.

In both policies, transitions from the current situation toward the desired situation if formulated. We choose to study the impact of the final/desired situation because that is in the end the legislation farmers have to comply with

A short overview of the proposed measures can be found in the Table 5.

Overview

See Table 5

For each of the measures, their precise model implementation is explained below:

1. Break crops

A list with the break crops (also called rest crops) has been published by the Dutch government: <https://www.rvo.nl/onderwerpen/mest/rustgewassen>

The rest crop requirement is implemented as additional code that filters the ROTAT+ output. All rotations not

matching the rest crop requirements are removed from the list with feasible rotations. The rationale is as follows:

- Counter for rest crops start in 2023
- Result of the counter is evaluated every 3 years, so the first evaluation is over the years 2023, 2024, and 2025.
- If one or more rest crops found -> pass and continue to the next cycle
- No rest crops found: -> fail
- This procedure is repeated until the end of the rotation. If no complete number of 3-year cycles fits in the rotation, at least one rest crop has to be found in the incomplete cycle.

For example the rotation:

Non-rest–Rest–Non rest–Non rest

Is not feasible: on average only once every four years a rest crop is implemented

Examples can be found below:

2023	2024	2025	2026	2027	2028	Result
NRC	RC	NRC	NRC	RC	NRC	pass
NRC	RC	NRC	NRC	NRC	RC	pass
NRC	NRC	RC	RC			pass
NRC	NRC	RC	NRC			fail
NRC	RC	NRC	NRC	RC	RC	fail

NRC non rest crop, RC rest crop

2. Catch crops

The catch crop measures consist of (1) a *recommended* catch crop after all crops and (2) a *compulsory* cover crop after corn

Recommended catch crops

On sandy and loess soil, a catch crop planted before October 1st is recommended to avoid nitrate leaching. This implies that crop harvest also has to be done before October 1st. An exemption is made for crops that are considered “winter crops.” A list with winter crops and allowed catch crops can be found at <https://www.rvo.nl/nieuws/vanggewassen-winterreelten-en-korting-gebruiksnorm>

If no catch crop is planted, the farmers get a discount on the total N norm next year. This implies that the farmers are allowed to use less nitrogen in the next year. The N discount is the following:

Inzaaidatum	Korting op stikstofgebruiksnorm
2 oktober t/m 14 oktober	5 kg N/ha
15 oktober t/m 31 oktober	10 kg N/ha
Vanaf 1 november	20 kg N/ha

Despite the N discount, it is unlikely that farmers start harvesting crops that are not matured before the 1st of October before the date to plant a catch crop. The most prevalent example will be the harvest of ware potatoes. The model implementation therefore is as follows:

- Winter crop (e.g., sugar beets, starch potatoes)—Do not plant catch crop without consequences
- No winter crop and “standard” harvest before the 1st of October (e.g., wheat, barley, seed onions)—Require to plant catch crop and avoid N discount.
- No winter crop and “standard” harvest after the 1st of October (e.g., ware potatoes)—Do not require catch crop and incur N discount

Compulsory catch crops

On all soils, planting a catch crop after corn becomes compulsory. The following options exist:

- Under sowing of catch crop, no final harvest date
- Plant catch crop after harvest: harvest before October 1st and plant catch crop
- Plant subsequent main crop serving as catch crop: harvest before October 31st and plant winter rye, winter barley, or winter wheat.

3. P norms

The nitrate directive wants to stimulate the use of compost and solid manure. Therefore the P in compost only counts for 25% in the calculation of the legal P application, this was 50%. The P in solid manure and champost counts for 75% in the legal P application, this was 100%.

For compost, this was already implemented as only filling in 50% of the P of compost in the manure table. For example, the P content of GFT compost is 2.2 kg ton⁻¹, but in the manure table, we used a value of 1.1 kg ton⁻¹. However, this implies that the P in compost also only counts for 50% in the calculation of the P advice. This is justified as not all P in compost is plant-available P. <https://edepot.wur.nl/541822>

Implementation

- We calculate the “Legal P” application apart from the “actual P” application that is used in the P advices
- For compost, for the legal P application, we count 50% of the P application (which is already 50%) of the total P content, see above. So, we calculate 50% of the P content in compost for the actual P application and 25% of the total for the legal P application
- For solid manure and champost, we count 75% of the total P application for the legal P application but we count 100% of the total application for the actual application.

4. N application autumn

The nitrate directive wants to limit the application of slurry in autumn. Therefore, the application of more than 60 kg N-total ha⁻¹ via slurry is forbidden after the 1st of August

Implementation

- Added agronomic constraint that forbids autumn slurry application after the 1st of August with more than 60 kg N-total.

5. Buffer zones

Buffer zones have a considerable financial impact because they result in a substantial loss of productive area. However, in the current scenario, the impact of buffer zones is not implemented as buffer zones are not a management variable included in the model.

6. Nutrient norms

As a result of the loss of derogation, the following measure applies:

“In nutrient polluted areas, the total fertilization with organic manure and mineral fertilizers is decreased gradually in such a way the percentages from January 1st, 2025 are 20 percent point lower than the percentages published in the Nitrate Directive.

Until further notice, the central and south sandy soils and loess soils are nutrient-polluted areas.

Implementation

- On farms on sandy soil (south) or loess soils, 20% discount on total N application space.

Appendix 4. Production management choices scenarios

See Table 6

Table 6 Production Management choices made by the bio-economic modeling approach FARManalytics for scenarios on arable case farm in the Netherlands

		Crop rotation												Rest crops (%)	Cover crops (% cc)	Cover crops types	Crop residues (keep/sell)	Manure & lime (avg. kg ha ⁻¹ y ⁻¹)					Fertilizer (avg. kg ha ⁻¹ y ⁻¹)						
		1	2	3	4	5	6	7	8	9	10	11	12					PS	CS	solid	compost	lime	N	P	K	S	Mg		
S	b	STP	SPB	SB	SP	SC	SB	STP	SC	SB	SP	SC	SPB	16.7	42.0	WR, RY	keep	4.2	27.9	0.0	1.7	1.3	BET	43	0	0	0	0	
	ss	SP	SC	SB	SP	SC	SB	SC	SPB	SC	SPB	SC	SB	16.7	75.0	AV, YM, WR	sell		33.3	7.5	7.4			21	0	0	13	0	
	fs	SP	SC	WB	WP	SC	WB							33.3	33.3	WR	sell	5.3	16.7	5.0	10.0	2.2	BET	50	0	0	9	0	
S-CR	b	WP	SB	KC	WW	WP	KC	KC	WW					25.0	37.5	WR, AV	keep							71	0	0	0	5	
	ss	WP	SB	KC	WW									25.0	50.0	YM, AV	sell	18.0	8.0		6.8	3.7	BET	34	0	0	3	0	
	fs	WP	SC	GC	GC	WP	SC	GC						37.5	25.0	AV	NA	20.1	9.0		3.8	4.5	BET	0	0	0	3	0	
L	b	WP	SO	SB	WW	WP	SPB	SB	WW	WP	SO	SB	WW	33.3	33.3	YM	keep	7.5	13.3			1.3	BET	11	0	67	0	0	
	ss	WP	WW	SB	SPB	WP	SPB	SB	SO					37.5	62.5	YM, AV	sell		5	22.9		9	2.5	BET	45	0	0	10	0
	fs	WP	SB	SPB	SO	WP	SPB	SB	WP	SPB	SO	SB	WW	25.0	75.0	AV, YM	sell	6.7	17		6.5	2.2	BET	34	0	0	10	0	
CO	b	GC	CA	WB	SPI	GC	SO	PE	GB					37.5	75.0	MIX, RY, YM	keep			17.1				0	0	0	0	0	
	ss	WB	PE	SO	GC	SPI	GC	GC	CA					37.5	37.5	MIX, AV	sell		30.0		4.2	4.3	BET	0	0	2	1	1	
	fs	GC	CA	WB	SPI	GC	SO	PE	GB					37.5	37.5	MIX, AV	sell		22.9		7.4	4.8	BET	0	0	2	1	1	
CN	b	SP	WW	WB	SP	WW	WB	SP	SB	WB				55.5	33.3	MIX	sell	4.5	5.0					108	20	58	26	0	
	ss	SP	WW	WB	SP	SB	WW							50.0	33.3	AV	sell		32.0	2.1				87	0	0	2	0	
	fs	SP	WW	SB	WW	SP	WW	SO	WW	SP	SB	WW		45.0	36.3	AV	sell		38.6	2.2				98	0	0	2	0	
CR	b	WP	WW	SB	WW	WP	WW	SO	WW					50.0	37.5	YM	sell	15.0		4.7		1.3	BET	108	0	74	31	0	
	ss	WP	WW	SB	WW	WP	WW	SO	WW					50.0	37.5	YM	sell	4.8	36.3	0.6	8.6	3.0	BET	87	0	0	2	0	
	fs	WW	SO	WF	SB	WW	FL	WF	SB					62.5	37.5	YM, WR	sell	5.0	22.5	2.7	8.5	2.6	BET	32	0	0	4	0	
CP	b	SP	SB	WW	TU	SP	SB	GS	SO					25.0	50.0	MIX, YM, GR	sell, keep			11.3		1.3	BET	93	8	9	0	0	
	ss	SP	SB	GS	SP	WW	TU	SB	SP	GS	SB	WW	TU	33.3	58.3	GR	sell	6.7	19.6			2.6	BET	41	0	0	0	0	
	fs	GR	SP	GR	GR	SB	SP	GR	TU					50.0	0	NA	NA	3.5	30			3.0	BET	78	0	1	0	0	
CSW-1	b	WP	WW	SO	WW	WP	WW	GS	PE	WP	WW	SB	SC	50.0	41.6	MIX, GR	keep	2.1	17.3	1.3				82	0	33	45	6	
	ss	WP	WW	SB	PE	WP	GS	SB	SC					37.5	62.5	AV, WR	sell, keep		30.2		8.9			52	0	0	7	0	
	fs	WP	GS	PO	PE	WP	GS	CE	SC					37.5	62.5	AV	sell, keep		28.8		8.9			25	0	0	5	0	
CSW-2	b	WP	WW	SB	WW	SP	WW	SO	WW	WP	WW	CA	WW	50.0	50.0	MIX	keep		18.8	11.3				118	0	61	31	19	
	ss	WP	WW	SB	WW	SP	WW	CA	WW					50.0	25.0	YM	sell	15	19.6		0.6			41	0	0	2	0	
	fs	WP	WW	SO	SB	WW	CA	WW	SP	WW	SB	WW		41.7	33.3	YM	sell	16.4	14.5		0.4			34	0	0	3	0	

Crops			Manure			Cover crops			
CE	: Celeriac	KC	: Corn (kernel)	SPI	: Spinach	BET	: Betacal	WR	: Winter radish
CA	: Carrots	PE	: Peas	STP	: Starch potato	PS	: Pig Slurry	RY	: Rye
FL	: Flax	SC	: Silage corn	TU	: Tulips	CS	: Cattle slurry	AV	: Avena Strigosa
GB	: Green beans	SO	: Seed onions	WB	: Winter barley			YM	: Yellow mustard
GC	: Grass clover	SP	: Seed potato	WF	: Winter field beans			GR	: Grass
GR	: Grass	SB	: Sugar beets	WP	: Ware potato				
GS	: Grass seed	SPB	: Spring barley	WW	: Winter wheat				

Appendix 5. Production management choices field beans

See Table 7

Table 7 Crop rotations, share of rest crops & field beans and average nitrogen (N) fertilizer application for baseline scenario, field beans with base revenue, and field beans with +50% revenue

Farm	Scenario	Crop rotation												Rest crops (%)	Field beans (%)	N fertilizer (avg. kg ha ⁻¹ y ⁻¹)
		1	2	3	4	5	6	7	8	9	10	11	12			
S	b	STP	SPB	SB	SP	SC	SB	STP	SC	SB	SP	SC	SPB	16.7	0	43
	fb base	SF	SC	SB	SP	SC	SB	SP	SC	SB	SC	SPB	SC	16.7	8.3	14
	fb + 50%	SF	SC	STP	SB	SC	SF	SC	SB	SP	SC	SB	SP	16.7	16.7	13
S-CR	b	WP	SB	KC	WW	WP	KC	KC	WW					37.5	0	71
	fb base	WP	SB	KC	WW	WP	SB	KC	WW	WP	SB	KC	SF	25	8.3	54
	fb + 50%	WP	SB	KC	WW	WP	SB	SF	WW	WP	SB	KC	SF	25	12.5	40
L	b	WP	SO	SB	WW	WP	SPB	SB	WW	WP	SO	SB	WW	33.3	0	99
	fb base	WP	SPB	SB	SPB	WP	WF	SB	SO					37.5	12.5	24
	fb + 50%	WP	SPB	SB	SPB	WP	WF	SB	SO					37.5	12.5	24
CR	b	WP	WW	SB	WW	WP	WW	SO	WW					50	0	108
	fb base	WW	SB	WW	WP	WW	SO	WF	WP					50	12.5	62
	fb + 50%	WW	SB	WW	WP	WF	SO	WW	WP	WW	SB	WF	WP	50	16.7	50
CSW-2	b	WP	WW	SB	WW	SP	WW	SO	WW	WP	WW	CA	WW	50	0	118
	fb base	WP	WW	CA	WW	SP	WW	SB	WF					50	12.5	21
	fb + 50%	WP	WW	CA	WW	SP	WW	SB	WF					50	12.5	21

SF spring field beans, WF winter field beans

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due privacy of the individual farmers but are available from the corresponding author on reasonable request.

Code availability The code is available on request to the author.

Declarations

Ethics approval Not applicable

Consent to participate Informed consent was obtained from all individual participants in this study.

Consent for publication Informed consent was obtained from all individual participants in this study to publish the data as presented in this manuscript.

Conflict of interest The authors declare no competing interests.

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