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How to make regenerative practices work on the farm: A modelling framework

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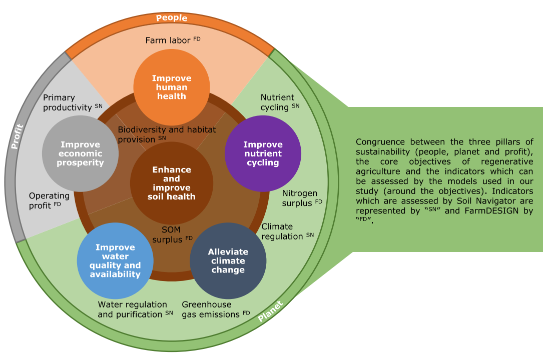
HIGHLIGHTS

- Regenerative agriculture has multiple objectives and there is a need to make these objectives explicit at the farm-level.
- We demonstrate a modelling framework for an ex-ante design and assessment for farming systems on regenerative objectives.
- This modelling framework takes context-specific management practices center-stage to optimize overall farm sustainability.
- Using a dairy case-study farm we show that soil functions can be improved at the expense of farm profitability.
- Further calibration and validation is needed to apply Soil Navigator on peat soils across Europe.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Well-managed agricultural land can provide ecosystem services and contribute positively to the environment. Many of these services are mediated through the soil and are referred to as soil functions. Regenerative agriculture is a mode of agriculture that uses soil conservation as the entry point to regenerate and contribute to these ecosystem services, with the aspiration that this will enhance not only environmental, but also social and economic dimensions of food production.
OBJECTIVE: The main objective of this paper is to create a modelling framework which allows the ex-ante redesign of diverse farming systems and assessment of ecosystem services associated with regenerative agriculture in diverse pedo-climatic conditions.
METHODS: Within this modelling framework we combined two models (Soil Navigator (SN) and FarmDESIGN (FD)) to consider soil attributes at the field-scale and environmental and socio-economic outcomes at farm-scale. We used a Dutch dairy-farm as case-study to demonstrate how this framework can be used to assess associated ecosystem services and explore alternative farm configurations.

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RESULTS AND CONCLUSIONS: Combining SN with FD indicated what ecosystem services could be improved in a local context. Together these models help to evaluate the impact of soil management practices as the basis for exploring the overall socio-economic and environmental sustainability of our dairy case-study farm. For our dairy case-study farm, we found a set of management practices that delivered four out of the five functions at a high capacity, at the expense of primary productivity (from high to medium) and farm profitability (from 55,620 to 40,720 € yr^{-1}). The decline in primary productivity, however, causes an improvement in other ecosystem services such as, climate regulation (increased from medium to high) and the soil organic matter surplus (increased with 7%). While this study successfully demonstrated an initial combination of SN and FD models for the ex-ante redesign and assessment of farming systems towards regenerative agriculture, further model development is essential to widen the applicability of this study to include emerging farming practices and new indicators of sustainability that are measured over a longer period.

SIGNIFICANCE: For regenerative agriculture to be meaningful for diverse farming systems, we need methods that give insight into the efficacy of regenerative management to meet multiple ecosystem services within local contexts. As such, our modelling framework can be used by researchers as a tool to help various stakeholders to assess and redesign farms based on the objectives of regenerative agriculture.

1. Introduction

The global food system has a detrimental impact on the environment and currently releases about 25% of annual anthropogenic greenhouse gas (GHG) emissions, causes about one-third of terrestrial acidification and is responsible for the majority of global eutrophication of surface waters (Poore and Nemecek, 2018). For the agricultural sector, as part of this global food system, a wide variety of sustainable farming approaches that aim to limit detrimental environmental impacts are gaining both public and academic attention. Farmers using these approaches show that while agriculture has detrimental impacts on the environment, well-managed agricultural land can also provide ecosystem services and contribute positively to the environment (FAO and ITPS, 2021). One of these farming approaches is regenerative agriculture, which takes the soil as the entry point (Schreefel et al., 2020) and hence, is most relevant to areas where environmental stresses result in soil degradation or poor soil health (FAO and ITPS, 2015; Stolte et al., 2016). On agricultural land, many of these ecosystem services are mediated through the soil. The capacity of the soil to support these services can be summarized into five soil functions: primary productivity, climate regulation, nutrient cycling, water purification and regulation, biodiversity and habitat provision (Bünemann et al., 2018; Haygarth and Ritz, 2009; Schulte et al., 2014). These five soil functions, supplied by agricultural land, meet societal demands for soil multifunctionality (e.g. to produce food but also biodiversity). These societal demands for soil multifunctionality are currently center-stage in international agreements such as the Paris Climate Agreement (United Nations, 2015), the Common Agricultural Policy (European Commission, 2019a), the Biodiversity Strategy (European Commission, 2021) and the European Green Deal (European Commission, 2019b).

A review by Schreefel et al. (2020), defined regenerative agriculture as "*a mode of agriculture that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating and supporting ecosystem services, with the aspiration that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production*". From this review regenerative agriculture seems to be a goal-orientated approach, the objectives for regenerative agriculture described by Schreefel et al. (2020) are, however, broad. The extent to which these objectives can be achieved, depends on their local context (e.g. management and pedoclimatic conditions). Moreover, regenerative practices are not equally relevant, applicable or effective for all farming systems (Giller et al., 2021; Luján Soto et al., 2021). For regenerative agriculture to be meaningful for diverse farming systems, a variety of actors (e.g. governmental agencies, sector organizations, industries and farmers) need methods that can give them insight in the efficacy of regenerative practices which influence the services ecosystems can deliver to meet multiple regenerative objectives within local contexts (Giller et al., 2021). These methods should not only give insight into which practices contribute to the transition towards regenerative agriculture, but also show farmers on which objectives they can focus within their local context. The feasibility of regenerative practices is, therefore, not only dependent on their efficacy to contribute for example to soil health, but also on their effect on other sustainability aspects (e.g., farm profitability and human wellbeing). If we are not able to show actors which objectives and practices contribute to a healthier soil and other sustainability aspects, it will hinder the transition towards regenerative agriculture.

The ex-ante redesign of diverse farming systems and assessment of regenerative objectives in pedo-climatic conditions requires a modelling framework that links regenerative farm management practices at field-scale to environmental and socio-economic outcomes at farm-scale. In agricultural system research, biophysical models are used for the ex-ante redesign of faming systems and assessment of associated farm practices to meet specific objectives. Despite their proven usefulness (Pannell, 1996; Reidsma et al., 2018), many of these models do not address the full complexity of farming systems (Silva and Giller, 2021; van der Linden et al., 2020). Silva and Giller et al. (2021), for example, argue that attention needs to be given in biophysical models to show the interactions between the different farm components. These interactions between farm components occur between hierarchical levels (e.g. between field and farm-level), between components within each level (e.g. multiple fields within a farm), and between the biophysical and socio-economic dimensions (van der Linden et al., 2020; van Ittersum et al., 2008). Most biophysical processes are measured at field-level, where for example carbon is sequestered and nutrients are utilized for crop production. However, decision-making processes at the farm-level are also guided by socio-economic factors. Although, farmers may consider both biophysical processes and socio-economic factors within decision-making processes, models are often oversimplified and therefore focus on one scale. Up-scaling biophysical processes from field to farm-level requires information transfer within each component (e.g. soil organic matter input effects on different environmental aspects) and across components (e.g. environment, social and economic aspects) (Ewert et al., 2011). The ex-ante redesign of farming systems and assessment of ecosystem services associated with regenerative agriculture, therefore, requires a link between models which can assess soil health at the field-scale with models which consider broader systems objectives at the farm-scale.

The complexity and performance of farm practices within the context of broader sets of environmental and socio-economic objectives can already be modelled by individual integrative farm models, e.g. FarmDESIGN and LiGAPS (Groot et al., 2012; van der Linden et al., 2020). These models allow actors to evaluate trade-offs and synergies between different farm management decisions and outcomes (e.g. Janssen and van Ittersum, 2007; Thornton and Herrero, 2001). However, most of these farm models make only tenuous references to soil health, and often assume a homogeneous soil type for the whole farm. As such, these models are limited in their capacity to optimize or assess the effectiveness of soil based regenerative practices in real-farm scenarios. Contrastingly, models that are specifically focused on the assessment of soil multi-functionality (e.g. Soil Navigator and Open Soil Index) operate at a field-level and acknowledge the diversity of soil properties within farms (Debeljak et al., 2019; Ros and Fujita, 2019). These soil assessment models, however, commonly lack an assessment of the environmental and socio-economic impacts of soil management practices at farm-level. In this paper, we demonstrate a modelling framework for the ex-ante redesign for diverse farming systems and assessment of ecosystem services associated with regenerative agriculture in pedo-climatic conditions that link soil management practices at field scale to environmental and socio-economic outcomes at farm scale. As such, we link two models: Soil Navigator (Debeljak et al., 2019) and FarmDESIGN (Groot et al., 2012) and evaluate the efficacy of this framework in exploring and optimizing the selection of regenerative objectives and soil management practices for diverse farming systems using a Dutch dairy-farm as a case study. Our aim is that this framework can be used by researchers as a tool to help various stakeholders to assess and redesign farms to transition towards regenerative agriculture.

2. Materials & methods

2.1. Relation of the selected models with regenerative agriculture and their mode of operation

We selected two innovative models used by researchers: Soil Navigator (SN) (e.g. Vazquez et al., 2020; Zwetsloot et al., 2020) and FarmDESIGN (FD) (e.g. Adelhart Toorop et al., 2020; Timler et al., 2020), to assess a broad range of indicators that relate to all objectives of regenerative agriculture (described by Schreefel et al., 2020), see Fig. 1. SN is a soil assessment tool developed to qualitatively assess simultaneously five soil functions at field-level (Debeljak et al., 2019): primary productivity (Sandén et al., 2019), nutrient cycling (Schröder et al., 2016), water purification and regulation (Wall et al., 2020), climate regulation (van de Broek et al., 2019), and biodiversity and habitat provision (Leeuwen et al., 2019). These five soil functions considered play a key-role in the supply and demand for soil-based ecosystem services (Schulte et al., 2014), and are largely congruent with the objectives of regenerative agriculture at farm-level, as defined by Schreefel et al.

Fig. 1. Congruence between the three pillars of sustainability (people, planet and profit), the core objectives of regenerative agriculture with underlying objectives (in the circles) and the indicators which can be assessed by the models (around the objectives). Indicators which are assessed by Soil Navigator are represented by "SN" and FarmDESIGN by "FD".

(2020). The objectives from Schreefel et al. (2020) relevant at the farm-level are to "*enhance and improve soil health*", "*alleviate climate change*", "*improve nutrient cycling*", "*improve water quality and availability*", "*improve economic prosperity*" and "*improve human health*". The congruence between the objectives of regenerative agriculture and the different soil functions are shown in Fig. 1 and summarized by the following bullet points:

- Improve economic prosperity is reflected by the soil function primary productivity which is the economic foundation for farmers and a prerequisite for agricultural sustainability (Sandén et al., 2019). Primary productivity is determined by the capacity of a soil to supply nutrients and water to produce plant biomass for human use, providing food, feed, fiber, and fuel within natural or managed ecosystem boundaries.
- The objective of regenerative agriculture to improve nutrient cycling is reflected in the soil function nutrient cycling, which indicates the capacity of the soil to receive nutrients, to make and keep nutrients available to crops, to support the uptake of nutrients by crops and to support their successful removal in harvested crops (Schröder et al., 2016).
- The objective of regenerative agriculture to improve water quality and availability is reflected in the soil function water purification and regulation which assesses the capacity of the soil to remove harmful compounds and to receive, store and conduct water for subsequent use (Wall et al., 2020).
- The objective to alleviate climate change is reflected by the soil function climate regulation which is determined by the magnitude of N_2O and CH_4 emissions and carbon sequestration (van de Broek et al., 2019).
- The objective of regenerative agriculture to enhance and improve soil health is reflected by the soil function biodiversity and habitat provision. Soil health is more than soil biodiversity alone, it is also the functional capacity of the soil to deliver on for example above ground biodiversity (Bünemann et al., 2018), which is not addressed in this function model. Biodiversity and habitat provision is described as the multitude of soil organisms and processes, interacting in an ecosystem, providing society with a rich biodiversity source and contributing to a habitat for aboveground organisms (Leeuwen et al., 2019).

SN captures the synergies (positive relationships between soil functions) and tradeoffs (negative relationships between soil functions) between soil functions and the effects of management practices on the five soil functions in the form of decision rules (Zwetsloot et al., 2020). These decision rules determine if soil functions are delivered at low, medium or high capacity. The required model input data include farm management attributes (i.e. tillage and the amount of N fertilizer applied to the field), environmental attributes (i.e. average temperature and precipitation) and soil attributes (i.e. clay content and soil organic matter). The capacity to supply the five soil functions were defined in SN by qualitative scores resulting from integrated hierarchical decision-support models which were structured, calibrated and validated for crop and grassland using datasets collected across Europe (Leeuwen et al., 2019; Sandén et al., 2019; Schröder et al., 2016; van de Broek et al., 2019; Wall et al., 2020). In addition to the assessment of soil functions, SN offers the possibility to optimize soil functions to meet user-set objectives: it will propose directions for change and farm management practices, needed to meet these objectives. More details about the construction of SN are described in supplementary materials S1 and by Debeljak et al. (2019).

FD is a static bio-economic whole-farm model which consists of a large array of interrelated farm components developed for the analysis and redesign of mixed crop-livestock systems (Groot et al., 2012). The model consists of flows that are quantified to calculate material balances, a feed balance, a labor balance and an economic balance on an annual basis. The flows can be used to assess the environmental performance of a farm (i.e. land use diversity, nutrient losses and soil organic matter accumulation) as well as the capacity to sustain socio-economic prosperity (i.e. farm profitability and labor requirements). FD also enables the exploration of optimized farm configurations, which are generated by a multi-objective optimization based on one or multiple user-defined objectives (e.g. minimize nutrient losses or maximize farm profitability), set constraints (e.g. upper and lower limits on animals' energy and protein requirements) and a variety of decision variables (e.g. upper and lower limits on crop areas or animal numbers). The new farm configurations can include optimized performance indicators and optimized field-use configurations. These optimized field-use configurations, for example, have optimized allocation of crop areas, new crop or animal products entering the farm, changes in herd size, animal type, fertilizers and feed use. More detail about the construction of FD are given in the supplementary materials S2 and described by Groot et al. (2012).

From the wide variety of indicators available in FD, a specific set of indicators shows overlap with the objectives of regenerative agriculture (Fig. 1), specifically operating profit, farm labor, nitrogen (N) surplus, GHG emissions and the soil organic matter (SOM) balance. Operating profit is congruent with the objective of regenerative agriculture to improve economic prosperity and is calculated as the sum of total farm returns minus farm costs. Farm labor is the only indicator used in our framework to reflect the "people" dimension of regenerative agriculture – wellbeing of the farmer. Farm labor is calculated as the sum of labor requirements due to crop and livestock management minus the hired labor and the hours spend of the farmer. The N surplus corresponds to the objective of regenerative agriculture to improve nutrient cycling and is quantified by subtracting the N exports (animal and crop produce and manures) from the sum of N inputs onto the farm in the form of crop products (e.g. purchased or off-farm collected feeds), animal products, manures and fertilizers, deposition, symbiotic fixation by leguminous plants and non-symbiotic fixation by free-living soil biota. GHG emissions relate to the objective of regenerative agriculture to alleviate climate change, accounting for soil carbon sequestration and emissions at farm-scale, such as emissions from animals (enteric), manure (direct emissions and volatilization), fertilizers, as well as diesel consumption and pesticide and fertilizer production and usage. The SOM balance indicates changes in organic matter in response to changes in farm practices and relates to the objective of regenerative agriculture to enhance and improve soil health. As such, this balance is an overarching indicator encompassing the three spheres of soil health and relates to all sub-objectives of regenerative agriculture to improve soil health. It is calculated as the difference between inputs and outputs of organic matter into the soil (from crop roots and residues, mulch, and farm-produced and imported manures) on the one hand, and losses by degradation of active SOM, added manure and erosion on the other. Fig. 1 illustrates the congruence between the objectives of regenerative agriculture, the model indicators used in this study and their relation to the three pillars of sustainability. An extended version of this figure is given in supplementary material S3.

2.2. Case-study farm

We used a conventional Dutch dairy farm on peat overlaying a clay soil to illustrate our framework for farm redesign. The use of a conventional farm allowed us to explore multiple permutations of regenerative farm practices that would contribute to meeting the objectives of regenerative agriculture. The case-study farm is located in the peat meadow area in the province of Zuid-Holland (Fig. 2) and has 22 fields of permanent grassland with a total farm area of 40.4 ha, used to feed approximately 100 cows. Farm specific data was collected in semi-structured interviews in September 2020. This data covered parameters related to the farm environment (e.g. climate and soils), farm management (e.g. fertilizer use, grazing system), yields of crops and animals with their related products and economics (e.g. farm expenses

Fig. 2. Map of the Netherlands divided into 12 provinces. The arrow locates the case-study farm in the province of Zuid-Holland (red).

and labor prices), crops and animals with their related products on an annual basis. The grassland close to the farm (16.9 ha) is used alternately for grazing and mowing. Grassland located further from the farmyard (23.5 ha) is used for mowing only. The cows are in the pasture for 4 h a day, 150 days a year; they remain in the barn for the remainder of the time. In addition to grass, the diet of the cattle is sustained with purchased feed such as maize, wheat straw and concentrate feed. The average yearly milk production is 8720 l per cow, equating to 21,384 kg milk ha^{-1}. The grassland is fertilized using cow slurry (254 kg N ha^{-1}; 85 kg P ha^{-1}) and inorganic fertilizer (75 kg N ha^{-1}; 10 kg P ha^{-1}). No synthetic pesticides were used. Parameters not readily available on the farm, such as the effective organic matter of grassland, were estimated using secondary literature with references provided in-text.

2.3. The ex-ante redesign of farming systems towards regenerative agriculture

We designed context-specific optimized farm configurations of regenerative practices using two sequential steps. The first step was to upscale soil functions to the farm-scale. The second step was to link field and farm-scale models for the redesign of our case-study farm, tailored to its local conditions. In the following section (2.3.1) we will first illustrate how we upscaled soil functions to the farm-scale, followed by the steps needed to systematically redesign the farm, using a combination of SN and FD (section 2.3.2).

2.3.1. Upscaling soil functions to the farm-scale

SN assesses soil functions at field-scale to acknowledge the potential variation in biophysical properties within the farm. In order to relate the performance of individual soil functions to the other environmental and socio-economic indicators that operate at farm-scale (e.g. operating profit, N surplus), we aggregated the assessment of soil functions from field to farm-level using area weighted averages. For this aggregation, we applied SN to areas of land that were considered homogeneous in terms of soil attributes and farmer management; as such we created separate models for fields used for alternate grazing and mowing, and fields used for mowing only. This difference in field-use was reflected in management attributes such as the percentage of yield obtained by grazing and the livestock density. Most other management attributes, such as fertilizer use, drainage management and pesticide use, were found to be uniform for our specific case-study farm. For farms with more diverse management, further disaggregation may be required, for example on arable farms with multiple crops and associated management practices.

Besides the uniformity of management and land use among fields, further disaggregation was also based on the uniformity of soil attributes (e.g. SOM content and clay percentage). Determining the variation between soil attributes among fields is essential to the context-specific recommendations of practices for particular fields. Soil attributes that varied within the predetermined thresholds (categories) within SN were considered uniform. The clay content between fields ranged for our dairy farm between 34 and 40%, which is within one of the five predetermined thresholds of 25–40%. There are, however, five different thresholds in SN that indicate the percentage of clay in the top 25 cm of the soil, each threshold is associated with different scores. Soil attributes from different fields ranging across thresholds were, therefore, further examined on their influence on the final assessment of soil functions using their weighting factors. Weighting factors were used in the five function models of SN to indicate the importance of the soil attributes on the final assessment of soil functions (Supplementary materials S1). We conducted a sensitivity analysis to determine the boundary between low and high weighting factors. The sensitivity analysis included a calculation of the weighting factors of all input attributes on soil functions. This resulted in a sorted list with the number of input attributes with their associated weighting factor (see supplementary materials S4). The inflection point, supported by expert opinion, was used to classify low and high categories for the weighting factors. Soil attributes with low weighting factors ($<8\%$) were deemed to have no or minimal effect on all scores of soil functions. Soil attributes with high weighting factors ($\geq 8\%$) could lead to further disaggregation of model applications if the input attributes of fields varied among thresholds. The influence of further disaggregation based on the variability in soil types and land use will improve the context specific recommendation of soil management practices from SN. Ultimately, the variation within our case-study farm could be captured satisfactorily using two categories of land (i.e. land used for alternatingly mowing and grazing; mowing only) and hence two model applications, which were aggregated to the farm-level using area weighted averages. In the result section we will present error bars besides the aggregated scores. These bars represent diverging soil function scores from the area weighted averages.

2.3.2. Linking field and farm-scale models

We subsequently employed FD to assess the directions for change by SN in the context of the wider socio-economic and environmental performance at the level of the farming system. As FD facilitates multi-objective optimizations, the output does not consist of a single optimized farming system; rather it shows a multitude of optimized solutions in the form of solution clouds, plotted against the objectives. Following farming systems optimization, the output of FD was re-entered in SN for a re-evaluation of the performance of soil functions. SN needs farm-level input data to optimize management inputs in the different field-scale models. Optimized management inputs can be related to for example livestock density, grassland diversity, fertilization rates and crop yields. Fig. 3 illustrates the farm optimization cycle between SN and FD. In the following section we will show how we aligned

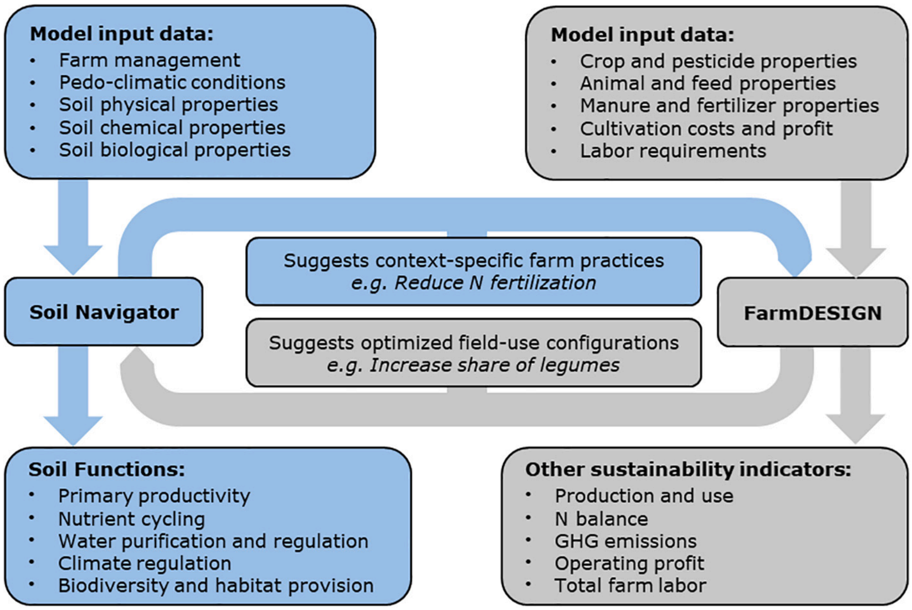

Fig. 3. Illustration of the farm optimization cycle between Soil Navigator (blue) and FarmDESIGN (gray).

and coupled SN and FD to reconfigure our case-study dairy farm, as well as its management practices, for a context-specific operationalisation of regenerative agriculture.

2.3.3. Obtaining improved farm practices from Soil Navigator

Current farm data was used to create an initial assessment of soil functions in SN and the other sustainability indicators in FD. After the initial assessment we employed the optimization of SN to obtain directions for change and farm practices which contribute to the improvement of soil functions. Previous studies, however, found that it is challenging to optimize all soil functions simultaneously to their maximum capacity (high) due to occurring trade-offs (Vazquez et al., 2020; Zwetsloot et al., 2020). Multiple iterations of optimization, with diverse objectives, may therefore be necessary to ensure all the soil functions individually reach a high capacity. Hence, to determine the optimal solutions and practices that contribute to all individual soil functions. For our case-study farm we needed one iteration to optimize all soil functions to their maximum capacity. Table 1 shows the suggested directions for change and farm practices from SN that we incorporated in FD at the farm-level.

2.3.4. Incorporating the improved soil management practices in FarmDESIGN

Besides the original land-use, management recommendation by SN were subsequently incorporated in FD as objectives, constraints and decision variables (Table 1). Where SN suggested to increase or reduce a certain practice or model input, this was included into FD as one of the objectives. For example, in our case-study farm SN recommended a reduction in total N fertilization; we reflected this in FD by including the objective to minimize available N from all fertilizers allocated to the soil. For some practices, constraints were added to avoid the use of, for example, mined N-fertilizers in the optimized scenario. Constraints were also set to maintain a realistic operating space for FD. For example, constraints were set for the feed balance to match animal requirements and availability of energy and protein and the dry matter intake capacity and saturation (digestibility of feed). Constraints can also be set to restrict the model to stay within national fertilization guidelines. This was, however, for our case-farm not needed because a fixed fertilization rate (94 kg N ha^{-1}) was used for the optimized scenario. More specifically, both SN and FD use the amount of N that is applied by the farmer to the fields (total N). In cases where SN introduced a new practice, a new form of dairy or grassland management was introduced, and the area allocated was modelled as a decision variable in FD. Decision variables allowed the model to allocate for example more area to grassland or herb-rich grassland based on set objectives and constraints. A complete list of conditions for FD is shown in supplementary materials S5.

The introduction of new practices or strategic adjustment required a degree of interpretation and parameterization using secondary data and expert opinion. For example, in our case-study farm, SN suggested the cultivation of crops with a high-water use, underlying soil functions

Table 1
Directions for change suggested by Soil Navigator (SN) for integration in FarmDESIGN (FD). The directions for change and farm practices from SN are implemented in FD as constraints ([a]), objectives ([b]) and decision variables ([c]) in which a new form of dairy or grassland management was introduced.

Suggested changes SN	To improve the soil function	Adjustments in FD
Reduce total N fertilization	Climate regulation	[b] Minimize available N fertilizers to soil (kg ha^{-1} yr^{-1})
		[b] Minimize N balance (kg ha^{-1} yr^{-1})
Apply solid manure/compost	Biodiversity and habitat provision	[c] Introduce solid manure
		[b] Maximize C in manure to soil (kg ha^{-1} yr^{-1})
		[a] Constrain mineral N fertilizer to 0 kg ha^{-1} yr^{-1}
Increase N offtake by grassland	Water purification and regulation	[c] Introduce herb-rich grassland
		[b] Maximize area with herb-rich grassland (ha)
Increase share of crops with a higher water use		[b] Maximize N-fixation (kg ha^{-1} yr^{-1})

indicated that this suggestion related to a low water storage capacity of the soil. SN gave examples of crops which could increase the water uptake and storage capacity using for example winter cereals, spring cereals with legumes or grass, grass with legumes or other crop mixtures with legumes. It remained, however, unclear how these crops contribute to improved water storage, if these crops could be used in the local-context or its share in the rotation. Peat soils are for example considered unsuitable for arable land (e.g. cereals and perennial crops) and are predominantly used for grassland (Verhagen et al., 2009). Based on secondary literature (e.g. Hayes et al., 2019; Mytton et al., 1993) and expert opinion (all co-authors and four grassland experts, see acknowledgements) we chose to implement this recommendation by introducing herb-rich grassland with ~30% white clover and reparameterized the input attributes for farm profitability, labor requirements, N surplus, GHG emissions and the SOM surplus accordingly (Table 2). The input attributes in Table 2 can, therefore, be different for the reference and optimized scenario. For example, values for the effective organic matter rate of herb-rich grassland are lower compared to permanent grassland. The reason that the effective organic matter of herb-rich grassland is lower compared to permanent grassland relates to the inclusion of herbs (for the dominant part white clover). White clover, for example, has an effective organic matter value of 850 kg ha^{-1}, while permanent grassland has an effective organic matter value of 2000 kg ha^{-1} (Bosch and de Jonge, 1989). The effect of for example herbs does not only affect the effective organic matter rates but also values for N-fixation in both models. In FD we addressed specific N-fixation rates for specific legumes (e.g. clover) and adjusted appropriate fertilization rates accordingly. In SN specific N-fixation rates cannot be addressed, instead SN takes into account the number of years legumes are used and the share of legumes on the field as input attributes to determine scores for nutrient cycling and primary productivity. In this study we have used the Dutch feed evaluation system and units (i.e. VW, SW, VEM and DVE) (Tamminga et al., 1994; van Es, 1975). Table 2 shows some of these input attributes for grazed grass and silage obtained from mowing. The complete table of changed input attributes is provided in supplementary materials S6, this also includes a justification of the changes made. This also includes grass silage obtained from the fields which were used for alternately mowing and grazing.

2.3.5. Multi-objective optimization

The multi-objective optimization of FD allowed further exploration of optimized farm configurations using other regenerative objectives such as farm profitability, labor or GHG emissions. The multi-objective optimization uses a Pareto-based Differential Evolution algorithm in which alternative farm configurations were created which outperformed the reference scenario on at least one of the regenerative objectives (Groot et al., 2012). The model was allowed to select combinations of the reference and optimized land use to create a broad solution space of optimized farm configurations. We used a fixed seed for optimization to generate a solution space which remained constant when exploring optimized farm configurations with the same conditions. This was needed to ensure a stable output of FD ready for use in SN. We used 4000 iterations per model run to reveal a stable solution space of 2000 solutions. From the solution space, any farm configuration can be selected and viewed in the FD model, to further inspect the performance on a wide range of farm sustainability indicators. The solution space is normally used by farmers and stakeholders together to decide which configuration is most appropriate for a farming system. Instead, we used a multi-objective filtering approach to decide which of the 2000 configurations best reflected the recommendations of SN. We did this by ranking all farm configurations from 0 (best) to 2000 (worst) for each individual optimization objective. The solution with the lowest aggregate score was selected as the best overall solution and was re-entered into SN, in order to assess the improvement of soil functions that resulted from the optimization. Table 3 shows the seven input attributes that changed for this second iteration of SN, for both grassland dedicated to alternated grazing and mowing and grassland dedicated to mowing only. These seven input attributes changed were related to the inclusion of herbs in grassland and changes in manure management. It is important to highlight that the manure type in Table 3 does not only refer to the nitrogen and carbon contents as two independent attributes, but also to the relation between them such as the C:N ratio.

Table 2
A part of the composition table used to reparameterize the reference scenario in FarmDESIGN with optimized literature values based on the suggested directions for change and practices from SN.

Input attribute	Unit	Reference scenario		Optimized scenario	
		Permanent grassland		Herb-rich grassland	
		Grazed grass	Grass silage	Grazed grass	Grass silage
Nitrogen fixation	kg ha^{-1}	0	0	172	172
Effective org. matter	kg ha^{-1}	2000	2000	1540	1540
Cultivation costs	€ ha^{-1}	988	988	988	988
Regular labor	h ha^{-1}	18	21	21	25
Price fresh matter	€ kg^{-1}	0	0.062	0	0.067
Dry matter yield	kg ha^{-1}	1969	11,453	1969	11,453
Feed saturation value (VW)	–	0.89	1.02	0.89	1.02
Feed structure value (SW)	–	1.88	3.02	1.88	3.02
Energy content (VEM)	–	960	888	979	906
Protein content (DVE)	g kg DM^{-1}	92	67	93	68

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Bosch and de Jonge (1989), CVB (2018), de Wit et al. (2004), Feedipedia (2020), van der Voort (2018), Blanken et al. (2018) and Goyens (2016).

Table 3
Input attributes for SN which changed between the reference and optimized scenario.

Input	Unit	Reference scenario		Optimized scenario	
		Grazed and mowed grass	Grass silage	Grazed and mowed grass	Grass silage
Number of years with legumes	yr	0	0	5	5
Share of legumes on the field	%	<10	<10	>10	>10
Grassland diversity	N species	1	1	>2	>2
Application of mineral fertilizer	Yes/No	Yes	Yes	No	No
Mineral N fertilization	kg N ha^{-1}	75–100	75–100	0	0
Type of manure	–	Slurry	Slurry	Solid	Solid
Organic N fertilizer	kg N ha^{-1}	>200	>200	75–100	75–100

3. Results

3.1. Windows of optimized farm opportunities

The exploration of our dairy case-study farm resulted in an optimized solution space of 2000 alternative farm configurations. Fig. 4 shows relationships between the farm-level objectives set based on the suggestions of SN (i.e. increase N-fixation, reduce fertilizer N supply, increase manure C supply and reduce the farm N surplus). The relationships show the existence of both synergies and trade-offs between optimization objectives. A synergy was found between the objective to reduce the N surplus and to reduce fertilizer N supply

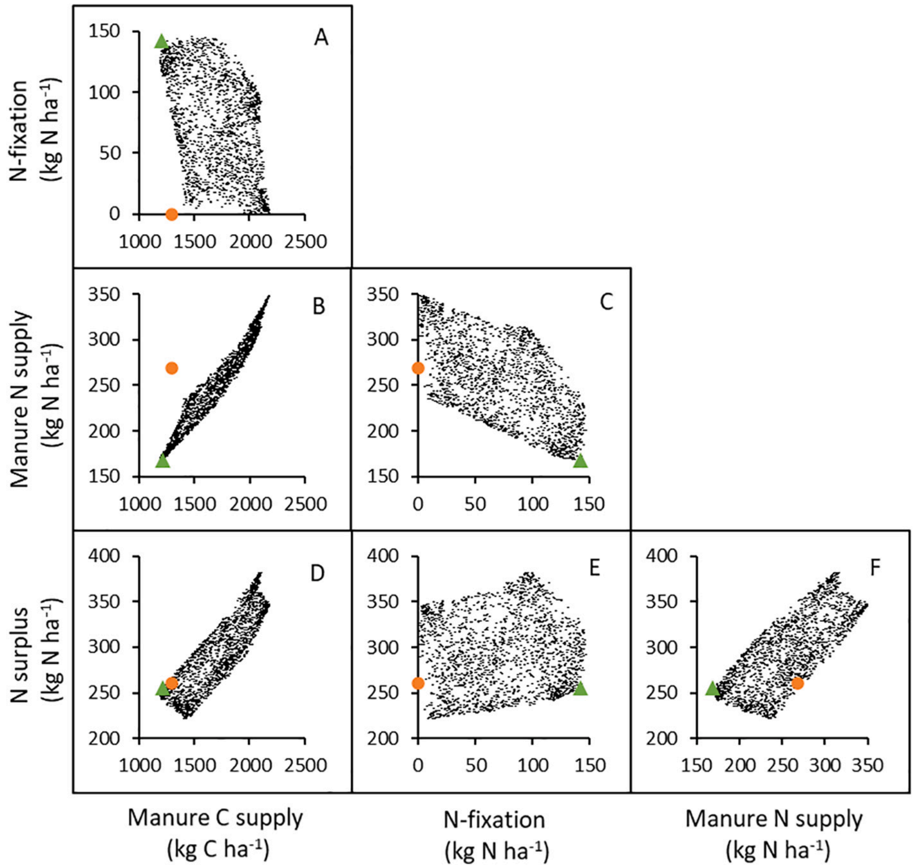

Fig. 4. Relationships between the objectives N fixation, N surplus, fertilizer N supply, and manure C supply for the dairy case-study farm. Each dot (black) indicates an alternative farm configuration, the orange dot and green triangle mark the performance of the reference and selected optimized farm configuration respectively.

(Fig. 4F), i.e. reducing fertilizer N supply also leads to a reduction in the N surplus. A trade-off was found trying to increase the manure C supply reflecting the use of solid manure while reducing the fertilizer N supply (Fig. 4B), i.e. an increase in manure C supply is in this case also associated with a higher fertilizer N supply. This relationship is vary depending on the type of manure used. Another trade-off was found between the objective to increase manure C supply and the objective to reduce the N surplus (Fig. 4D), i.e. a higher manure C supply increased the N surplus. The objective to maximize N-fixation did not result in synergies or trade-offs but showed a rather broad solution space (Fig. 4A, C and E).

The exploration in FD yielded 2000 optimized farm configurations using the land use of the reference scenario and optimized scenario in different extents. Only ~14% of the optimized farm configurations were shown to have 75 to 100% of the total farm area allocated to the optimized scenario. Moreover, ~28%, ~29% and ~ 29% of the optimized farm configurations used the optimized scenario within the range of 50–75%, 25–50%, 0–25% of the total farm area, respectively. This indicates that using the current objectives in FD leads to a small set of optimized farm configuration which allocated most of the land to the optimized scenario. Moreover, none of the configurations had 100% of the land-use allocated to the optimized scenario. Using the multi-filtering approach, we selected the overall best performing farm configuration and reassessed the performance indicators in FD and the five soil functions SN.

3.2. Assessment on the themes of regenerative agriculture

In this study we modelled all five soil functions in SN (Fig. 5A) and farm profitability, N surplus, labor requirements, SOM surplus and GHG emissions in FD (Fig. 5B) to illustrate that the model output can help different stakeholders to assess and redesign farms based on the regenerative objectives. The error bars in Fig. 5A represent model applications (models used for alternated mowing and grazing, and for mowing only) which showed diverging scores on soil functions from the calculated area weighted averages. The results show that the optimization resulted in four of the five soil functions performing at a 'high' level, at the expense of the function primary production, which dropped to 'medium'. The reason for this decline is that SN indicates that the implemented soil management practices (e.g. reduction in N-fertilization) are suboptimal for primary production. We, however, show that this decline in primary production leads to an increase in the supply of other soil functions (i.e. water purification and regulation, biodiversity and habitat provision and climate regulation). Fig. 5 shows that this reduction in primary production was associated with a 27% decrease in farm profitability (from 55,620 to 40,720 € yr^{-1}), mainly as a result of an increase in the purchase of concentrate feed needed to satisfy animal nutrition requirements. Water purification and regulation increased from a low to a medium function score, due to the integration of herb-rich grassland and the lower N fertilization. The objective to reduce N-fertilization and reduce the N surplus did not result in a significant lower N surplus and stayed stable (from 258 to 256 kg N ha^{-1}). The decrease in N surplus was limited, mainly due to an increased uptake of concentrate feed and a higher N-fixation rate. Like the N surplus, the soil function nutrient cycling remained unchanged at high capacity in the optimized scenario. The functions biodiversity and habitat provision also remained high in the optimized scenario as a result of increased grassland diversity and the implementation of solid manure. The use of solid manure instead of slurry also increased the SOM balance by 7%. The use of solid manure instead of slurry and mineral fertilizers outweighed the difference in effective organic matter which is higher for permanent grassland compared to herb-rich grassland. Climate regulation improved to high,

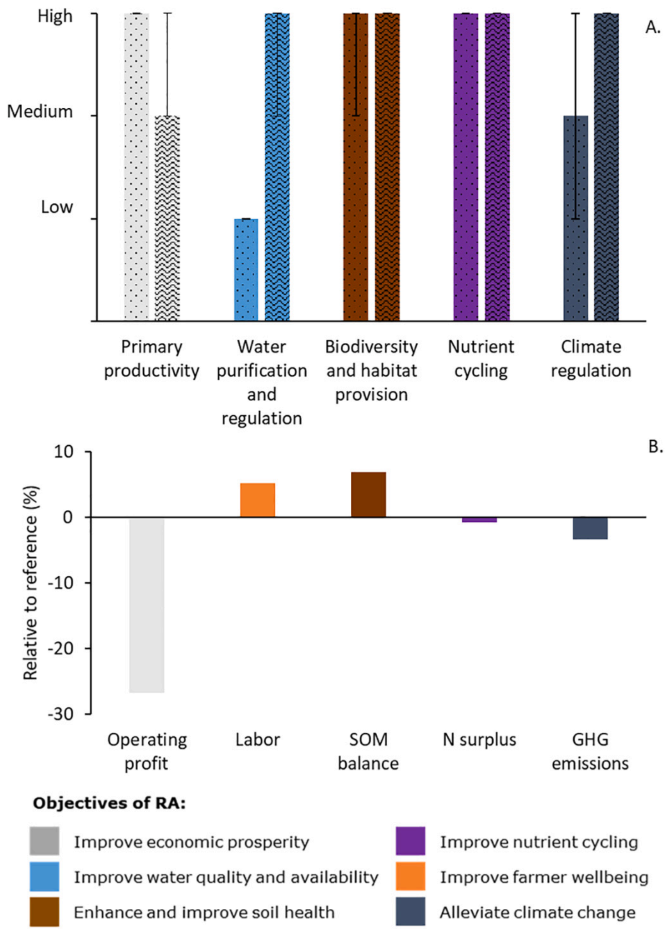

Fig. 5. The performance of soil functions (A) for the reference scenario (dotted bars) and the optimized scenario (waved bars) of the case-study farm. Error bars represent function scores which were diverging from the calculated area weighted averages, indicating within-farm variability. The performance of other sustainability indicators (B) are shown relative to the reference scenario.

in response to the reduction in N fertilization of the soil. Overall GHG emissions at the farm-level showed a small decline of 3% (from 30 to 29 Mg CO_2 eq. ha^{-1}) mainly due to a reduction in N-fertilization. Farm labor showed a small increase of 5% due to a higher labor requirement of the optimized scenario (from 2989 to 3147 h yr^{-1}). A more extensive version of Fig. 5 can be found in supplementary materials S7. The effect of farm configuration with diverging land use ratios for this case-farm on soil functions are shown in supplementary S8. Supplementary materials S8 for example shows that if less than 75% of the area of land was allocated to the optimized scenario, it would yield in a reduced performance of soil functions i.e. water purification and regulation. Land use with an area of less than 25% allocated to the optimized scenario would also yield in a reduced climate regulation score.

4. Discussion

4.1. Supporting tailor-made solutions in regenerative agriculture

The optimalisation of farming systems towards regenerative agriculture is complex and comes with a high knowledge requirement, as it requires detailed insights into soil multifunctionality at a field-level and knowledge about broader systems objectives at a farm-level. Jones et al. (2017) highlighted the lack of integrated models that can assist with such complex challenges that operate across multiple scales. Instead of creating a single model, our study showed that different models can be used together to address the complexity of the soil while at the same time addressing wider sustainability aspects (i.e. farm labor, GHG emissions). Specifically, we successfully combined and applied a field-scale model of soil functions, with a farm-scale model on environmental and socio-economic sustainability, to operationalize regenerative agriculture for the context-specific redesign and assessment of a Dutch dairy farm. By definition, regenerative agriculture uses soil conservation practices as the entry point for environmental and socio-economic sustainability (Schreefel et al., 2020), and it is these practices that take center-stage in the recommendations of SN. At the same time, multi-objective optimization of FD showed that even for an individual farm there are multiple viable reconfigurations.

4.2. Reflection on the modelling of our case-study dairy farm

Peat soils are in the Netherlands considered unsuitable for arable agriculture and, are therefore, predominantly used as permanent grassland for grazing animals – typically dairy cattle. This traditional use of land has resulted in an open landscape with important cultural-historical features. Intensification has resulted in high productivity and resource use-efficiency. At the same time, resource losses are externalized, and other environmental indicators have deteriorated due to increased drainage, intensive grazing and fertilizer use, which have increased CO_2 emissions, and mineralization rates, with associated losses of SOM and nutrients (Schothorst, 1977). This is reflected in our assessment of the reference scenario in which SN presented high productivity and nutrient cycling in the soil, similar to SN results from 52 Dutch farms (Vazquez et al., 2020). Following SN, primary productivity decreased to a medium level due to a reduced use of nitrogen fertilization required to optimize other soil functions. FD showed that farm profitability was also reduced mainly due to an increased purchase of concentrate feed, to compliment the diet of the farm animals. A higher import of concentrate feed is not in-line with the objectives of regenerative agriculture, and reduced farm profitability could hinder the transition towards regenerative agriculture. In future studies it would therefore be of interest to also consider the objectives of regenerative agriculture in the optimization of FD.

Our study shows high scores for soil biodiversity for both the reference and the optimized scenario. While this result was unexpected in light of the reported declines in soil biodiversity in the Netherlands (Rutgers et al., 2010, 2019), the scores in SN are context specific (e.g. land use). This corresponds with the findings of Reidsma et al. (2006), who showed that levels of biodiversity are very dependent on land use, soil type and climatic regions. The decision rules in SN are currently set-up to evaluate biodiversity within an agricultural perspective. From an agricultural perspective, peat soils with permanent grassland and the use of herb-rich grass mixtures are associated with improvements in soil life and structure (van Eekeren et al., 2010). SN is, furthermore, sensitive to input attributes with a high weighting factor, such as the use of no-tillage and a high SOM. On peat soils no-tillage is a common practice and a high SOM is self-evident, which may lead to the overestimation of SN function score for biodiversity and habitat provision.

The score for climate regulation was medium for the reference scenario and this improved to high in the optimized scenario due to the reduction of N fertilization. Although this is a valid measure to reduce N_2O emissions, it is surprising that SN did not recommend an increase in groundwater levels or, concurrently, a reduction in artificial drainage. Peat soils in the Netherlands are associated with high CO_2 emissions due to peat oxidation from drainage to enable grazing of typically cattle (Schothorst, 1977). Currently the role of livestock on peat soils is under debate and increasing the water level is an oft-suggested measure to reduce CO_2 emissions from peat soils (Querner et al., 2008). A recent study of De Jong et al. (2021) shows that rewetting peatlands can reduce CO_2 emissions with more than 30%. This study evaluated the role of peatlands for paludiculture instead of dairy farming. Although SN is developed for pan-European coverage of soils with land use and climate, we found that calibration and validation of SN remains limited on peat soils. The five function models used 94 to 251 sites for calibration and validation across Europe (van de Broek et al., 2019; Wall et al., 2020), we found that only five of these sites were on peat soil. Vazquez et al. (2020) used 52 farms in the Netherlands for assessment on soil functions and did not include peat soils. We, therefore, recommend further calibration and validation of SN for peat soils in the Netherlands.

The low score for water regulation and purification improved to a high score, due to the integration of herbs in grassland which improved grassland diversity in the respective time horizon of five years. Including clover is a well-known practice to improve soil functions on sandy and clay soils. However, its role for peat soils is subject to debate: while our case-study farm has a soil pH (pH-KCl) of 5.5, the average pH of peat soils in the Netherlands is 4.7 (Rutgers et al., 2007), which is suboptimal for clover growth. The use of clover in grassland is recommended only for soils with a pH >5.2 (de Wit et al., 2004; van Eekeren, 2007). The reduction of N-fertilization also significantly contributed to improving the score of water purification and regulation, showing that some regenerative practices may contribute to multiple soil functions.

The social dimension of regenerative agriculture was in this study reflected by farm labor. We acknowledge that farm labor by itself is a suboptimal indicator to reflect the wellbeing of farmers and the objective of regenerative agriculture to "*improve human health*". We would, therefore, recommend in future studies to also take indicators into account which can reflect human wellbeing. Brown et al. (2021) for example suggests that even subjective wellbeing measures can be used to assess regenerative agriculture. Although, farm labor may not give insight in the wellbeing of a farmer, it does give context regarding the social dimension of regenerative agriculture. Moreover, increased labor requirements may result in for example increased job opportunities and reduced labor requirements may result in more leisure time for the farmer.

4.3. Recommendations and prospects for future modelling

Like most models, SN and FD are designed and parameterized to simulate common farming systems. In this study we modelled a dairy farm. This, however, could, also have been any other common farm type i.e. a conventional arable farm or mixed farm. Besides common farming systems, regenerative agriculture aspires to be equally relevant to, and in fact promote, the establishment of new farming systems, such as agroforestry or strip-cropping (e.g. Ditzler et al., 2021). These farming systems often yield their positive effect on a wide range of interrelated ecosystem services over a longer time period (Robertson et al., 2014; Teague and Kreuter, 2020). Neither SN, nor FD, are designed to simulate these emerging farming systems over a multi-year time period. While we have shown that linking FD and SN to be an effective first step to customize regenerative agriculture for diverse farming systems, we recommend to further develop SN to include a wider variety of farming and farm practices that could influence soil functions (e.g. grazing strategies, fixed traffic lanes).

5. Conclusion

This study demonstrated that we can use SN and FD together by researchers as a tool to help different stakeholders to assess and redesign farms based on regenerative objectives. Combining SN with FD allowed evaluating the impact of soil management practices as the basis for optimizing the overall socio-economic and environment sustainability of a farm, which is aligned with the definition of regenerative agriculture. The modelling framework we present in this paper gives therefore, not only new insights in the consequences of implementing different soil management practices on soil health, but also the consequences for other sustainability aspects such as labor requirements and farm profitability. For our case-study dairy farm, we found a set of practices that delivered four out of the five functions at high capacity. While this high performance came at a lower primary productivity score, it also reduced farm profitability. Reduced farm profitability could hinder the transition towards regenerative agriculture. While this study successfully demonstrated an initial combination of SN and FD models for the ex-ante design and assessment of farming systems towards regenerative agriculture, further model development is essential to widen the applicability of this study to include emerging farming systems and new indicators of sustainability that are measured over a longer time period. Furthermore, we would recommend to further calibrate and validate SN for peat soils across Europe.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103371.

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