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Tailor-made solutions for regenerative agriculture in the Netherlands

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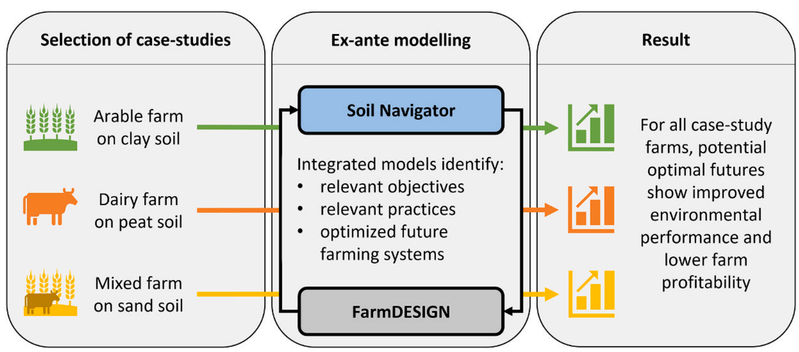
HIGHLIGHTS

- This study explored a novel modelling framework to redesign farms towards regenerative agriculture.
- This framework can be used to analyze a multitude of tailor-made solutions for diverse farming systems.
- From this framework farmers can select the solutions that fit their local context and intrinsic motivations best.
- For our case-study farms, environmental performance improved when regenerative management practices increased.
- This improvement in environmental performance, however, came at the expense of farm profitability.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Regenerative agriculture is a farming approach that uses soil health as the entry point to contribute to multiple objectives, such as improved nutrient cycling and climate regulation. To reach these objectives farmers can apply different practices. The objectives and practices, however, are not equally relevant or applicable for every farming system and local context.
OBJECTIVE: The main objective of this paper, therefore, was to find out how tailor-made solutions towards regenerative agriculture can be identified and evaluated as such that they result in meaning-full advice for farmers.
METHODS: In this study a well-established modelling framework to redesign farming systems was applied to three typical but diverse Dutch farming systems. The modelling framework combined the models Soil Navigator and FarmDESIGN to simultaneously assess five soil functions at field-level and general sustainability indicators (e.g. greenhouse gas emissions) at farm-level. We applied the modelling framework to an arable farm on clay soil, a dairy farm on peat soil, and a mixed farm on sand soil. We subsequently explored a multitude of tailor-made solutions composed of combinations of practices for these farming systems, each showing solutions that contributed in varying degrees towards the objectives of regenerative agriculture.

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RESULTS AND CONCLUSION: In total, we created 4000 alternative solutions per case-study farm. For all farming systems, environmental performance was improved in the solutions dominated by the use of regenerative practices. For example, for the arable, the dairy, and the mixed case-study farm, greenhouse gas emissions were reduced by 50% (from 4 to 2 Mg CO_2 eq. ha^{-1}), 6% (from 30 to 28 Mg CO_2 eq. ha^{-1}), and 23% (from 21 to 16 Mg CO_2 eq. ha^{-1}), respectively, while maintaining soil functionality at high capacity for four out of the five soil functions. This overall improvement in environmental performance due to the application of regenerative practices, also resulted in reduced farm profitability for all case-study farms by on average 50%. We discuss that a mechanism to incentivize farmers for their tailor-made contribution to regenerative agriculture is for stakeholders to shift focus from solely primary productivity to also other ecosystem services.
SIGNIFICANCE: This study contributes to the wider implementation of regenerative agriculture, by showing which regenerative objectives and farming practices can contribute to the transition towards regenerative agriculture in contrasting contexts. The modelling framework that is used, can underpin regenerative management for farmers and other stakeholders to help, for example, the valorization of multiple regenerative objectives in business models.

1. Introduction

The urgency to move towards healthy and regenerative food systems is increasingly acknowledged in international agreements such as the Common Agricultural Policy (European Commission, 2019a), the Biodiversity Strategy (European Commission, 2021), and the European Green Deal (European Commission, 2019b). For the agricultural sector, as part of our global food system, a wide variety of sustainable farming approaches aim to produce a sufficient amount of food, while respecting the boundaries of our planet (FAO and ITPS, 2021). Regenerative agriculture is one of these farming approaches and was defined by Schreefel et al. (2020) as: *"an approach to farming that uses soil health as the entry point to regenerate and contribute to multiple ecosystem services, with the aspiration that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production"*. Although literature states that regenerative agriculture aims to be a farming approach with a positive impact on various dimensions of sustainable food production (e.g. Fenster et al., 2021a; LaCanne and Lundgren, 2018), it often remains unclear how farmers can contribute to the objectives of regenerative agriculture.

Recent critiques of regenerative agriculture state that the objectives of regenerative agriculture are broad and not specific for local contexts (Giller et al., 2021). The local contexts of farming systems can be very different indeed (climate, landscape, and management) and set the conditions to the objectives and solutions (e.g. tillage and fertilizer application). Therefore, tailor-made solutions are key to make regenerative agriculture a success. The body of scientific literature on the impacts of tailor-made solutions has increased recently, including studies on measurement schemes for regenerative agriculture (Brown et al., 2021; Elevitch et al., 2018; Luján Soto et al., 2020), the assessment of practices (Fenster et al., 2021b; Kröbel et al., 2021), measurements of impacts (LaCanne and Lundgren, 2018; Luján Soto et al., 2021), and the institutional changes required (Gosnell et al., 2019; Vermunt et al., 2022). However, it remains unknown from these studies to what extent tailor-made solutions can contribute to the objectives of regenerative agriculture. To support farmers in their transitions towards regenerative agriculture, an approach is needed that shows which solutions could contribute to regenerative objectives relevant in their local contexts.

Farm focused models have proved to be effective tools for the assessment and *ex-ante* redesign of farming systems (Pannell, 1996; Reidsma et al., 2018). From the myriad of farm-models used by researchers, Schreefel et al. (2022) developed a modelling framework specifically designed to explore the consequences of regenerative farming solutions, and design more sustainable future farming systems. More specifically, this framework uses soil management practices at field scale as the basis for optimizing the overall environmental and socio-economic sustainability of a farm. As such, this modelling framework is the first to combine assessments of soil health with assessments of the overall environmental and economic sustainability of farms. Soil health refers in this paper to the multifunctionality of the soil to support a vital living ecosystem (Creamer et al., 2022). To accumulate knowledge, support debates, and provide stakeholders with the knowledge needed to transition towards regenerative agriculture, we build upon the framework of Schreefel et al. (2022) to explore tailor-made solutions for contrasting farming systems.

To do this, the Netherlands was selected as a suitable case study because of their intensive agricultural landscape. Currently, 54% of the surface area in the Netherlands is used for agriculture, dominated by dairy and arable farming (CBS, 2020; CLO, 2020). The dairy sector contributes significantly to national emissions, producing 85% of the ammonia (CBS, 2019) and 11% of the total GHG emissions (van Eerdt and Westhoek, 2019). Dairy farmers rely heavily on imports of concentrate feed: 40% of the cow's protein intake is derived from imported feed (van der Meulen, 2021). Furthermore, ~60% of the dairy farmers export parts of their manure from the farm (Luesink, 2021), while arable farmers use relatively large amounts of inorganic nitrogen fertilizers (106 kg N ha^{-1} yr^{-1}) (Leeuwen, 2021). We use three typical Dutch farming systems (i.e. arable farming on clay soil, dairy farming on peat soil, and mixed farming on sandy soil). These typical Dutch combinations of soil and farming systems each have their own challenges (e.g. soil compaction on clay soils, carbon emissions from drained peat soils, and nutrient leaching from sandy soils) and give ample opportunity for the exploration of tailor-made solutions towards regenerative agriculture for contrasting contexts.

2. Methods

Fig. 1 illustrates our approach to explore tailor-made solutions. First, we selected typical Dutch farming systems and subsequently used *ex-ante* redesign for exploring a multitude of tailor-made solutions composed of combinations of practices. The *ex-ante* redesign procedure consisted of the following sub-steps: a) from field to farm-level assessment using the soil as the starting point, b) tailoring practices to local conditions, c) creating explorative regenerative scenarios, and d) exploring alternative farm configurations. The steps will be discussed in more detail below.

2.1. Selection of typical Dutch farming systems

In order to make this research widely interpretable, we aimed to find case-study farms representative of a larger group of similar Dutch farming systems. To select representative case-study farms we used the 14 different Dutch agricultural regions according to Central Bureau of Statistics (CBS, 2022). The 14 agricultural regions and soil types in the Netherlands are shown in Fig. 2. Data on farm characteristics for the regions were obtained from the main Dutch agricultural database: '*Bedrijveninformatienet*' (https://www.agrimatie.nl). To find regions typically known for dairy farming on peat soil, arable farming on clay soil, and mixed farming on sandy soil we assessed the homogeneity of the soil and the similarities in farm characteristics (e.g. farm type, farm layout, farm management, cropping patterns, primary cash crops, livestock holdings, and market orientation). The regions with the largest number of farming systems were used as a benchmark to further select case-study farms: the southern clay region for arable farming, the western peat meadow region for dairy farming, and the eastern sand region for mixed farming.

In order to select case-study farms, we approached representative farming systems from the selected regions to determine their willingness to participate in data collection. Farm specific data for the selected case-study farms were collected using a self-made survey tool containing semi-structured questions in September 2020. These data covered parameters related to the farm environment (e.g. pedoclimatic conditions), farm management (e.g. fertilizer use, cropping pattern), yields of crops and animal performance with related products, and economics (e.g. farm expenses and labor prices) on an annual basis. An overview of farm characteristics of the benchmark and case-study farms is shown in Table 1 (additional information is provided in supplementary materials S1). Parameters not readily available on the farm, such as the effective organic matter of grassland, were estimated using secondary literature.

The *arable case-study farm* on clay soil had 45 ha of cropland, which was divided in 16.3 ha to produce ware potatoes, 10.7 ha for sugar beet, 8.9 ha for winter wheat, 5.8 ha for chicory, 2.5 ha for kidney beans, and 0.7 ha for lucerne. Crop residues were removed from the land and the main source of fertilization was pig slurry (on average 107 kg N ha^{-1}; 35 kg P ha^{-1}) and inorganic fertilizers (on average 88 kg N ha^{-1}). A wide range of synthetic pesticides was applied for crop protection and disease suppression.

The *dairy case-study farm* on peat overlaying a clay soil had a total farm area of 40.4 ha, used to feed 99 dairy cows. The grassland close to the farm (16.9 ha) was used alternately for grazing and mowing. Grassland located further from the farmyard (23.5 ha) was used for mowing only. The cows were in the pasture for 4 h a day, 150 days a year; for the remainder of the time the cows remained in the barn. In addition to grass, the diet of the cattle was supplemented with purchased maize, wheat straw, and concentrate feed. The grassland was fertilized using cow slurry (240 kg N ha^{-1}; 85 kg P ha^{-1}) and inorganic fertilizers (75 kg N ha^{-1}; 10 kg P ha^{-1}). No synthetic pesticides were used.

The *mixed case-study farm* on sandy soil had both grassland and arable land to produce fodder crops. The grassland was separated in 23.6 ha grass used for alternated grazing and mowing and grasslands at a greater distance from the farmyard (10.4 ha) were used for mowing only. The cows were in the pasture for 7 h a day, 239 days a year; they

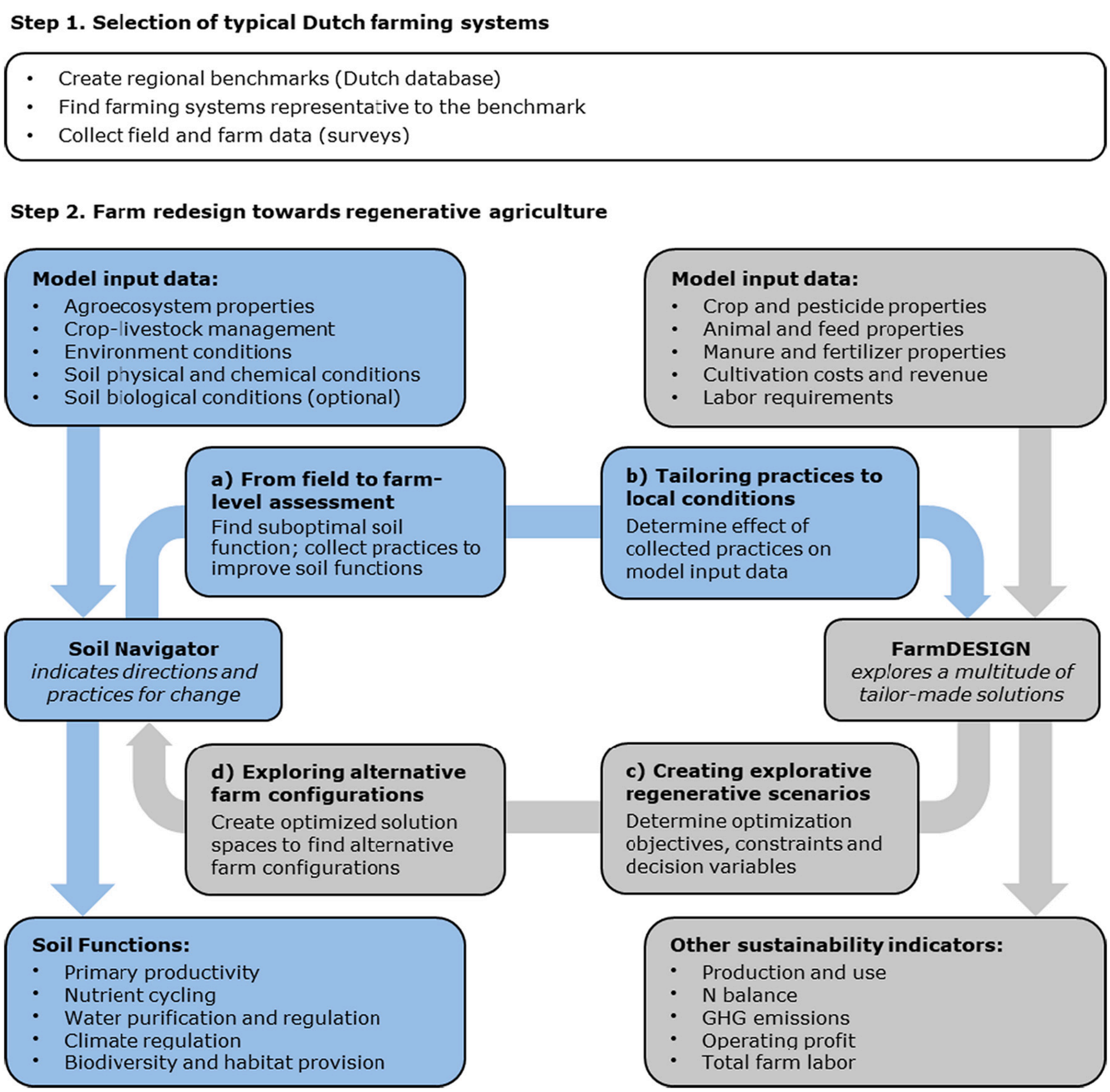

Fig. 1. Visualization of the methodology used to explore tailor-made solutions for typical Dutch farming systems towards regenerative agriculture, using the modelling framework of Schreefel et al. (2022). In blue the steps in the farm redesign cycle associated with Soil Navigator and in grey with FarmDESIGN. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

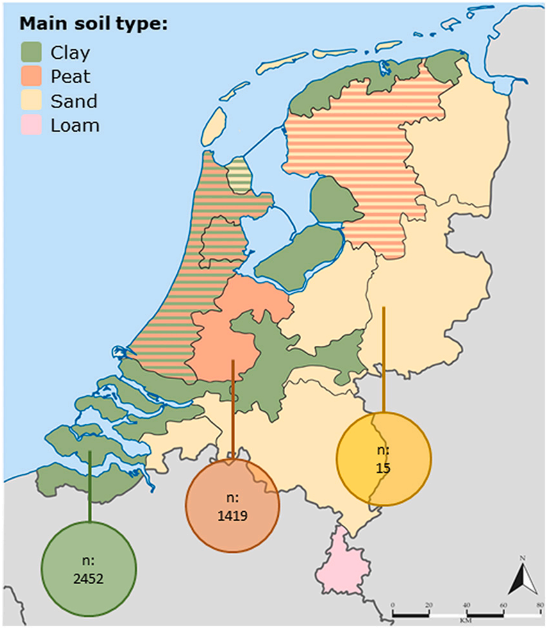

Fig. 2. Map of the Netherlands divided in 14 agricultural regions showing the selected benchmarks for different farm and main soil types, based on CBS (2022). The selected regions are indicated with a text-cloud that shows the number (n) of farming systems in the Dutch database used as benchmark.

remained in the barn for the remainder of the time. In addition to grass, the diet of the cattle was supplemented with fodder crops produced on the farm and purchased concentrate feed. The area used to produce fodder crops was divided in 10.9 ha of maize, 5.6 ha of winter wheat, 1.7 ha of lucerne and peas (fed as whole plant silage), 2.5 ha of fodder beet, and 1.8 ha of summer barley (fed as whole plant silage). The grassland was fertilized using cow slurry (130 kg N ha^{-1}; 33 kg P ha^{-1}) and inorganic fertilizer (100 kg N ha^{-1}). The arable land was also fertilized with cow slurry (on average 116 kg N ha^{-1}; 35 kg P ha^{-1}) and inorganic fertilizer (48 kg N ha^{-1}). A limited amount of synthetic pesticides was used for crop protection and disease suppression.

2.2. Farm redesign towards regenerative agriculture

The *ex-ante* redesign process to explore tailor-made solutions towards regenerative agriculture used the modelling framework of Schreefel et al. (2022). Schreefel et al. (2022) determined that the objectives relevant at the farm-level were to “enhance and improve soil health”, thereby increasing the contribution of soil within the farming system to support multiple ecosystem services; “alleviation of climate change”, “improvement of nutrient cycling”, “improvement of water quality and availability”, “improvement in economic prosperity”, and “improvement in human health”. The modelling framework combines two models (see Fig. 2 and the next two sections for a detailed explanation of each model):

1. Soil Navigator (SN): a decision support tool to assess and optimize five soil functions at the field-level (Debeljak et al., 2019).
2. FarmDESIGN (FD): a bio-economic model to explore and optimize overall farm sustainability (Groot et al., 2012).

The optimization of SN allowed for the recommendation of soil management practices that improve and optimize the five soil functions. These practices were subsequently incorporated in FD to identify potential synergies and trade-offs with other sustainability indicators.

2.2.1. Soil navigator

SN was used to assess soil multifunctionality as the entry point for farm redesign, in line with the scientific definition of regenerative agriculture (Schreefel et al., 2020). SN is a field-level decision support tool developed to qualitatively assess five soil functions simultaneously as low, medium, or high over a five-year period (Debeljak et al., 2019): primary productivity, nutrient cycling, water purification and regulation, climate regulation, and biodiversity and habitat provision. These five soil functions play a key-role in the supply and demand for soil-based ecosystem services (Schulte et al., 2014) and, therefore, were used in the modelling framework of Schreefel et al. (2022). SN captures the synergies (positive relationships) and trade-offs (negative relationships) between these soil functions in response to changes in management (Zwetsloot et al., 2020). The input data required for SN include data on the environment (i.e. average air temperature and precipitation), farm management (i.e. tillage and the amount of N fertilizer applied to the field) and the soil (i.e. clay content and soil organic matter). The capacity of the soil to supply the five functions resulted from integrated hierarchical decision-support models. These models were structured, calibrated, and validated for grassland and cropland using datasets collected across Europe (Sandén et al., 2019; Schröder et al., 2016; van de Broek et al., 2019; van Leeuwen et al., 2019; Wall et al., 2020). Although SN was developed for pan-European coverage of soils, Schreefel et al. (2022) highlighted that calibration and validation on peat soils has thus far remained limited. Besides the assessment of soil functions, SN offers the possibility to optimize soil functions based on user-set objectives (e.g. medium or high scores for any of the functions). SN shows if the objectives can be achieved; it proposes directions for change and farming practices (i.e. solutions) needed to meet the objectives (further details about the construction of SN are described in supplementary materials S2 and by Debeljak et al. (2019)).

2.2.2. FarmDESIGN

FD was used to show a multitude of different farm configurations (i.e. combinations of solutions) that each contribute in varying degrees to the objectives of regenerative agriculture. FD is a static, bio-economic

Table 1
Overview of the farm characteristics of the benchmark with standard deviation and selected case-study farms.

	Arable farms on clay		Dairy farms on peat		Mixed farms on sand	
Indicators	Benchmark	Case-farm	Benchmark	Case-farm	Benchmark	Case-farm
Farm area (ha)	44 ± 51	45	48 ± 30	40	92 ± 64	54
Number of cows per farm	–	–	84 ± 54	99	71 ± 63	115
Livestock density (LU ha^{-1})*	–	–	2.0 ± 1	3.3	2.2 ± 1	2.8
Time grazing (d yr^{-1})	–	–	111 ± 83	150	123 ± 42	239
Time grazing (h day^{-1})	–	–	7 ± 2	4	7 ± 2	7
Milk yield (kg cow^{-1})	–	–	8422 ± 1147	8720	9362 ± 1151	8242
Milk yield (kg ha^{-1})	–	–	13,304 ± 4863	21,384	16,381 ± 5510	16,170
Concentrate use (kg DM cow^{-1})	–	–	2344 ± 549	2687	2420 ± 561	1940
Inorganic fertilizer use (kg N ha^{-1})	143 ± 24	88	104 ± 62	75	74 ± 46	63
Pesticide use (kg AI ha^{-1})**	7 ± 0	6.7	0 ± 0	0	1 ± 1	1.4

*LU = livestock units; **AI = Active Ingredients.

whole-farm model consisting of a large array of interrelated farm components developed for the analysis and redesign of mixed crop-livestock systems (Groot et al., 2012). FD quantifies farm-level resource flows calculating annual balances for materials, animal feeds, economics and labor. The resource flows are grouped into modules and are used as proxy indicators to assess both the environmental and socio-economic performance of a farm. From the wide variety of indicators available in FD, a selected set of indicators showed to be congruent with the objectives of regenerative agriculture (Schreefel et al., 2022) and are used in this study: soil organic matter (SOM) balance, nitrogen (N) balance, GHG emissions, operating profit, and farm labor balance. Besides the quantification of flows, FD also enables the exploration of optimized farm configurations, which are generated by a Pareto multi-objective optimization, based on two or more user-defined objectives (e.g. minimize GHG emissions and maximize farm profitability), a set of decision variables (e.g. upper and lower limits on animal numbers or crop areas) and preset constraints (e.g. lower and upper limits on animal feed requirements). The new farm configurations are new land-use and resource allocation configurations that result in optimized performance indicators (e.g. reduced GHG emissions). These new configurations have, for example, new crop or animal products being introduced on the farm, different crop areas and allocation of crop products, and changes in herd size (more details about the construction of FD are given in the supplementary materials S3 and described by Groot et al. (2012)).

2.2.3. From field to farm-level assessment using the soil as the starting point

SN is used as a starting point to assess the current status of the five soil functions for each field. However, in order to relate these functions to other farm sustainability indicators (e.g. GHG emissions and farm profitability) soil functionality must be expressed at farm-level. To aggregate the performance of each of the soil functions from field to farm-level, we first assessed the divergence between fields, based on agroecosystem conditions (e.g. land-use), management (e.g. tillage), environmental conditions (e.g. annual precipitation), and soil conditions (e.g. ground water table). Fields with the same conditions and management were merged into a single functional unit (one model application). Separate functional units (multiple model applications) were created for fields with diverging conditions or management. For example, for the dairy case-study farm most fields on the farm were grassland with the same agroecosystem, management practices, environment, and soil characteristics. The dairy case-study farm, therefore, resulted in two separate functional units, one that was dedicated to grassland used for alternately grazing and mowing; the other for mowing only. Due to more divergence in land-use (multiple crops) and related management practices, the arable and mixed case-study farms were captured using six and seven functional units, respectively. Supplementary materials S4 show the variation of soil attributes between fields, which did not lead to further disaggregation of functional units. The qualitative assessments of soil functions from the individual functional units were aggregated to the farm-level using area-weighted averages. Variation between functional units within the farm is presented in the result section using error bars.

After aggregation, we employed the optimization function of SN to determine how each soil function that currently performed at sub-optimal capacity could be improved. This resulted in an inventory (Table 2) of directions for change (e.g. reduce total N fertilization) along with suggested farming practices (e.g. use solid manure). Where these directions for change and suggested practices were congruent with the objectives of regenerative agriculture, they were used to create scenarios for regenerative soil management. For example, for the mixed case study farm SN suggested to increase inorganic N fertilizers to improve nutrient cycling and primary productivity. Although the use of inorganic fertilizers may indeed contribute to nutrient cycling and primary productivity in the soil, it is not in line with the overall objective of regenerative agriculture to reduce external inputs. For this reason we added two directions for change to the use of inorganic fertilizers and synthetic pest and weed control.

Table 2
Directions for change along with farming practices suggested by Soil Navigator for improving the three case-study farms. The asterisk (*) refers to additional practices included according to the review of Schreefel et al. (2020). Soil functions were abbreviated: water purification and regulation (WR), biodiversity and habitat provision (BD), climate regulation (CR) and nutrient cycling (NC). Empty spaces indicate that the directions of change or farming practices were not suggested for the specific case-study farm.

Soil function	Directions for change	Suggested farming practices			
		Arable farm	Dairy farm	Mixed farm	
				Grassland	Cropland
WR	Increase share of legumes	Increase area of lucerne	Introduce species-rich grassland	Introduce species-rich grassland	
	Reduce N application		Introduce species-rich grassland		
	Increase irrigation frequency/rate	Increase irrigation			
BD	Apply solid manure	Introduce solid manure	Introduce solid manure		Introduce solid manure
	Increase soil organic matter and soil C/N ratio	Reduce tillage frequency/ intensity Return crop residues to the soil Introduce solid manure Introduce cover crops			Introduce cover crops
	Increase grassland diversity			Introduce species-rich grassland	
	*Improve habitat for soil organisms and reduce pesticide leaching	Avoid synthetic pest and weed control			Avoid synthetic pest and weed control
CR	Reduce total N fertilization	Limit total N fertilization	Limit total N fertilization	Limit total N fertilization	Limit total N fertilization
	*Improve N fertilizer self-reliance	Avoid inorganic fertilizers	Avoid inorganic fertilizers	Avoid inorganic fertilizers	Avoid inorganic fertilizers
NC	Reduce soil bulk density				Introduce solid manure Return crop residues to the soil

2.2.4. Tailoring practices to local conditions

SN provided directions for change along with farming practices applicable to the local context of the case-study farms. The effect of the suggested practices on the input attributes for SN and FD, however, was still unknown. Therefore, we tailored the suggested practices to local conditions within a five-year period. Tailoring of practices to local conditions to achieve the desired effect is currently an unautomated process and requires expert opinion. For example, for the dairy and mixed case-study farms, SN suggested to increase the share of legumes. The type of legumes to be used and their share in grasslands remained unclear. Based on secondary literature (e.g. Hayes et al., 2019; Mytton et al., 1993) and expert opinion (all co-authors and four experts per case-study farm, see acknowledgements) we chose to implement species-rich grassland and reparametrized the input attributes for SOM balance, N balance, GHG emissions, farm profitability, and labor requirements accordingly. The selected mixture of forb species for the case-study farms, however, differed from each other. For example, for the dairy case-study farm on peat soil, we used white clover only, with a share of 30% in grassland. For the mixed case-study farm on sandy soil, conditions were more favorable (e.g. better pH) for a wider variation of forb species. This allowed the use of red clover which has deeper roots compared to white clover, and hence made a larger contribution of effective organic matter. Part of the reparametrized input data is shown in Table 3–5, using the Dutch feed evaluation system and units (Tamminga et al., 1994; van Es, 1975). The complete table of changed input attributes and justification for all crops of the case-study farms is provided in supplementary materials S5.

2.2.5. Creating explorative regenerative scenarios

After tailoring the suggested practices to local conditions, we created two scenarios in FD for each case-study farm. The first scenario allowed the model to choose between combinations of reference and regenerative management (combined scenario). The second scenario allowed regenerative management only (regenerative scenario). Using these two scenarios increased the diversity of farm configurations towards regenerative agriculture. The scenarios in FD were further accompanied by constraints, decision variables and objectives. Constraints were set to maintain a realistic operating space. For example, constraints were set for the feed balance to match animal requirements and availability of energy, protein, dry matter intake capacity and saturation (to match animal intake capacity). Decision variables gave FD room for exploration as they allow the user to indicate in which range a variable can change. For example, in what range animal numbers or crop areas may increase or decrease. A complete list of parameter settings for the three case-study farms is shown in supplementary materials S6.

The objectives of regenerative agriculture were set in FD to give directions for optimization (e.g. reduce GHG emissions). The regenerative objectives were, however, not all equally relevant for the different case-study farms. In order to determine which regenerative objectives were most important at the farm-level a survey was conducted during a workshop, to demonstrate the working principle of the modelling framework to a wide variety of stakeholders (farmers, researchers, NGO's, government, and industries). The survey yielded 20 responses indicating the three most important objectives to be incorporated in FD for each case-study farm. The three most important objectives for arable farming on clay soil were deemed to be to maximize SOM (27%), minimize external inputs (26%), and maximize operating profit (18%). The most important objectives for dairy farming on peat soil were to minimize GHG emissions (29%), maximize profit (18%), and minimize external inputs (18%). The most important objectives for mixed farming on sandy soil were to minimize external inputs (27%), maximize operating profit (26%), and minimize the N balance (22%). Supplementary materials S7 shows more detail about the results of the survey.

Table 4
Part of the composition table of the dairy case-study farm showing annual input data used in FarmDESIGN for reference and regenerative management.

		Reference management Permanent grassland		Regenerative management Grass-clover	
Input attribute	Unit	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
Required labor	h ha^{-1}	18	21	21	25
Price fresh matter	€ kg^{-1}	0	0.06	0	0.07
Dry matter yield	kg ha^{-1}	1969	28,561	1969	28,561
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: Blanken et al. (2018), Bosch and de Jonge (1989), CVB (2018), de Wit et al. (2004), Feedipedia (2020), Goyens (2016), and van der Voort (2018).

2.2.6. Exploring alternative farm configurations

For each of the scenarios, we ran a multi-objective exploration in FD to create solution spaces which consist of alternative farm configurations (consisting of a combination of practices). The solution spaces can be used to find configurations most suitable to the individual farm, and to find relationships (e.g. synergies and trade-offs) between the optimization objectives. These relationships were found through visual inspection and regression analysis (supplementary materials S8). The multi-objective exploration was run separately for the combined and regenerative scenario, resulting in two solution spaces that each consisted of 2000 farm configurations. From the solution spaces, any farm configuration can be selected in the FD model, to further examine the performance for a wide range of farm sustainability indicators.

Table 3
Part of the composition table of the arable case-study farm showing annual input data used in FarmDESIGN for reference and regenerative management.

		Reference management				Regenerative management			
Input attribute	Unit	Lucerne	Sugar beet	Potato	Winter wheat	Lucerne	Sugar beet	Potato	Winter wheat
Nitrogen fixation	kg ha^{-1}	122	0	0	0	122	0	0	0
Effective org. matter	kg ha^{-1}	1550	375	875	2514	1550	2149	1749	3504
Cultivation costs	€ ha^{-1}	333	1300	3100	1071	281	1579	2657	621
Required labor	h ha^{-1}	5	25	30	17	5	75	34	19
Price fresh matter	€ kg^{-1}	0	0.04	0.14	0.16	0	0.04	0.14	0.16
Dry matter yield	kg ha^{-1}	10,000	21,800	7368	8680	8571	14,497	5575	7315

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Bom (1983), Bosch and de Jonge (1989), de Wolf et al. (2019), Feedipedia (2020), van Geel and Brinks (2018), Gren (1994), Scheepens et al. (2001), Schröder et al. (2003), Starmans et al. (2015), van der Voort (2018), and van der Weide et al. (2008).

Table 5
Part of the composition table of the mixed case-study farm showing annual input data used in FarmDESIGN for reference and regenerative management.

Input attribute	Unit	Reference management				Regenerative management			
		Grazed grass	Grass silage	Fodder beet	Maize	Species-rich grazed grass	Species-rich grass silage	Fodder beet	Maize
Nitrogen fixation	kg ha^{-1}	0	0	0	0	190	190	0	0
Effective org. Matter	kg ha^{-1}	2000	2000	375	675	2000	2000	1775	675
Cultivation costs	€ ha^{-1}	1200	1200	1621	1579	1200	1200	1946	1801
Regular labor	h ha^{-1}	25	30	31	37	30	35	91	107
Price fresh matter	€ kg^{-1}	0.00	0,06	0,05	0,06	0.00	0,07	0,05	0,06
Dry yield	kg ha^{-1}	5084	10,219	15,400	15,567	5466	10,985	13,090	15,567
Feed saturation value (VW)	–	0,89	1,01	0,69	0,79	0,90	1,02	0,69	0,79
Feed structure value (SW)	–	1,88	2,82	1,10	1,50	2,00	2,90	1,10	1,50
Energy content (VEM)	–	960	888	1079	1000	989	915	1079	1000
Protein content (DVE)	g kg DM^{-1}	92	67	104	70	95	69	104	70

Values were based on farm interviews, expert opinion (all co-authors and three grassland experts, see acknowledgements) and the following secondary literature: Blanken et al. (2018), Bom (1983), Bosch and de Jonge (1989), CVB (2018), de Wit et al. (2004), de Wolf et al. (2019), Feedipedia (2020), van Geel and Brinks (2018), Goyens (2016), Gren (1994), Scheepens et al. (2001), Schröder et al. (2003), Starmans et al. (2015), van der Voort (2018), and van der Weide et al. (2008).

Three configurations were selected to be compared with the reference configuration. The first configuration (Configuration 1) was selected from the solution space of the combined scenario (combination of the reference and regenerative scenarios). We used a multi-objective filtering approach to decide which of the 2000 configurations best reflected the objectives obtained from the survey. We did this by ranking all configurations from 0 (best) to 2000 (worst) for each individual optimization objective. The configuration with the lowest aggregated score was selected and compared with the reference configuration. A second farm configuration (Configuration 2) was selected based on the largest area of land dedicated to regenerative management within the combined scenario. Through Configuration 2, it was possible to show to what extent regenerative management was used. The last farm configuration (Configuration 3) was selected from the solution space created by running the regenerative scenario only. We used the multi-filtering approach again to find the overall best configuration. The selected farm configurations were re-entered into SN, in order to assess the improvement of soil functions that resulted from the explorations in FD. Table 6, Table 7, and Table 8 show some of the input attributes that changed for this second iteration of assessment in SN for the different scenarios. Configurations 1 and 2 use both the reference and regenerative scenario (combined scenario) in different extents; Configuration 3 uses solely the regenerative scenario. The complete table of changed input attributes can be found in supplementary materials S9.

3. Results

SN showed which soil functions could be improved using various farming practices for the different case-study farms (Section 2.2.3 and Table 2). Through FD we created in total 4000 solutions per farm consisting of solution spaces of 2000 farm configurations with a combination of reference and regenerative management practices and 2000 farm configurations with regenerative management practices only (Figs. 3, 5, and 7). In the following sections we will show these solution spaces for the case-study farms and discuss the synergies and trade-offs between the optimization objectives. Furthermore, we will discuss the impact of the optimizations on soil functions, as well as the other sustainability indicators.

3.1. Arable case-study farm

3.1.1. Solution spaces of farm configurations

Fig. 3 shows the solution spaces for the arable farm. The area of regenerative farmed land varied largely across alternative configurations (supplementary materials S11). For example, the majority (71%) of configurations used regenerative practices on 50 to 75% of their total farm area. The solution space of the combined scenario was larger than that of the regenerative scenario which accounts for all farms. The smaller solution space for the regenerative scenario resulted from additional constraints that for example did not allow the import of inorganic fertilizers and synthetic pesticides. The farm configurations outperformed the reference configuration on all objectives except for

Table 6
Input attributes for SN which changed between the reference and regenerative scenario of the arable case-study farm.

Input	Unit	Reference scenario				Regenerative scenario			
		Sugar beet	Chicory	Potato	Winter wheat	Sugar beet	Chicory	Potato	Winter wheat
Tillage	Yes/no	Yes	Yes	Yes	Yes	No	No	No	No
Use of catch crops and crop residues in the field	yr	0	0	0	5	5	5	5	5
Application of mineral fertilizer	Yes/no	yes	yes	yes	yes	no	no	no	no
Mineral N fertilization	kg N ha^{-1}	75–100	125–150	75–100	75–100	0	0	0	0
Mineral P fertilization	kg P ha^{-1}	<10	<10	<10	<10	0	0	0	0
Type of manure	–	No	No	Pig slurry	Pig slurry	Solid manure	Solid manure	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	0	0	>200	>200	75–100	50–75	125–150	100–125
Chemical pest management	Yes/no	yes	yes	yes	yes	no	no	no	no
Irrigation rate	mm h^{-1}	0	0	6–12	0	6–12	6–12	6–12	6–12
Irrigation frequency	Days	0	0	<10	0	<10	<10	<10	<10

Table 7
Input attributes for SN which changed between the reference and regenerative scenario of the dairy case-study farm.

Input	Unit	Reference scenario		Regenerative scenario	
		Alternated grazing and mowing	Mowing only	Alternated grazing and mowing	Mowing only
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	–	Cow slurry	Cow slurry	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	>200	>200	75–100	75–100

Table 8
Input attributes for SN which changed between the reference and regenerative scenario of the mixed case-study farm.

Input	Unit	Reference scenario					Regenerative scenario				
		Alternated grazing and mowing	Mowing only	Maize	Fodder beet	Winter wheat	Alternated grazing and mowing	Mowing only	Maize	Fodder beet	Winter wheat
Tillage	Yes/ no	No	No	Yes	Yes	No	No	No	No	No	no
Number of years with legumes	Yr	0	0	–	–	–	5	5	–	–	–
Grassland diversity	–	1	1	–	–	–	>2	>2	–	–	–
Use of catch crops and crop residues in the field	Yr	–	–	0	1	3	–	–	5	5	5
Application of mineral fertilizer	yes/ no	yes	yes	yes	yes	yes	No	No	No	No	No
Mineral N fertilization	kg N ha^{-1}	75–100	75–100	<50	75–100	75–100	–	–	–	–	–
Mineral P fertilization	kg P ha^{-1}	<10	<10	<10	<10	<10	–	–	–	–	–
Type of manure	–	Cow slurry	Cow slurry	Cow slurry	Cow slurry	Cow slurry	Solid manure	Solid manure	Solid manure	Solid manure	Solid manure
Organic N fertilizer	kg N ha^{-1}	125–150	125–150	125–150	125–150	100–125	75–100	75–100	100–125	125–150	125–150
Chemical pest management	Yes/ no	yes	yes	yes	yes	yes	no	no	no	no	no

operating profit. Increasing operating profit has a trade-off with increasing the SOM balance (Fig. 3D), reducing pesticide use (Fig. 3E), and reducing imported fertilizers (Fig. 3F). These relationships relate to larger areas in farm configurations with regenerative management yielding more effective organic matter due to, for example, returning crop residues to the soil and making use of cover crops. Avoiding the use of pesticides, reducing total N fertilization and fully substituting solid manure for additional inorganic N fertilizers would lead to lower crop production yields, and hence lower profits. The objective to increase the SOM balance had a synergy with reducing imported fertilizers (Fig. 3C). Supplementary materials S8 gives quantification regarding synergies and trade-offs for all case-study farms. Supplementary material S10 shows a sensitivity analysis of the decision variables and their influence on the various objectives in the combined scenario. Reducing imported fertilizers showed a slight trade-off with reducing pesticide use (Fig. 3B).

3.1.2. *Assessment on the objectives of regenerative agriculture*

Fig. 4 shows the performance of the selected farm configurations (Configurations 1,2, and 3) from the solution spaces in Fig. 3 (absolute values are presented in supplementary materials S11). Where the majority of land is managed under regenerative practices, four out of five soil functions can be achieved at high capacity at the farm-level (Configuration 3). Nutrient cycling, however, declined from high to medium, when changing to regenerative management. More specifically, the functional units for regenerative sugar beet, chicory, and potato showed reduced underlying scores for the nutrient harvest index (supplementary materials S11). Although soil nutrient cycling performed at medium capacity, the farm N balance was reduced by 60% for the three configurations (from 117 to ~40 kg N ha^{-1}) mainly due to a reduction of imported fertilizers (especially inorganic fertilizers). Soil conditions to enhance optimal primary production remained the same in SN and performed at high capacity. For the regenerative scenario in FD, reduced yield values were the main driver for a reduction in operating profit, despite a considerable reduction in external input costs was established (e.g. fertilizer costs were reduced on average from 18,450 to 4050 € yr^{-1}). Reduced fertilization in combination with the use of cover crops led to improvements of the climate regulation scores among configurations. In addition, GHG emissions at the farm-level were reduced for all selected configurations by 50% (from 4 to 2 Mg CO_2 eq. ha^{-1}; from 172 to 94 Mg CO_2 eq.) mainly by reducing external inputs (inorganic fertilizers and synthetic pesticides). Diesel use, however, increased due to the seeding of cover crops, mechanical weeding, and the use of irrigation. These practices, in combination with reduced fertilization, improved the score for water purification and regulation from low to high for all selected configurations. The function biodiversity and habitat provision improved from medium to high as a result of better soil structure, hydrology, and nutrient supply due to reduced tillage, eliminating pesticides, using solid manure, and returning crop residues to the soil. The use of solid manure and returning crop residues to the soil also increased the SOM balance at the farm-level by on average 97%. Farm labor increased for all selected farm configurations by 30–48%, due to a considerable higher labor requirement associated with regenerative crop maintenance. The higher labor requirement is a result of a large demand for hand weeding as a consequence of the elimination of synthetic pesticides. For example, sugar beet requires 65 h ha^{-1} of hand weeding if no synthetic pesticides are used

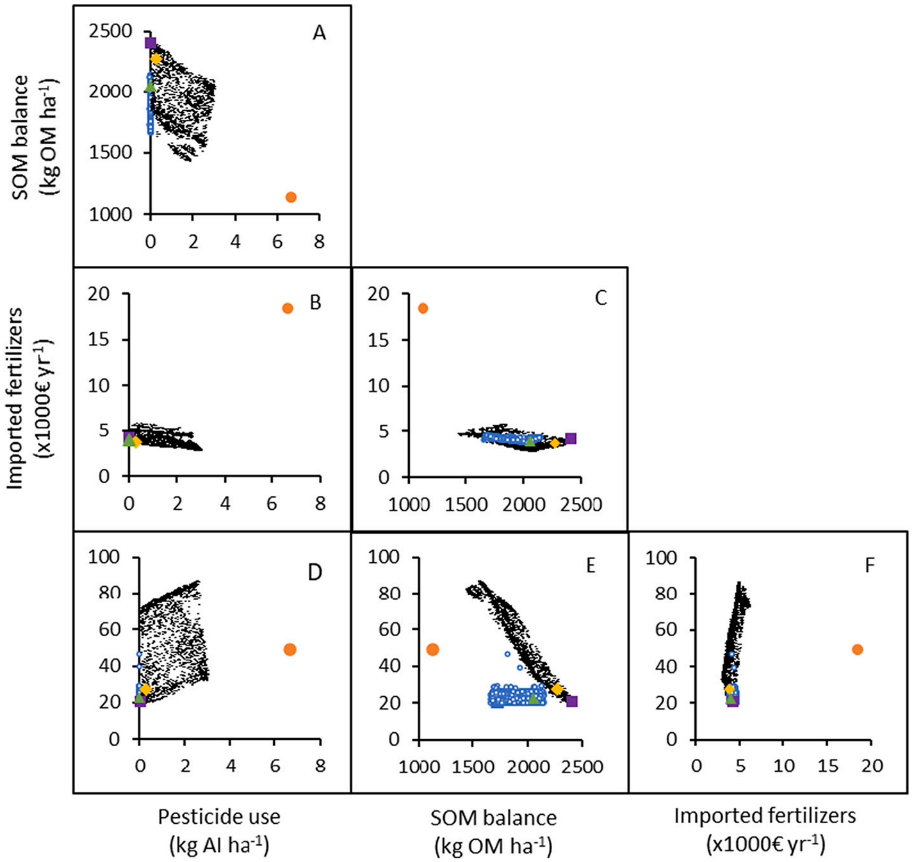

Fig. 3. Solution spaces of alternative farm configurations in terms of imported fertilizers, pesticide use, SOM balance and operating profit for the arable case-study farm.

(Praktijkonderzoek Plant and Omgeving B.V., 2009).

3.2. Dairy case-study farm

3.2.1. Solution spaces of farm configurations

Fig. 5 shows the solution spaces for our dairy case-study farm. The solution space of the combined scenario has 52%, 37%, 11%, and 0% of the farm configurations within the range of 0–25%, 25%–50%, 50%–75%, and 75–100% of the total farm area used for regenerative management respectively (supplementary materials S11). The two scenarios resulted in two different solution spaces with the regenerative scenario showing a more condensed solution space compared to the combined scenario, similar to the results for the arable case-study farm. Among the solution spaces of both scenarios we found synergies and trade-offs. The near-linear relationships in Fig. 5A, D, and E share the same underlying drivers: Fig. 5A shows a synergy between the objective to reduce imported feed and to reduce GHG emissions, i.e. reducing the import of concentrate feed leads to lower animal numbers and GHG emissions. Fig. 5D shows a trade-off between increasing operating profit and reducing GHG emissions, i.e. an increase in operating profit also leads to an increase in GHG emissions. A trade-off was also found between reducing imported feed and increasing operating profit (Fig. 5E). These relationships are a result of the increase in operating profit which relies on an increase in animal numbers and more milk production, and a higher external feed requirement, both resulting in increased GHG emissions. The objective to reduce external feed allowed the model to find solutions in which feed requirements match on-farm produced feed. Fig. 5B, C, and F do not show a particular relationship for the combined scenario, rather a broad solution space. The regenerative scenarios of Fig. 5B, C, and F clearly show that no imported fertilizers were used in these scenarios.

3.2.2. Assessment on the objectives of regenerative agriculture

Fig. 6 shows the performance of the selected configurations from the solutions spaces (absolute values are presented in supplementary materials S11). It illustrates that four out of five soil functions can be achieved at high capacity if the majority of the land is used in a regenerative way. The selected configurations 1, 2, and 3 had various shares of land allocated to the regenerative scenario, i.e. 35%, 66%, and 100% respectively. The increase in land allocated to the regenerative scenario came at the expense of the soil function primary productivity, which declined from high to medium due to for example a reduction in N-fertilization rates. However, this decline in primary production was associated with an increase in the supply of other soil functions (i.e. water purification and regulation, nutrient cycling, and climate regulation). Fig. 6 shows that compared to the baseline, farm profitability reduced by 40–60% (from 33,412 to 26,521 € yr^{-1}) for all selected configurations. The decrease in farm profitability was a result of lower animal numbers, hence less milk production. The reference and selected configurations 1, 2, and 3 included 99, 91, 93, and 87 dairy cows, respectively. Lower animal numbers were selected by the model to maintain animal nutrition requirements with lower quantities of imported feed and to reduce GHG emissions. Water purification and regulation increased from low to high capacity for the fully regenerative scenario only, with the integration of grass-clover and lower N fertilization. The objective to reduce quantities of imported fertilizers and feeds did not result in a significantly lower N balance, as it remained more or less stable for the selected configurations (from 258 to 274 kg N ha^{-1}). The decrease in farm N balance was limited, mainly due the increased N fixation which compensated for the reduction in total N fertilization (imported fertilizers and manure). The soil function nutrient cycling improved from a medium to a high capacity for the selected configurations 2 and 3, due to including clover that improved

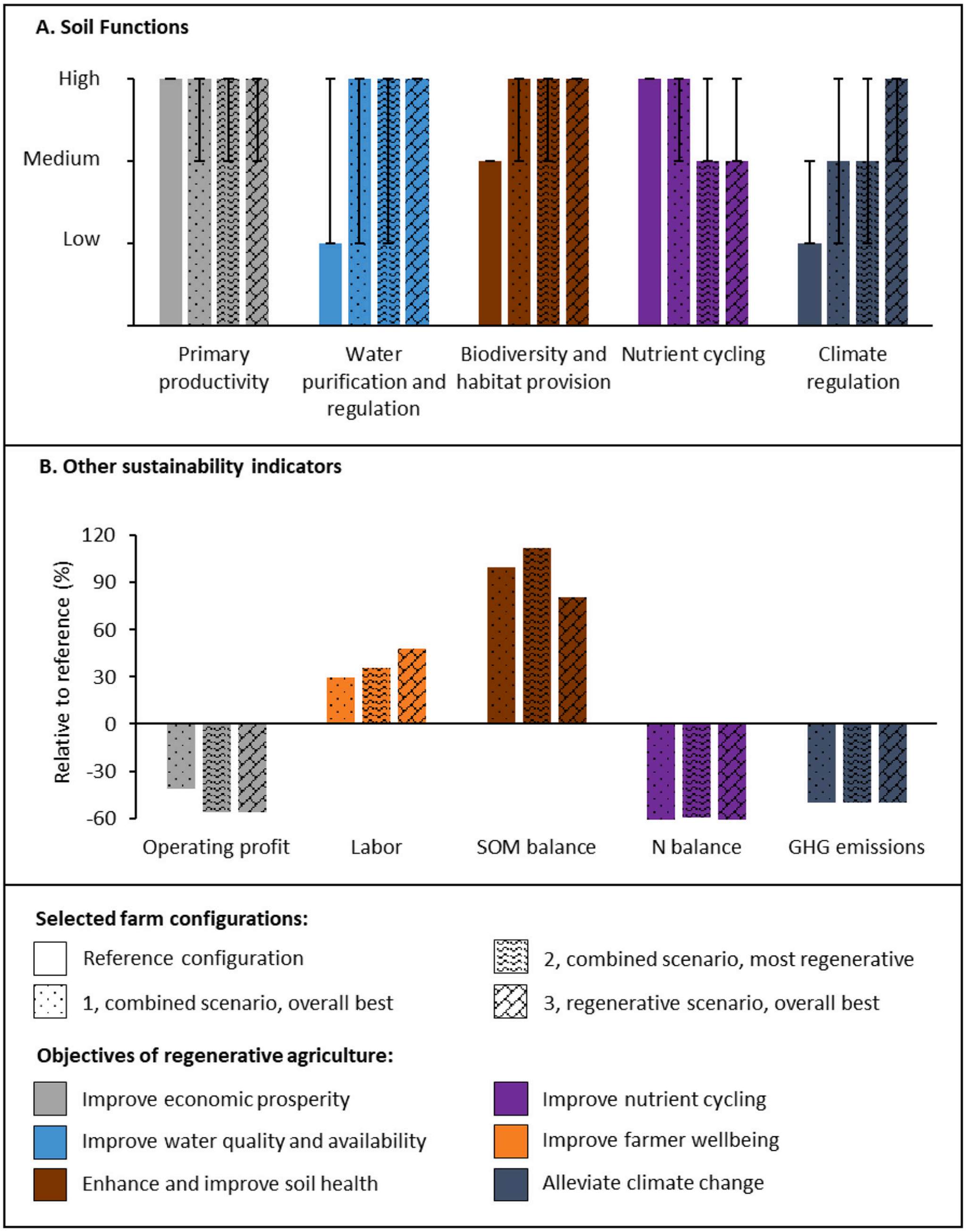

Fig. 4. The performance of farm configurations on the objectives of regenerative agriculture for the arable case-study farm, discriminated in soil functions (A) and other farm sustainability indicators (B). Error bars represent functional units with divergent scores from the area weighted averages, indicating within-farm variability. The performance of other sustainability indicators are shown relative to the reference scenario. The colors correspond to the objectives of regenerative agriculture.

nutrient recovery. The soil function biodiversity and habitat provision remained high for the selected farms as a result of increased grassland diversity and the application of solid manure. The farm SOM balance increased on average 28% for selected configurations 1 and 2. This indicates that the use of solid manure, which has a higher effective organic matter compared to slurry and inorganic fertilizers, outweighed the lower effective organic matter input from grass-clover compared to permanent grassland. In addition, lower animal numbers reduced the availability of manure, further reducing the SOM balance of configuration 1. Climate regulation improved from medium to high, in response to a reduction in total N fertilization, and hence N_2O emissions. The high score for climate regulation should be interpreted with caution, considering the limited calibration and validation of SN on peat soils (Schreefel et al., 2022). Decreases in overall GHG emissions (from 26 to 28 Mg CO_2 eq. ha^{-1}; from 1230 to 1050 Mg CO_2 eq.) reflected the improvements for climate regulation in configurations 1 and 3. However in configuration 2, a slight increase in GHG emissions was observed. This was due to a higher import of concentrate feed and slightly higher animal numbers. Farm labor decreased for the selected farms within the range of 2% to 4% (from 2863 to 2928 h yr^{-1}) due to lower animal numbers.

3.3. *Mixed case-study farm*

3.3.1. *Solution spaces of farm configurations*

Fig. 7 shows the solution spaces for our mixed case-study farm, in which the combined scenario showed to have no alternative farm configurations dominated by regenerative management; in 84% of the farm configurations <25% of the land was managed regeneratively (supplementary materials S11). For the remainder of the farm configurations (16%), 25–50% of the land was managed regeneratively. Similar to the other case-study farms, the combined scenario resulted in a greater

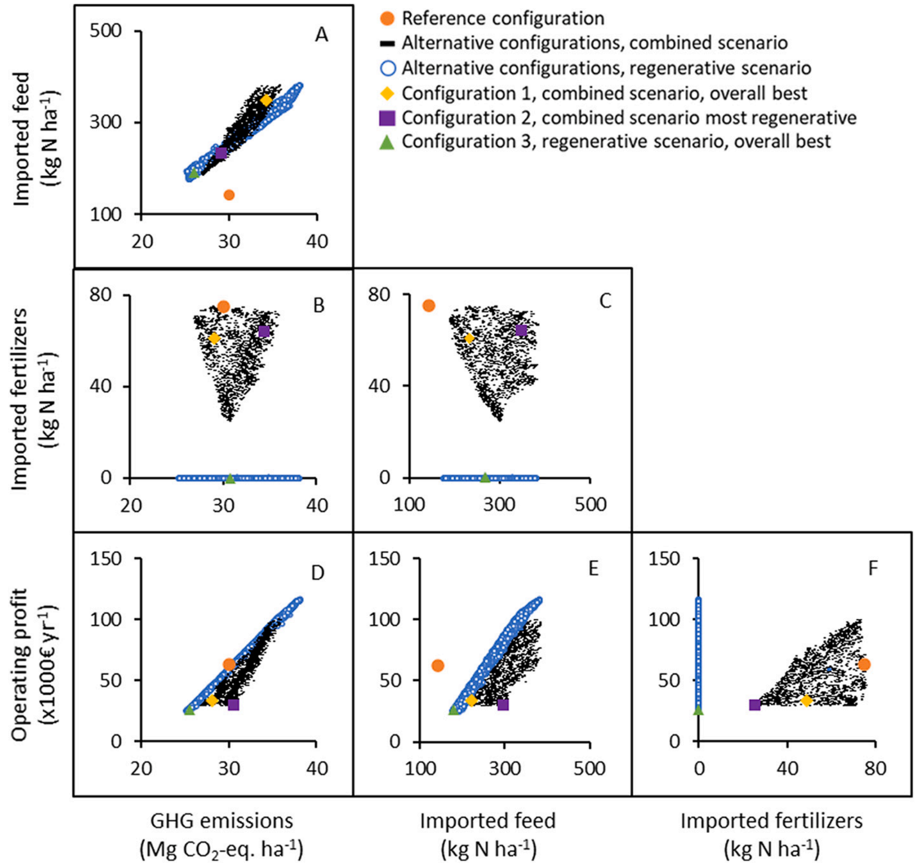

Fig. 5. Solution spaces of alternative farm configurations in terms of GHG emissions, imported fertilizers, imported feed and operating profit for the dairy case-study farm.

solution space in which farm configurations outperformed the reference configurations to different extents. Moreover, synthetic pesticides and inorganic fertilizer were reduced or even eliminated for all farm configurations (Fig. 7B, C, G, H, I, and J). Furthermore, we observed a synergy between the objective to reduce pesticide use and imported fertilizers (Fig. 7I), similar to the arable case-study farm. Another synergy was found between the objective to reduce imported feed and reduce the N balance, i.e. reducing imported feed leads to a reduced farm N balance. Trade-offs were found in the regenerative scenario for the objective to increase operating profit and reduce the farm N balance and imported feed (Fig. 7D and E). Similar to the dairy case-study farm, this trade-off relates to higher feed imports required to maintain higher animal numbers and operating profits. Different from the dairy case-study farm, we found a clear inflection point in Fig. 7E which indicates that operating profit can be increased until 70,000 € yr^{-1} by using a limited amount of imported feed to support 80 cows. Moreover, the inflection point relates to the self-reliance of the farm. Supplementary material S11, specifically shows that when animal numbers increase above 80 cows, the farm is not self-sufficient in e.g. grass silage and concentrate feed needs to be imported to maintain animal requirements.

3.3.2. Assessment on the objectives of regenerative agriculture

Similar to the other case-study farms, the selected configurations of the mixed case-study farm show improvement in soil functions when moving towards regenerative management (Fig. 8). For the mixed case-study farm specifically, four out of five soil functions can be achieved at high capacity when transitioning fully to regenerative management. Configurations 1, 2, and 3 allocated 31%, 32%, and 100% of their land to regenerative management. Primary productivity remained at high capacity, although farm profitability was reduced by on average 44% (from 66,719 to 37,122 € yr^{-1}), driven by lower animal numbers (to reduce feed imports and reduced crop yields) and increased crop cultivation costs related to increased labor requirements for hand weeding. Improved scores for water purification and regulation related to combinations of measures that affected grassland and cropland differently. Reducing N fertilization and using cover crops for example reduced N leakage for cropland. However, for grassland incorporating more species (e.g. clover) reduced total N fertilization and leakage, while the water storage capacity of the soil was improved from low to medium by applying solid manure which improved soil structure. Improved soil structure (from low to medium) and biology (from low to medium) also contributed to a high score for biodiversity and habitat provision; associated practices improved the average SOM balance by 119%. The amount of solid manure used was strongly related to animal numbers and the fixed demand for fertilization for the incorporated crops. Configurations with lower animal numbers, therefore, had a lower SOM balance. The N balance increased due to the higher N-fixation rates of species-rich grassland and greater import of animal feed, outweighing the reduction in N fertilization rates for grass- and cropland. The soil function nutrient cycling improved due to a higher nutrient recovery rate for grassland when including legumes. Incorporating cover crops, increasing the share of legumes and reducing total N fertilization did not improve the score for climate regulation which remained medium. If, however, we distinguish between grassland and cropland we see that grassland has a higher score for climate regulation, while cropland has on average, a medium score because of lower carbon sequestration (supplementary materials S11). In addition, farm-level GHG emissions declined by 17% compared to the reference (from 21 to 16 Mg CO_2 eq. ha^{-1}; from 1178 to 916 Mg CO_2 eq.) due to a reduction in animal numbers (supplementary materials S11 shows the absolute values for Fig. 8).

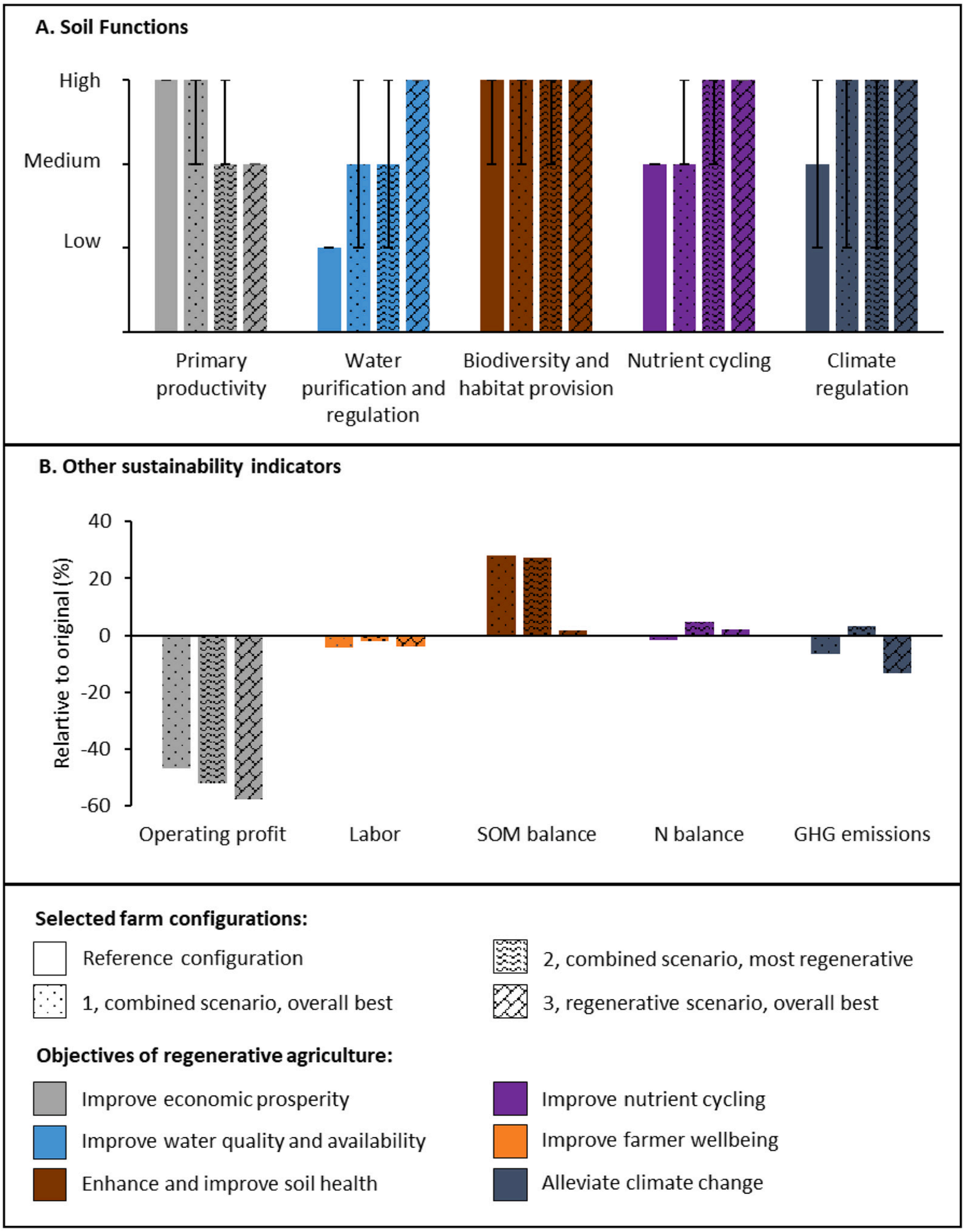

Fig. 6. The performance of farm configurations on the objectives of regenerative agriculture for the dairy case-study farm, discriminated in soil functions (A) and other farm sustainability indicators (B). Error bars represent functional units with divergent scores from the area weighted averages, indicating within-farm variability. The performance of other sustainability indicators are shown relative to the reference scenario. The colors correspond to the objectives of regenerative agriculture.

4. Discussion

4.1. A diversity of solutions

The common mode of Dutch farming has focused on increasing primary productivity, through the use of mined and synthetic fertilizers, concentrate feed, and synthetic pesticides, in order to meet the increased crop and livestock needs with great precision (Meerburg et al., 2009). These practices, however, are avoided in regenerative agriculture because they have strong trade-offs with regenerative objectives (e.g. the negative impacts of pesticide use on soil biodiversity (Oosthoek, 2013)) and are therefore not in line with the regenerative philosophy (Rhodes, 2017). Although regenerative agriculture has overarching objectives (e.g. improve soil health), Giller et al. (2021) felt that the concept of regenerative agriculture had little meaning at the individual farm-level. In our previous work (Schreefel et al., 2022), we created a framework that combined two models to explore alternative futures for individual farms, using soil health as the basis of a redesign of farming practices. This study has further explored this modelling framework and addressed the challenge set by Giller et al. (2021) by providing farm-level interpretations of regenerative agriculture. We assessed and redesigned diverse Dutch farming systems taking into account their contrasting pedo-climatic conditions, resulting in tailor-made solutions for individual farms. These tailor-made solutions differed between farms, both in terms of prioritized objectives, and the management practices associated with regenerative agriculture.

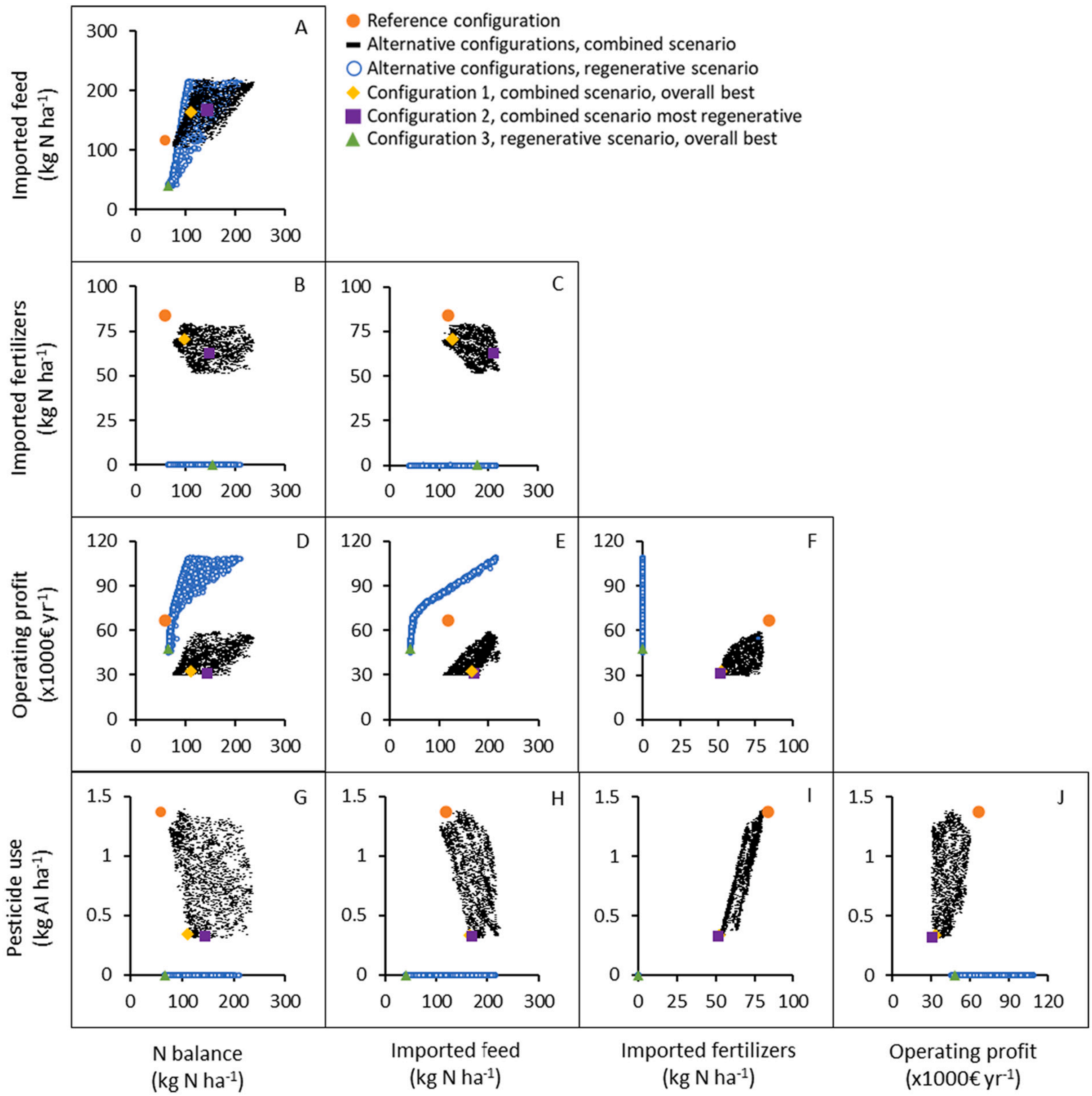

Fig. 7. Solution spaces of alternative farm configurations in terms of N balance, imported fertilizers, imported feed, pesticide use and operating profit for the mixed case-study farm.

These tailor-made solutions improved regenerative objectives for all case-study farms, and more specifically, showed that four out of five soil functions can be achieved at high capacity. This was a stronger improvement than expected, since obtaining three out of five soil functions at high capacity is considered feasible for cropland farms, as a result of the occurrence of trade-offs between the soil functions (Zwetsloot et al., 2020). Showing synergies and trade-offs between soil functions, regenerative objectives, and farming practices is key for farmers to decide what management practices best suit their local conditions and individual preferences (Groot et al., 2012). Moreover, to support on-farm decision making we show solution spaces instead of single optimized solutions. Showing farmers solution spaces with a multitude of farm configurations gives farmers a negotiation perspective, in which they have the opportunity to select the solution that fits their intrinsic motivations the most (e.g. Groot and Rossing, 2011; Mandryk et al., 2014). Although, this framework was used in this study as a tool to support on-farm decision making, it might be used in participatory processes with farmers and other stakeholders; to consider both regenerative objectives and intrinsic motivations of the farmer that lead to the final selection of the farm redesign (see also Lacombe et al., 2018; López-García et al., 2021). Moreover, most models and tools to date have failed to be adopted by a wider audience (e.g. researchers and consultants) due to multiple reasons (e.g. complexity and availability) (de Olde et al., 2018). To increase user operability we selected two publicly available models with extensive user guides (Soil Navigator: http://www.soilnavigator.eu/; FarmDESIGN: https://fse.models.gitlab.io/COMPASS/FarmDESIGN/).

4.2. Profit more important than productivity

In this study we highlight that, for all case-study farms, environmental performance improved at the expense of farm profitability. The reduction in farm profitability was mainly associated with reductions in animal numbers to improve feed self-sufficiency, reductions in crop yields, and higher labor requirements. Declining crop yields within the first five years of regenerative management are a well-known symptom

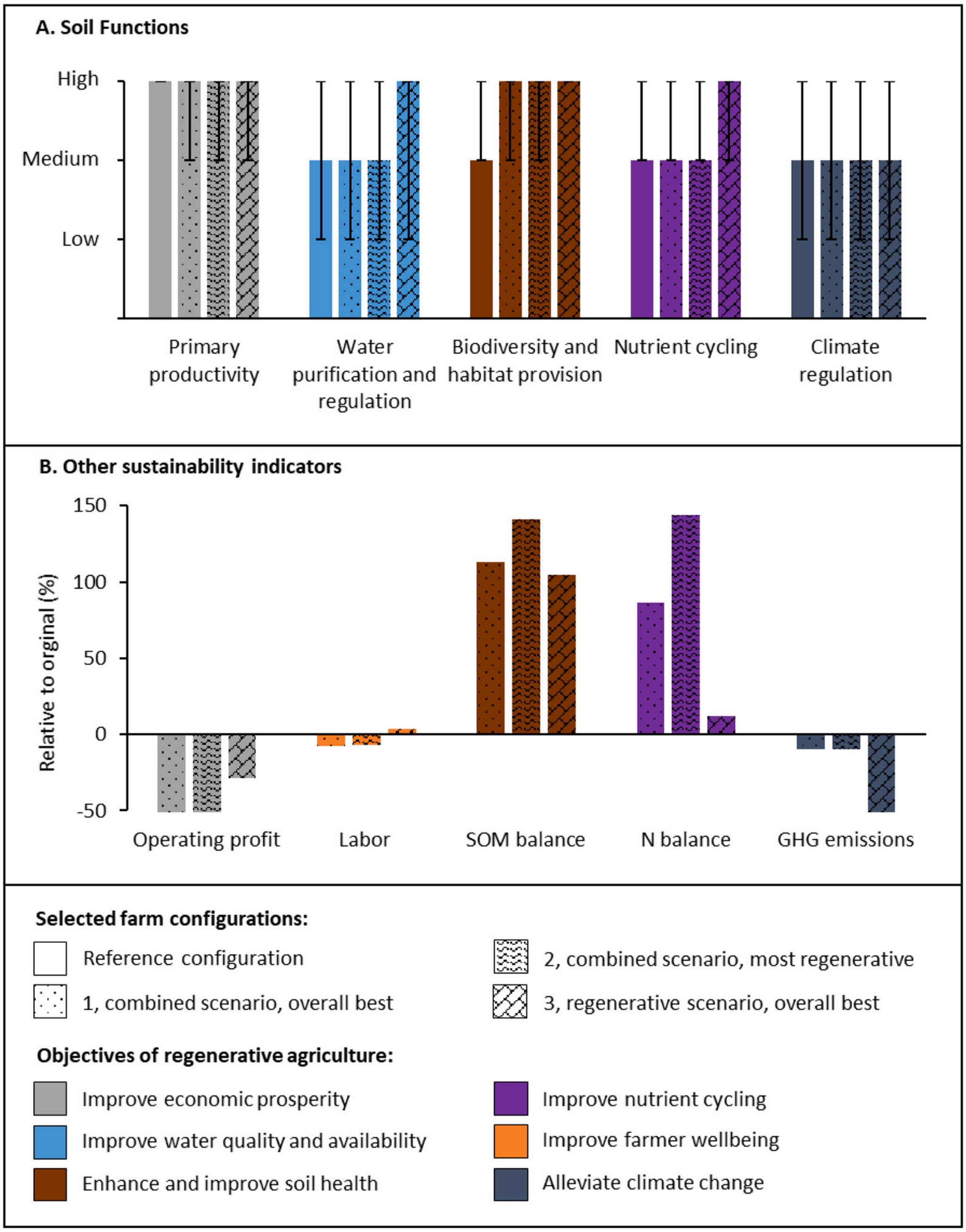

Fig. 8. The performance of farm configurations on the objectives of regenerative agriculture for the mixed case-study farm, discriminated in soil functions (A) and other farm sustainability indicators (B). Error bars represent functional units with divergent scores from the area weighted averages, indicating within-farm variability. The performance of other sustainability indicators are shown relative to the reference scenario. The colors correspond to the objectives of regenerative agriculture.

of transitions towards regenerative and organic management (LaCanne and Lundgren, 2018; Luján Soto et al., 2021; van der Voort, 2018). The reductions in yields are a result of, for example, the elimination of synthetic pesticides, which may result in an increased incidence of pests and diseases (Aktar et al., 2009), or a result of reduced tillage which can lead to weed infestations (Pittelkow et al., 2015). Under regenerative management as well as organic management, yield stability relies on the natural resilience of the farming system (Li et al., 2019). Various studies (e.g. Chee, 2004; Power, 2010), therefore, argue that primary productivity alone is a suboptimal indicator to evaluate the performance of a regenerative farming system, which besides productivity also contributes to the supply of other regenerative objectives (LaCanne and Lundgren, 2018). Yields may stabilize over a longer time span (>10 years) (Li et al., 2019; Schrama et al., 2018; Seufert et al., 2012). Increased labor will, however, remain a key driver for reduced farm profitability due to, for instance increased hand weeding in sugar beet or winter wheat production (van der Voort, 2018).

There are examples of regenerative farming systems around the globe that demonstrate that achieving multiple regenerative objectives and having viable business models is possible (e.g. Khumairoh et al., 2018; Koppelmäki et al., 2019). Currently the majority of Dutch farmers, however, prioritize economic profitability over environmental and social objectives of food production (Kik et al., 2021). Schulte et al. (2019) shows that Dutch citizens expect farmers to deliver on multiple regenerative objectives from their land. The disparity between the prioritization of farmers and the expectations of citizens can be solved by changing both policies and industries to valorize regenerative objectives (i.e. ecosystem services) in business models (Chee, 2004). These business models should not be built around single objectives such as carbon credits (Williams et al., 2005), but consider multiple regenerative objectives relevant to the local context. Furthermore, the valorization of regenerative objectives should not disadvantage farmers in the transition period in which yields may be reduced (Dabbert and Madden, 1986), while the positive effects in regenerative objectives are still increasing (Geisen et al., 2019). Ideas for such business models are already in existence (e.g. price premiums (Chee, 2004) and subsidies (Lotz et al., 2018)), however, it is currently unclear what role industries and policies could play in supporting such business models to support the valorization of regenerative objectives (Gosnell et al., 2019; Sivertsson and Tell, 2015). The European Commission (2022) is currently developing a Soil Health Law as part of the EU soil strategy for 2030, which highlights the multifunctional role that soils are expected to contribute to a range of ecosystem services. This law could provide an opportunity to stimulate a wider transition towards regenerative agriculture, highlighting soil health as the entry point for multifunctional agricultural systems and supporting farmers in this transition through subsidies.

4.3. The future of modelling: Increasing complexity

In this study we selected case-study farms which represented typical but also conventional farming systems in the Netherlands. This allowed for the exploration of a wide range of regenerative farming practices such as the use of solid manure, the reduction in tillage, synthetic pesticides, and inorganic fertilizers. The farming practices suggested by SN were, however, limited to the inventory of practices available in SN. The full range of regenerative farming practices may include more practices than SN is able to assess, such as including additional regenerative crops, using multiple fertilizers on a field or farm, using fixed traffic lanes, using light-weight machinery, and differentiating between the impacts of synthetic pesticides (some are more harmful than others). Other practices will require radical changes within the model, such as improved spatial-temporal crop rotations (e.g. strip cropping). For the livestock sector, it requires more intensive integration of crop-livestock systems, which does not separate land for fodder production and grassland for grazing but integrates these systems such as agroforestry and silvopasture. It may be challenging to model practices that require such a radical systems change due to the intricate synergies and trade-offs occurring between the model components, which must then be captured and parameterized.

Besides increasing the complexity of models, attention should also be given to the modelled time horizon. A majority of modelling studies work on an annual basis or within a five-year crop rotation (e.g. Adelhart Toorop et al., 2020; Timler et al., 2020). Yet, many of the desired effects of regenerative agriculture only become visible over a longer time horizon. For example, increasing the SOM content on mineral soils can take more than five years (Powlson et al., 1998). Only after this period the positive effects on water and nutrient retention, and yields can be noticed (Menšík et al., 2018). At the same time, most of the costs associated with a transition to regenerative practices occur in the initial phase, while economic benefits to the farmer commonly accrued in the long term only. Therefore, we suggest that modelling studies extend their time horizon, to capture the benefits, economic as well as environmental, associated with regenerative management. Currently, this is challenging as data on the long-term effects of regenerative practices for different pedo-climatic conditions are largely lacking (Johnston and Poulton, 2018).

5. Conclusions

This study showed that transitions towards regenerative agriculture requires tailor-made solutions and management practices for individual farming systems. By building upon the modelling framework of Schreefel et al. (2022), we made specific what regenerative agriculture means for individual farming systems, by showing which regenerative objectives and farming practices can contribute to the transition towards regenerative agriculture in contrasting contexts. Furthermore, we created a wide diversity of tailor-made solutions contributing in varying degrees towards the objectives of regenerative agriculture. We specifically showed for the case-study farms (arable farming on clay soil, dairy farming on peat soil and mixed farming on sandy soil) that overall environmental performance was improved (e.g. soil functions, GHG emissions, pesticide use and inorganic fertilizers). This improvement, however, came at the expense of farm profitability, which can hamper the wider implementation of regenerative agriculture. The modelling framework that is used, can underpin regenerative management for farmers and other stakeholders to help, for example, the valorization of multiple regenerative objectives in business models. To stimulate a wider transition towards regenerative agriculture we recommend that policies and industries find methods to support viable business models for regenerative agriculture.

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.

Data availability

Data will be made available on request.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103518.

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