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Understanding resilience of farming systems: Insights from system dynamics modelling for an arable farming system in the Netherlands

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ABSTRACT

Farming systems in Europe are facing economic, social, environmental and institutional challenges. Highly intensive, climate-exposed, arable farming systems like the Veenkoloniën in the north of the Netherlands are particularly vulnerable to many of these challenges. Just in the past twenty years, the Veenkoloniën has lost half of its small and medium sized family farms specialised in cultivating starch potatoes. While starch potato production continues to be stable as the remaining farms are increasing the size of their operation, local stakeholders are concerned that the farming system in the Veenkoloniën is endangered. In this paper we investigate this issue by using a system dynamics simulation model to explore what the potential structures are that could threaten the long term future of starch potato production and to identify leverage points that can enhance the resilience of the system. Our analysis shows that, so far, farmers' active engagement in a processing cooperative has been an important element to their resilience to cope with economic and environmental challenges. In practice, the cooperative has been able to act as a buffer and stabilise prices for farmers in the region by implementing strategies that increase the value of their products, open new markets and increase starch potato production.

1. Introduction

Farming systems are a complex component of food systems. They are primarily focused on food production. Farming systems consist of all the subcomponents that are pertinent to farm production, but they have blurred boundaries with other components of the food system (e.g. retailing, processing, etc.) and involve a wide range of stakeholders and players (FAO, 2021). As a consequence, farming systems address multiple and sometimes competing objectives like increasing production, improving the quality of farmers' livelihoods, and enhancing environmental sustainability.

In trying to meet these objectives, farming systems in Europe are facing an increasingly broad range of environmental, economic, social and institutional challenges (Meuwissen et al. 2020). Operating in this complex environment requires stakeholders to anticipate the challenges ahead and to prepare for them by enhancing the resilience of farming systems. One of the many farming systems working towards achieving long-term sustainability in an increasingly challenging environment is the farming system in the Veenkoloniën, in the Netherlands. Traditionally, this farming system has been dominated by the cultivation of starch potato in a rotation with cereals and sugar beets. A review of the starch potato production in the region conducted by Bont et al. (2007) found that the production of starch from potatoes accounted for up to 50% of the income of arable farms and supported more than 7000 direct and indirect jobs in the region.

The presence of Avebe, an agro-industrial cooperative dedicated to starch processing, has resulted in stable prices and demand for the farmers in the area. Avebe is the only company in the Netherlands that processes starch from potatoes and currently has 1400 members (approximately 900 in the Veenkoloniën) that are supplying a steady flow of starch potatoes every year (Avebe, 2018b; Klok, 2019). Avebe receives roughly half of all its starch potato supply from the Veenkoloniën. This supply represents about one third of the global market share of the starch potato value chain (Strijker, 2008). All the starch potato growers in the Veenkoloniën own Avebe shares, which come with the obligation to deliver starch potatoes to Avebe (van Dijk et al., 2019). Avebe's factories process the potatoes that are produced by all shareholders and sell the resulting starch or other products for an added value on the world market. The profits of Avebe then get redistributed back to the shareholders according to the volume and quality of starch potatoes they delivered, and the number of shares they own (Avebe, 2018a). So far, this synergy between Avebe and the starch

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potato farmers in the Veenkoloniën has proven successful and has helped farmers to overcome significant challenges (like the elimination of subsidies) thanks to innovation and vertical integration driven by Avebe (Meuwissen et al., 2019).

However, there are growing concerns amongst local stakeholders in the Veenkoloniën that this success might be reaching its limits and that starch potato cultivation might stop being a profitable economic activity in the region (e.g. Diogo et al., 2017). While the amount of starch potato produced and the cultivated area in the region have kept increasing, since 2000 the number of farms cultivating starch potatoes has decreased significantly. The substantial reduction in the number of farmers, potentially due to poor economic performance of smaller producers, raises questions about how resilient the system is and whether it will be able to withstand future challenges. This paper develops a simulation model to explore how this farming system might respond to future challenges.

In simple terms, resilience describes the capacity of a system to absorb a disturbance and to reorganise itself in ways that allow it to operate under new conditions (Biggs et al., 2012; Folke, 2006; Walker et al., 2002, 2004);. A common way to conceptualise resilience is to think of the system moving about within a particular region in state space in which the system tends to remain within the same "stable state" (Beisner et al., 2003) or "basin of attraction" (Walker et al., 2004, p. 5).

The various basins of attraction that a system may occupy within this region, and the boundaries that separate them, are known as "stability landscapes" (Walker et al., 2004). Complex systems are known to have multiple basins of attraction within a stability landscape (Walker et al., 2004; Beisner et al., 2003), and resilience is often conceptualised in terms of the system potential to withstand disturbances without shifting from their current (often desirable) basin of attraction to a different one (Folke et al., 2010).

When systems are affected by a disturbance, they might alternate between basins of attractions, return to the same configuration after a small disturbance or shift to a different basin of attraction after a large one (Beisner et al., 2003). Failure to anticipate these shifts between basins of attraction can be costly and sometimes even catastrophic ((Carpenter et al., 2001)). An alternative to anticipating shifts between basin of attractions is to use simulation models to explore the impact disturbances have in the variables and processes that control the system's behaviour (Bennett et al., 2005; Rodriguez-Gonzalez et al., 2020). Complex systems are characterised by comprehensive mechanisms that push the system toward a particular basin of attraction. When affected by a disturbance, a chain reaction of changes through the system triggers feedback loop mechanisms that either move the system toward a different basin of attraction or help it to remain within the current one (Resilience Alliance, 2010).

The aims of this study were threefold. First, we aimed to explore the impact disturbances might have on the long-term performance of the starch potato farming system in the Veenkoloniën region. Second, we aimed to explore the feedback loops within the system structure that influence/condition the resilience of the system. Finally, our third goal was to use the insights gained to identify potential strategies that might help to increase the resilience of this farming system.

The paper proceeds as follow. We start by describing the simulation model developed to characterise the starch potato system in the Veenkoloniën. Next, we elaborate on the steps we followed to use this model in the assessment of the resilience of the system. These sections are followed by the results and analysis sections where we summarise and reflect on the main insights gained from our research.

2. Materials and methods

2.1. Modelling methodology

System dynamics (SD) is a modelling methodology grounded in control theory with a focus on understanding how feedback loop mechanisms drive the behaviour of a system (Marandure et al., (2020); Kopainsky et al., (2018); Lane (2008); Sterman (2000) and Ford (1999)). SD focuses on exploring and improving the performance of complex systems (Forrester, 1961) and has been widely used to model socio-ecological systems in a variety of contexts (e.g. Lopes and Videira; 2017, Kopainsky et al., 2015; Bueno and Basurto, 2009).

The purpose of SD is to identify the structure of a system (system variables and their relationship) that generates observed system behaviour so that solutions can be identified and tested in the model. With this aim SD modellers build a formal simulation model that overcomes cognitive limitations to grasp the complexity of the system and allows to make reliable inferences about the system behaviour, (Morecroft, 1988).

An important initial step in the modelling process is the development of the so called dynamic hypothesis (Richardson, 1981), i.e., a feedback loop structure that is hypothesized to cause observed and/or experienced behaviour (Sterman, 2000). The process to derive this dynamic hypothesis varies from case to case. In this study, the dynamic hypothesis was developed using qualitative text data and stakeholder mental models presented in the deliverables of the Horizon 2020 SURE-Farm project (Towards Sustainable and REsilient EU FARMing systems) (Reidsma, 2019; Reidsma et al., 2020; Paas et al., 2021)

The aim of the dynamic hypothesis is to make the causal structure driving system behaviour explicit. In practice, this is often done by capturing causal relationships between different variables in Causal Loop Diagrams (CLDs). CLDs use one way arrows indicating that the indicator from which the arrow originates is the cause of change in the indicator at which the arrow is pointed. The direction of this change is indicated using '+' or '-' letters next to the arrow heads. A '+' indicates that both variables change in the same direction (for example if one increases the other also increases) while a '-' indicated that the variable at the end of the arrow changes in the opposite direction than the one at the nod (see Fig. 1 for an example).

The term feedback loop is used to indicate circular causal relationships like the ones shown in Figure. Generally, there are two types of feedback loops; balancing loops, represented with a 'B', and reinforcing loops represented with an 'R' (Morecroft, 2015; Ford, 2009). In a balancing loop (B) a change in the condition of a given variable leads to a counteracting or balancing change when the effects are traced around the loop. By comparison, a reinforcing loop (R) amplifies or reinforces change. In a realistic multi-loop system, behaviour over time arises from the interplay of balancing and reinforcing loops. The interplay of feedback loops quickly results in complex behaviour patterns that require computer simulation. The dynamic hypothesis captured in a CLD is therefore translated into a simulation model by using mathematical equations to represent the relationships between variables and validated

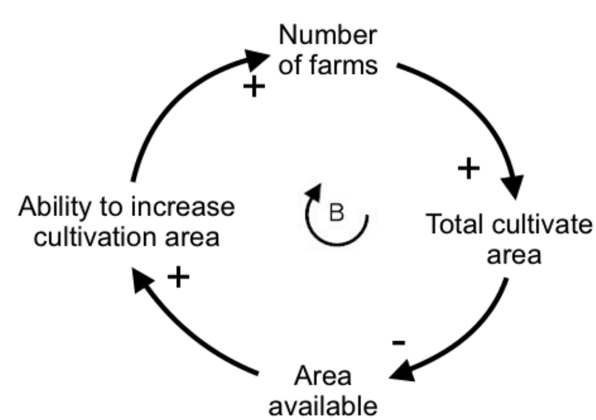

Fig. 1. Examples feedback loop nomenclature. A '+' indicates that both variables change in the same direction (for example if one increases the other also increases) while a '-' indicated that the variable at the end of the arrow changes in the opposite direction than the one at the nod.

by comparing the simulated behaviour against historical reference modes of behaviour. In this case, we used country and regional statistical data to inform and quantify model structure and variable choices. Next, we briefly present the model structure by describing the main feedback loop mechanisms captured in the model. More details about the model equations can be found in the Appendix and in (Schütz, 2020).

2.2. Model structure

The aim of this study was to produce a model that can a) explain the dynamics driving the decline seen in the number of starch potato farms in the Veenkoloniën (see Fig. 2), b) simulate the expected behaviour of the system in terms of starch potato production and farm income and c) allow us to explore the potential benefits and drawbacks of strategies identified in the SURE-Farm project that aim to contribute to maintaining a stable number of starch potato farms in the region.

The model represents both the economic dynamics happening within farms and the dynamics between farms and the cooperative Avebe. As mentioned before, Avebe is believed to have been a critical component for the sustainability of the farming system in the past and remains an instrumental part of the system when trying to understand production and income of farmers. In simple terms, the model developed:

- provides the outputs for the system indicators: starch potato production, total cultivation area, farm number, farm size and farm income,
- assumes profitability of starch potato cultivation as the main driver of system behaviour
- simulates the consequences of farmers' decisions to either scale up to improve profitability or to stop cultivating starch potatoes,
- differentiates between the behaviour of small farms as opposed to larger farms,
- explores the feedback between starch potato production and Avebe
- allows testing of the impact of challenges and strategies on model behaviour

The main balancing (B) and reinforcing (R) loops in the model can be examined in three parts:

1 The feedback loops **R1, B1, B2** and **B3** that describe only starch potato farms and farmers' decisions.
2 The feedback loops **R2** and **B4** that describe the interaction between starch potato farmers and Avebe.
3 The feedback loops B5, R3 until R6 that describe Avebe and their strategies.

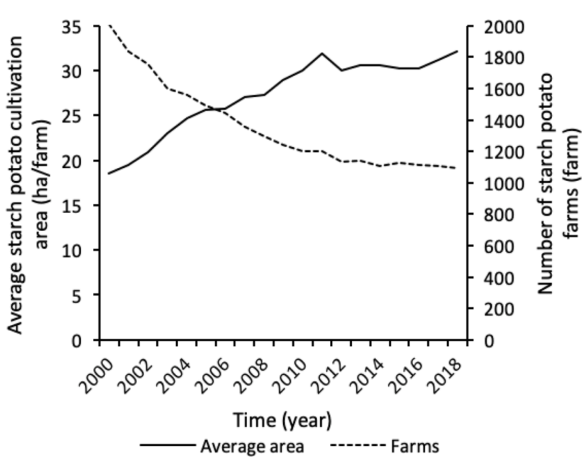

Fig. 2. The number of specialised starch potato farms in the Veenkoloniën [farms] (dashed line – right axis) and the respective average farm size [ha/farm] (solid line – left axis) (CBS, 2019).

Of the feedback loops in Fig. 3, the feedback loop **R2** ('Co-operative benefit') is of particular importance because it captures the relationship between the farmers and the co-operative. Feedback loop **R2** can be read as follows: the total *starch potato production* is the product of the *total cultivation area*, the *fraction of starch potato in the crop* rotation plan and the *starch potato yield* (see Fig. 3C). The total volume of starch potatoes is delivered to Avebe and processed into starch (and other products). The net profit of Avebe is determined by the price of their products (*price paid to Avebe*) and their *total costs*. This net profit is used to pay farmers a price that will maintain a reasonable profitability compared to profits from other crops.

Avebe depends on this steady flow of starch potatoes and thus depends on maintaining their member pool, or at least their combined cultivation area (Beldman, 2015; Bont et al., 2007). The cooperative is therefore committed to maintaining a reasonable *relative profitability of starch potato farms* (Avebe, 2014). The *relative profitability of starch potato farms* also depends on the *income starch potato production* (controlled by Avebe) and factors outside Avebe's control like *cultivation costs* and the *income from other crops (wheat and sugar beet)*.

The feedback loops **B1, B2** and **B3** portray, in a simplified way, the farmers' decision-making process and offer an explanation to the small changes seen in the *average cultivation area* in comparison to the large decrease in the number of farms (see Fig. 2). Asjes and Munneke (2007) hypothesise that the main driver of these trends is the low profitability of starch potato cultivation. Small farms in the region have very low incomes and often do not find successors (Asjes and Munneke, 2007; Bont et al., 2007; Bont and Everdingen, 2010). These represent most farms that have been lost (Bont et al., 2007). Larger farms compensate for the low profitability of starch potatoes by increasing their size (Asjes and Munneke, 2007; Vos, 2019).

These dynamics are captured in the model as shown in Fig. 3. A decrease in the *relative profitability of starch potato farms* can be compensated for by increasing the *cultivation area per farm* (Fig. 3 **B1**: "Economies of scale"). Farms can increase their cultivation area if there is *area available* (Fig. 3 **B2**: "Scaling"). However, as the total cultivation area in the region is limited, not all farms can simultaneously increase in size and the *number of farms* is constrained (Fig. 3 **B3**: "Limits to growth").

2.3. Quantifying and validating the model structure

There is no standard process for turning a diagram into a model (often called quantification). However, there are general steps modellers follow as good practice (see more detail in Sterman, 2000). The steps we followed to quantify the model were:

a) Identify and estimate parameters or input variables: Input variables are those that are not calculated by the model itself but are provided to the model as an input so that it can calculate the remaining variables. In an SD model there are often only few inputs as the majority of variables are calculated within the model. The model inputs and the data sources used in the model are summarised in Table 1.[123]
b) Define mathematical relationships for remaining variables: The causal relationships indicated by arrows in the model diagram are operationalised through mathematical equations. The type of equation used will depend on the nature of these relationships (e.g.,

[1] The time frame 2004-2013 of the FADN data represents the shortest time frame of all the time series data collected from different sources. To ensure data compatibility between sources, all other time series data were trimmed also to this time frame.
[2] For R script see Appendix.
[3] FADN classifies sample farms based on UAA size class. Based on available data, the model assumes that there are three farm sizes: small farms (24ha/farm), medium farms (37ha/farm) and large farms (130ha/farm).

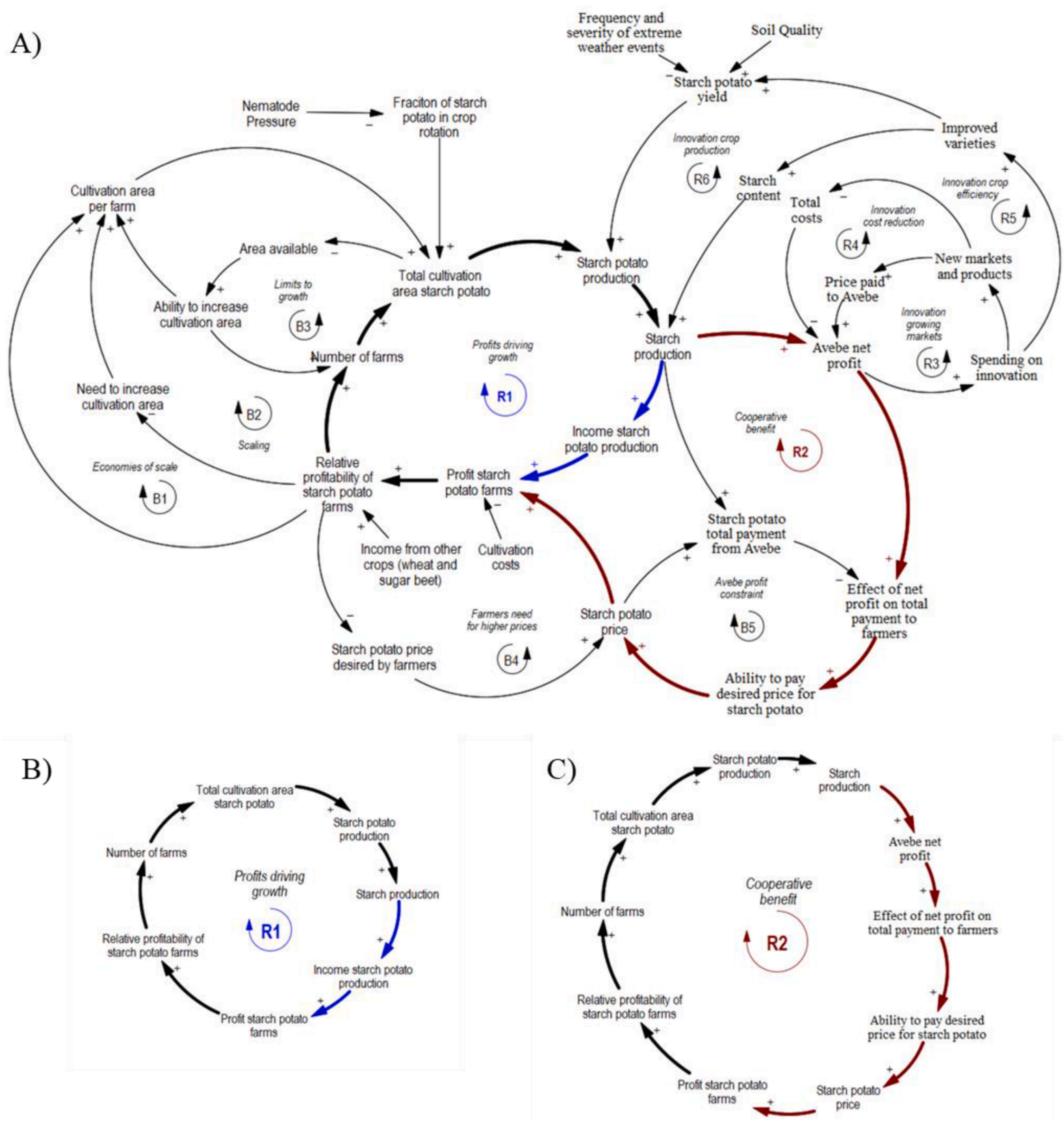

Fig. 3. A causal loop diagram showing A) the model structure explaining starch potato production in the Veenkoloniën, B) the reinforcing feedback loop R1 (profits driving growth) and C) the reinforcing feedback loop R2 (cooperative benefits). Positive causalities are indicated by *a* + and negative causalities by a – next to each arrowhead. A central "B" represents a balancing feedback loop and an "R" represents a reinforcing feedback loop.

linear, exponential, etc.). Eqs. (1) and 3 show examples of the equations used in the model; the full list of model equations can be found in the Appendix.[4]

The model was calibrated against historical data. Model calibration

$$\text{Average\_farm\_income[EUR / farm]} = \big(\big(\text{Farm\_profit[small]} * \text{Farms [small]}\big) + \big(\text{Farm\_profit[medium]} * \text{Farms[medium]}\big) + \big(\text{Farm\_profit[large]} * \text{Farms[large]}\big)\big) \big/ \text{Total\_number\_of\_farms} \tag{1}$$

$$\text{Total\_available\_area[ha](t)} = \text{Total\_available\_area(t} - \text{dt)} + \big(\text{Change\_in\_total\_area} - \text{Loss\_of\_available\_area\_to\_other\_industries\_or\_farms}\big) * \text{dt} \tag{2}$$

is the process of estimating the model parameters to obtain a match between observed and simulated behaviours (Oliva, 2003, p. 552). The results of the model calibration for five selected indicators are shown in Fig. 4. As shown in the figure, the model is able to reproduce the

[4] For the model farms were split into three categories based on the average arable land they occupied: small (24 ha/farm), medium (37 ha/farm) and large (130 ha/farm)

Table 1
The data requirements and processing steps for all required data inputs module.

Data input	Data source	Further explanation and data processing
Costs per hectare of starch potato farmsbetween the years 2004 and 2013 [EUR/ha]Model variables: • *Costs per ha small farms* • *Costs per ha medium farms* • *Costs per ha large farms*	FADN (2019)	The FADN data were filtered to include only farms in the NUTS3 regions NL111, NL112, NL131, NL132 and to include only starch potato farms that do not have livestock units. The costs per hectare were calculated by adding fixed and variable costs. Averages were calculated for each year for each farm size class.
Profit per hectare of other arable farms between the years 2004 and 20,13[1] [EUR/ha]Model variables: • *Profit per ha other small arable farms* • *Profit per ha other medium arable farms* • *Profit per ha other large arable farms*	FADN (2019)[2]	The FADN data were filtered to include only farms in the NUTS3 regions NL111, NL112, NL131, NL132 and to include only arable farms. The total profit per hectare of other arable farms was calculated by taking the difference between "Total crops output per ha" and total costs per ha, where total costs per ha was calculated in the same manner as for starch potato farms (see above). Averages were calculated for each yearfor each farm size class[3].
Yields between the years 2004 and 2013 [ton/ha]Model variables: • *Starch potato yield* • *Sugar beet yield* • *Wheat yield*	CBS (2019)	The yields correspond to the average fresh weight per ha harvested in the regions Groningen and Drenthe. The sugar beet variety is *Beta vulgaris* and the wheat yield includes all grasses of the genus *Triticum*.
Crop prices [EUR/ton]Model variables: • *Starch potato price* • *Sugar beet price*	Agrimatie (2019), Avebe (2018b)	Crop prices for sugar beet and wheat were taken from Agrimatie, which has data for the whole of the Netherlands. The starch potato price corresponds the starch potato performance price awarded by Avebe to its members. This was recovered from a number of Avebe annual reports. The performance price includes the added value that Avebe can give by selling starch and protein products and giving a share of the revenue to all members.
Avebe costs [EUR]Model variables: • *Avebe all costs*	Avebe annual reports	Avebe annual reports between 2001 and 2018 were retrieved from avebe.com and other sources (Avebe 2018b). The total costs were calculating by taking the difference between net revenue and operating profit.
Price of products [EUR/ton]Model variables: • *Price of products*	Avebe annual reports	Avebe annual reports between 2001 and 2018 were retrieved from avebe.com and other sources (Avebe 2018b). The price of products was calculated by taking the total revenue and dividing this by the total amount of starch potatoes that were processed in a given year.

observed past behaviour patterns of these indicators.

The inputs of the model (see Table 1) are time series sourced from historical data sources. After 2020, the model is run using the actual values seen in 2020. This can be understood as continuation of the status quo with farmers receiving a starch potato price that maintains relative profits reasonably constant. For simplicity we are using this status quo as the departing point of our analysis. However, we recognise that such equilibrium is not a forecast for a 'business as usual' scenario but instead an extrapolation of the current situation.

2.4. Resilience to what? Challenges & disturbances

Based on Paas et al., (2019) we focused on the system's response to two main challenges in the environmental domain: C1) nematodes in the soil, and C2) decreasing soil quality in combination with increased occurrence of extreme weather events. In addition, two main challenges in the economic domain were investigated: C3) increasing profits from other crops relative to the profits of starch potatoes and C4) high and rising costs of specialised starch potato farms.

These challenges have a direct impact on the farmers' profits and the feedback loop **R1** ("Profits driving growth") and **R2** ("Co-operative benefit") as they reduce starch potato production and the profits of farmers and Avebe. However, the nematode pressure (C1) has mainly an impact on **R2** ("Co-operative benefit") as Avebe's profit depend mostly on the starch production, but farmers might compensate lower *income from starch potato production* with *income from other crops.*

To conceptualise these challenges in the model, we represented them as system disturbances (σ). Herrera (2017) defines a disturbance (σ), as shown in Eq. (3), in terms of the Magnitude (M) of the challenge (e.g. 5% decrease on yields) and the time duration (d) the system is affected by such challenge (e.g. 2 years).

$$\sigma = M \times d \tag{3}$$

Where:

M: is the magnitude of the challenge affecting the system (% of the increase/decrease of the variable affected)
d: is the disturbance duration in time units.

In practice disturbances are changes to the model parameters that happen in the future between a time t and a time $t + d$. For simplicity, in this analysis it was assumed that the disturbances will affect the system in a $t = 2021$ and that the disturbances will stop within the time horizon considered in the model (Bender et al., 1984; Herrera de Leon and Kopainsky, 2019) .

The four disturbances explored in this study are shown in Table 2. Using Monte Carlo simulations (1000 iterations), we varied the magnitude (M) from 0% to 50% (following a uniform distribution) and the duration (number of years the system is affected by each σ) from 0 to 20 years (following an uniform distribution) for each disturbance (σ). For example, for σ_2 M varied between 0 ton/ha (0% of the 45 ton/ha used as a base) and 22.5ton/ha (50% of the 45 ton/ha used as a base) for a time period between 0 and 20 years.

2.5. Assessing resilience using a system dynamics model

Assessing resilience is not straightforward (Beisner, 2012; Tendall et al., 2015)) but it is possible to get a relative indication of resilience (expressing whether a system configuration is more resilient than another system configuration) by comparing the simulated behaviour of the system after it has been affected by a disturbance against its behaviour in the absence of a disturbance. Namely, we can look at how big of a disturbance a system can withstand before moving to a different basin of attraction (Gunderson, 2000: 426). This is a convenient approach because the change towards a different basin of attraction can be measured but is also evident from inspecting the simulation results. For instance, Fig. 5 shows the behaviour of the system when affected by two different disturbances. In Fig. 5A, the system changes its behaviour while being affected by a disturbance but, as soon as the disturbance ends, it bounces back to its original basin of attraction. Alternatively, in Fig. 5B, the same system is affected by a larger disturbance that moves the system to a different basin of attraction. When the disturbance ends,

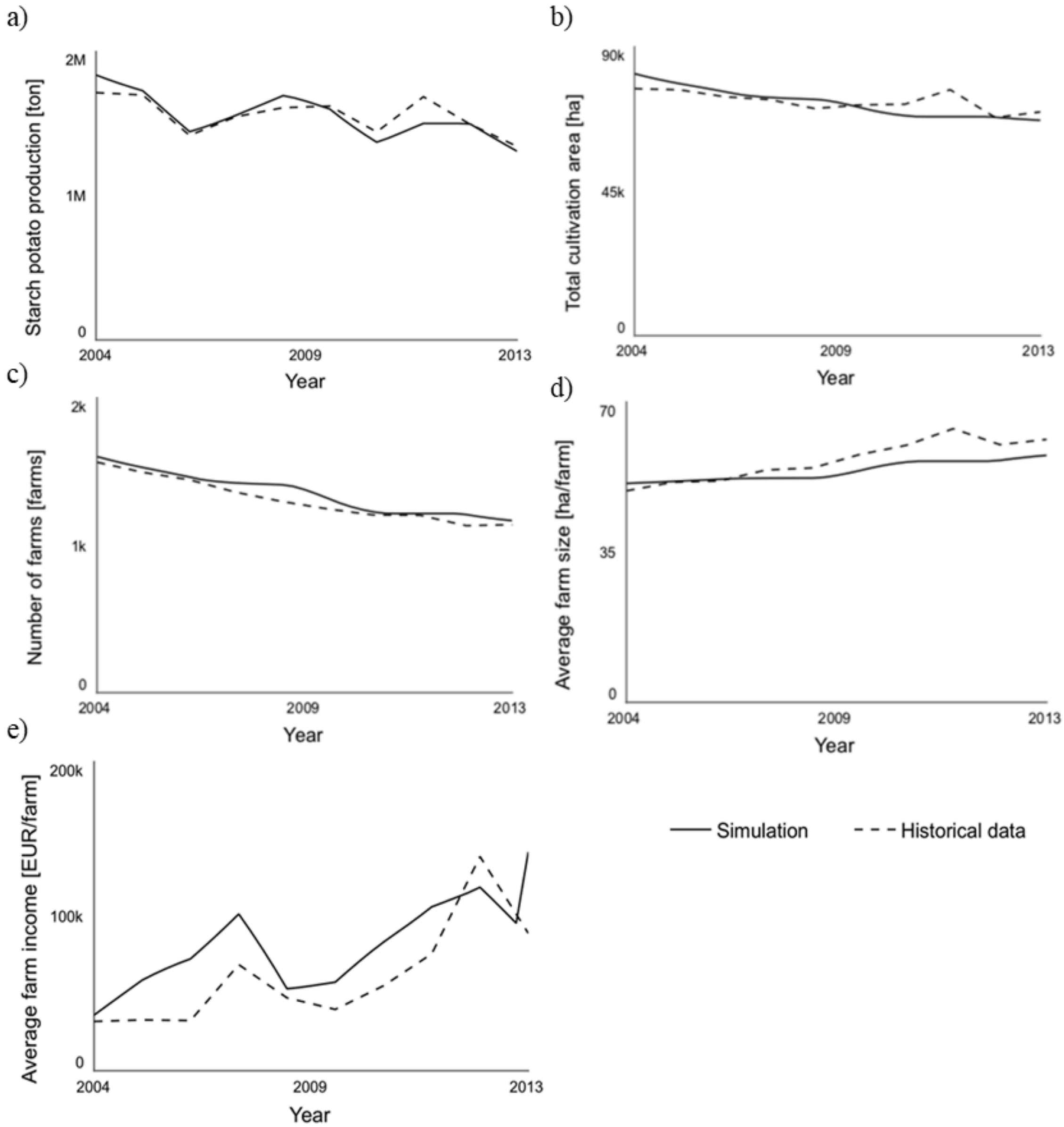

Fig. 4. Simulated and historical behaviour for A) starch potato production [ton], B) total cultivated area[*ha*], C) number of farms [farms], D) average farm size [ha/farm] and E) average farm income [EUR/farm].

Table 2
Disturbances analysed.

Disturbance	Description	Variable affected	Base value	Interval for disturbance Magnitude (M)	Interval for disturbance duration (d)
σ_1	Decrease of starch potato in crop rotation due to nematode pressure	Fraction of starch potato in cultivation plan	50%	Reduction of 0%-25%	0 to 20 years
σ_2	Decreasing soil quality in combination with increased occurrence of extreme weather events	Starch potato yield	45 ton/ha	Reduction of 0 ton/ha to 22.5 ton/ha	
σ_3	Increase in profit per ha of other crops	Profit per ha of other medium arable farms	1864 €/ha	Increase of 0 €/ha to 932 €/ha	
σ_4	Increase in production costs of starch potato	Costs per ha	Small farm: 2410 €/ha Medium farm: 2120 €/ha Large farm: 1970 €/ha	Increase of Small farm: 0 to 1205 €/ha Medium farm: 0 to 1060€/ha Large farm: 0 to 985€/ha	

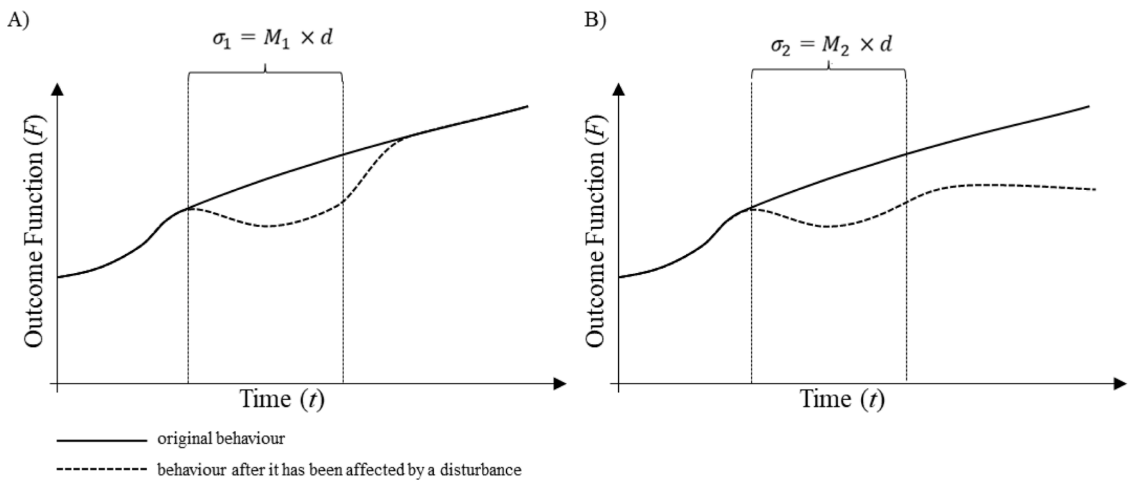

Fig. 5. The behaviour of an outcome function F(x) when the system is affected by a disturbance and the behaviour of the outcome function A) remains in its original basin of attraction and B) changes to a different basin of attraction.

the system remains in this new state and does not bounce back to its original behaviour.

In this paper, we used the maximum disturbance the system can withstand before changing basin of attraction as a measure of the resilience of the system by simulating the behaviour of the system when exposed to different σ and identifying the smallest combination of M and d (σ; see Eq. (3)) that could make the behaviour move to a different basin of attraction. This proxy for resilience, proposed by Herrera (2017) as the system elasticity (σ_E), offers an easy to calculate parameter to compare resilience between different systems (e.g., current system and modified system). A system with a higher σ_E could be considered more resilient than a system with a lower $\sigma_{E.}$

2.6. Modelling strategies to enhance resilience

One of the purposes of the modelling exercise is to explore strategies that can improve the resilience of the system, in this case by enhancing its response to the tested disturbances. For our case study, we used a subset of potential strategies identified by ,) (Paas et al., 2019; Paas et al., 2021)through participatory workshops including farmers and members of Avebe. The strategies considered are:

Strategy 1 (*S1*): Plant breeding to increase starch content.
Strategy 2 (*S2*): Increasing average yields by breeding/using nematode resistant and climate resilient varieties and by improving farm management practices (e.g., irrigation or precision agriculture).
Strategy 3 (*S3*): Increasing value of starch products and extracting and selling potato protein.

For simplicity, the SD model does not include these strategies in detail. Instead, the impact of these strategies was tested separately by modifying parameters (e.g., the starch content) directly in the model. This approach offered flexibility for testing contributions of each strategy to the system resilience separately. The parameters changed in each strategy are shown in Table 3.

Using the model it was possible to simultaneously test the different values considered for each strategy (see Table 3) while the system was affected by disturbances with different magnitudes and durations (see Table 2). This approach allowed us to understand the benefits of increasing the% value applied for a particular strategy on mitigating the impact of each disturbance tested. Similarly, it also allowed us to identify the impacts that will be more difficult to mitigate with the proposed strategies and to compare the effectiveness of each strategy in terms of its ability to prevent the system moving to a different stability domain.

Table 3
Parameters considered in the strategies proposed to enhance system resilience.

Strategies	Parameter	% Variation applied
Strategy 1 (S1)	Starch content	+ 0% to 50%
Strategy 2 (S2)	Starch potato yield	+ 0% to 5%
Strategy 3 (S3)	Avebe product value	+ 0% to 50%

3. Results

3.1. Simulation results

Fig. 6 shows a base simulation up to the year 2050 based on historical trends of exogenous inputs such as yields, costs and prices. Before 2020 the cultivation area and total number of farms were decreasing (Figs. 6B and 6C), while average farm size was increasing (Fig. 6D). The starch potato production (Fig. 6A) and the average profit per farm (Fig. 6E) were fluctuating in the initial years, the former showing a slight decrease and the latter a slight increase towards 2020.

Fig. 7 shows the simulated behaviours for each of the variables reported in Fig. 6 when the system is affected by a disturbance σ_2 (decrease in average yield) in 2020. The results show that there are cases where the system can go back to the original basin of attraction and cases where the system moves towards a new basin of attraction

As explained in Section 2, of all the simulations produced in the Monte Carlo experiment, we were only interested in those cases that result in the system moving to a new basin of attraction. We were interested in identifying the smallest combination of M and d that produced such behaviour (elasticity). Table 4 shows the elasticities for the four disturbances considered in this study and the two main outcome functions of the system: starch potato production and farm income. The results in the table show that the system is more resilient to changes in production costs of starch potato (σ4) than it is to an increase in profits of other crops (σ3). Something similar can be said about the comparison between σ4 and the environmental disturbances affecting starch potato yields (σ1 and σ2).

As can be seen in Table 3, the same outcome function (starch potato production; farm income) shows different degrees of resilience to different disturbances. For example, the system's elasticity, and hence the system resilience, of the average *starch potato production* is larger for σ_4 than for environmental disturbances (σ_1 and σ_2). The lower resilience to environmental disturbances can be, at least partially, explained by the **R2** ('Cooperative benefit') in Fig. 3. Environmental disturbances (σ_1 and σ_2) directly affecting the *starch potato production* reduce *Avebe's net*

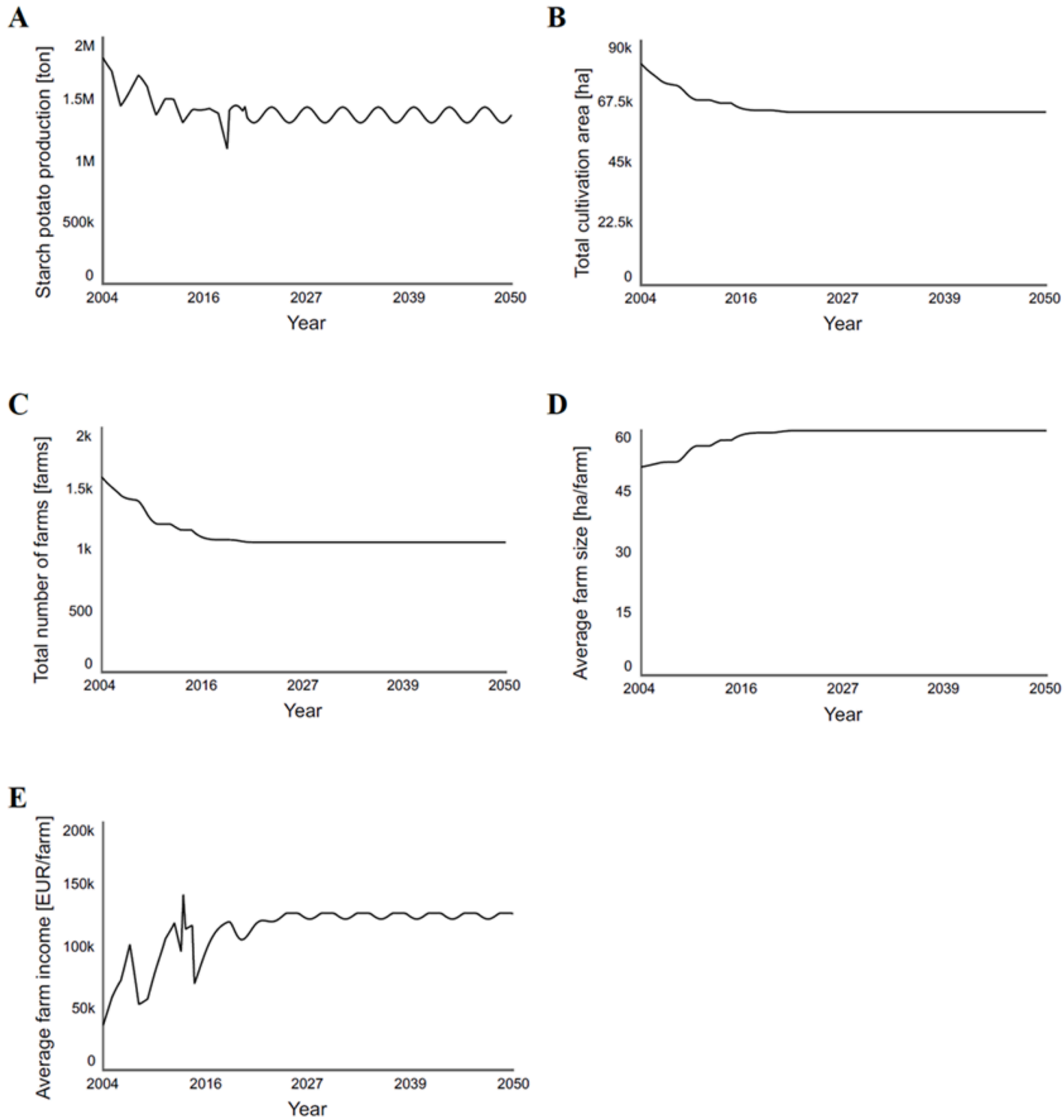

Fig. 6. The simulated (A) starch potato production [ton], (B) total cultivation area [ha], (C) total number of farms [farms], (D) average farm size [ha/farm] and (E) average farm income [EUR/farm].

profits and affect their ability to pay high prices to farmers. This results in farming facing simultaneously the challenge of having low production volumes and low prices. Alternatively, if the disturbances are mainly economic and affect the farm income (σ_4) directly, then the effect on *Avebe's net profits* is low and Avebe will be in a better position to compensate farmers for higher costs by increasing the price paid for the starch potatoes. These differences in the system responses highlight the importance of **R2** in farmers' resilience to economic disturbances and suggest that **R2** and social self-organisation is an important resilience attribute.

3.2. Strategies to enhance resilience

The three strategies proposed before (S1: Increasing starch content, S2: Increasing average yield by means of decreasing yield variability, S3: Increasing Avebe product value) were introduced to the model by modifying parameters (see Table 3) in 2020 and onwards. Implementation delays were not considered. Fig. 8 illustrates the impact of the strategies considered on the resilience to the four disturbances. These charts show the end state of the system when the disturbance and strategies take different values. The colour of the dots represent whether the system was (change dark dots) or not (no change empty dots) in a different basin of attraction at the end of the simulation.

For all the strategies and increase in the x-axis represents and increase in the values used of each strategy. For example, for the Strategy 1 (S1) as we move to the right (values in the x axis increase) the% of increase in the starch potato used in the simulation increases. Likewise, an increase in the y-axis values reflects an increase in the severity of the disturbances. The straight lines illustrate the boundaries between the combinations that result in changes to the basin of attraction.

4. Discussion

The first aim of this study was to explore the impact disturbances might have on the long-term performance of the starch potato farming system in the Veenkoloniën region. The results of our study show that environmental challenges reducing starch potato yields were found to have a higher impact in the system and relatively small changes in yields

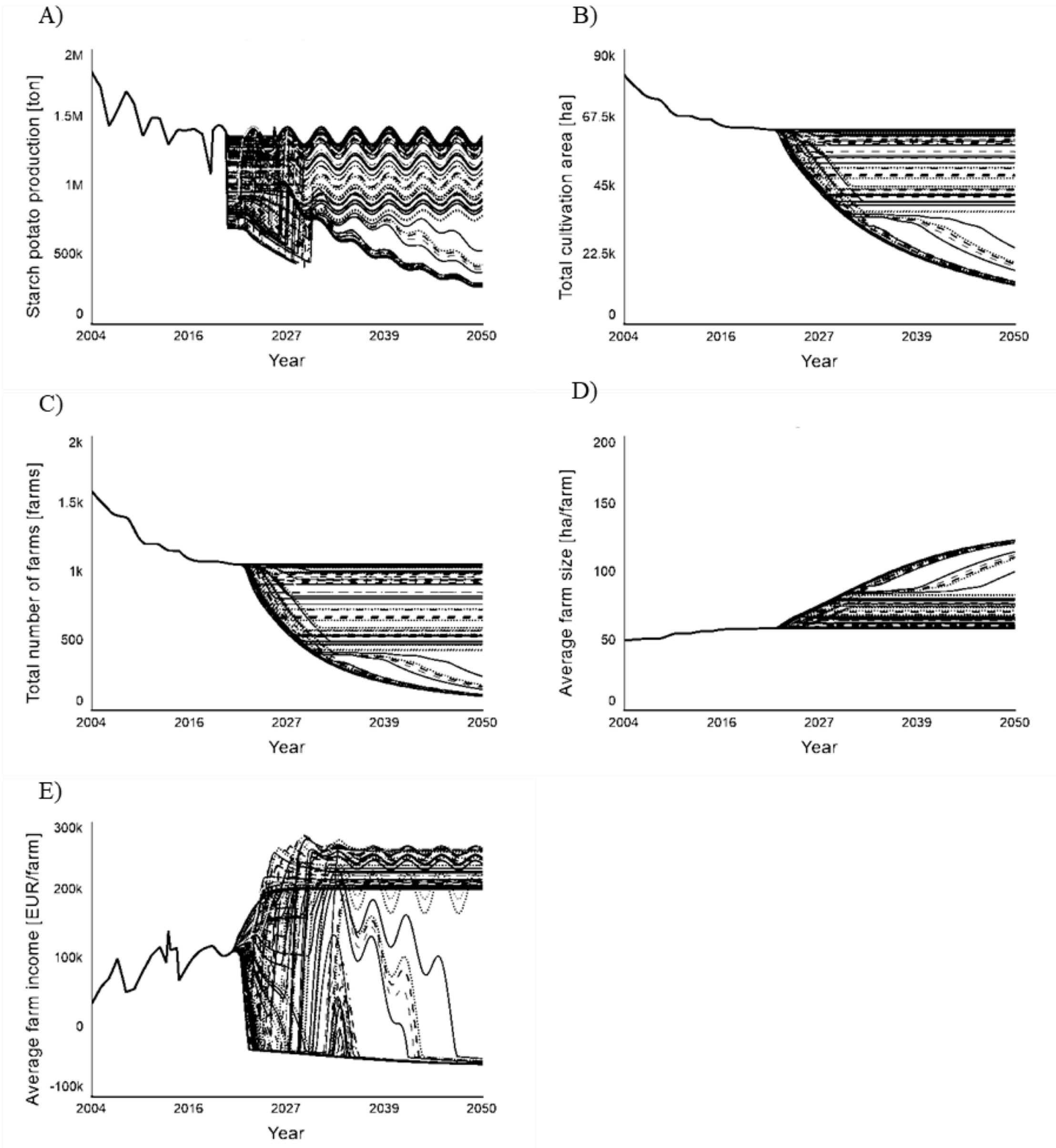

Fig. 7. Simulated behaviours after shocking the system with the disturbance σ_2 (decrease in average yield from 0 to 50%) in 2020 for (A) starch potato production [ton], (B) total cultivation area [ha], (C) total number of farms [farms], (D) average farm size [ha/farm] and (E) average farm income [EUR/farm].

might move the starch potato production and the farmers income to a different (less favourable) basin of attraction.

For instance, to shift the farmers income to a different stability domain farm cost will need to double (102% increase for σ_4 in Table 4) while the same results are seen when yields decrease by 33.4% over a year (see σ_3 in Table 4). These results support the perception of the Veenkoloniën stakeholders who participated workshops organised as part of the SUREFarm project and indicated that the number of farmers will decline considerably if extreme weather events significantly decrease yields.

These differences between the resilience to economic and environmental factors leads us to our second research question as we use the model to understand the feedback loops within the system structure that influence/condition the resilience of the system. As other authors have hypothesised, see for example Meuwissen et al., (2019), the apparent resilience of the farming system in the Veenkoloniën is probably driven by its relation with Avebe.

The simulation results indicate that this symbiotic relationship between Avebe and the farmers is indeed an enabler of resilience to economic challenges and that there is a clear difference in the system resilience to those disturbances the 'cooperative benefit' (**R2** in Fig. 3) can help with and those it cannot.

It is important to highlight that resilience resulting from this symbiotic relationship between farmers and Avebe might be bounded by other mechanisms. For example, when considering Avebe's financial position it can be seen that the same cash reserves used by Avebe to support farmers during difficult times are also needed for innovation that is required to increase product value and maintain farmers' competitiveness in the future. When yields are low **R2** takes priority over **R3** and **R6**. In those years, profit will be invested in paying the right price, rather than in innovation (as was done in 2018). However, if the disturbances are too severe, Avebe loses its ability to innovate as it depletes its cash reserves. When this threshold is crossed, the system experiences larger impacts for longer times and moves to new basins of attraction that are likely to be unsustainable for both Avebe and the farmers.

Table 4
Minimum disturbance that results in a change to a different basin of attraction for the starch potato production and the farm income.

	σ1: Decrease of starch potato in crop rotation due to nematode pressure	σ2: Decrease in average yield	σ3: Increase in profit per ha other crops	σ4: Increase in production costs starch potato
Base run value of model parameter	0.5 of total area	43 ton/ha	1860 €/ha	2120 €/ha
Elasticity *(σ_E) of starch potato production*	45 (%*years)	44 (% *years)	23 (% *years)	133 (%*years)
Elasticity *(σ_E) of Farm income*	43 (%*years)	34 (% *years)	19 (% *years)	102 (%*years)

While resilience is often associated with sustainability, there are some scenarios in which resilience might undermine the sustainability of the system sustainability. For instance, resilience can be improved in the short term (e.g. by reinforcing the ability of a farming system to maintain a high production level), at the expense of resilience and sustainability in the long term (if e.g. a production level is threatening natural resources which diminishes the ability to keep maintaining this production level) (Carpenter et al., 2001; Peterson, 2018; Robertson, 2005; van Apeldoorn, 2011). This phenomenon occurs when the sustainability goals of policy makers (as representatives for society) are in conflict with the productivity goals of other actors in agricultural systems, including the farmers and agro-industries (Peterson, 2018).

Finding a right balance between sustainability and resilience is an important aspect of the dynamics between farmers and cooperatives that is not only relevant to the Veenkoloniën but also to other farming systems in Europe. It is also a clear example that decisions actors make regarding their resources are not only relevant for resilience in the short term, but also on the long term (Mathijs and Wauters, 2020).

Our exploration of potential strategies to enhance resilience yielded three main insights. First, it can be noticed that the number of cases in which the system remains within the same basin of attraction increases with the implementation of any of the resilience enhancing strategies that we tested. It can thus can be concluded that all the strategies could be expected to increase, to some extent, the size of the disturbance the system can withstand and hence increase resilience.

The results also show that the proposed strategies are less effective for increasing resilience to environmental disturbances (σ_1 and σ_2) than to economic ones (σ_3 and σ_4). This difference can be seen in the difference between the areas covered by open dots in Fig. 8A – 8F (showing effectiveness against disturbances σ_1 and σ_2) and the same area in Fig. 8G – 8L (showing effectiveness against disturbances σ3 and σ4). For instance, a decrease of starch potato in the crop rotation (σ_1) by over 40%, or a decrease of the average yields by more than 30% (σ_2), always resulted in a system shift to a different basin of attraction, regardless of how aggressively/successfully the strategies could be implemented.

Finally, the results in Fig. 8 also show that S1 (Increasing starch content) and S3 (Increasing Avebe product value) outperform S2 (Increasing average yield by means of decreasing yield variability) in their effectiveness for increasing resilience to all the disturbances examined. The only considerable difference between the S1 and S3 was observed when analysing the resilience of the system to an increase in production costs of starch potato (see σ_4 in Fig. 8). In this case S1 outperforms S3 considerably and even moderate increases in the starch content (e.g. less than 20% increase in starch content) increased the resilience of the system considerably.

An important aspect of our analysis that requires further consideration is the role of randomness in the occurrence of extreme weather events. Currently we assumed equal probabilities for all potential disturbances in the tested intervals of magnitude and duration, but we recognise that some events are more likely than others. Introducing the effect of random events in the analysis might change not only our conclusions about the resilience of the system but also our observations regarding the effectiveness of strategies. Similarly, analysing the impact of stochasticity on innovation breakthroughs could also reveal new insights about the farming system and its potential development.

5. Conclusions

The behaviour of farming systems and other complex socio-ecological systems is the result of many different actors and components interacting within the system. When dealing with these types of systems, System Dynamics offers considerable benefits to understand the processes that influence system resilience. As presented in this paper, SD allows assessing resilience by providing a quantitative basis for the analysis of and insights about 'how' and 'why' the system might respond to disturbances.

The results of this study support perceptions of stakeholders and the results of other studies raising concerns about the long-term resilience of the system in the Veenkolonië. In particular, it seems that the system is more vulnerable to ecological disturbances affecting potato yields (like droughts due to climate change) or nematodes pressure than it is to economic and market disturbances. This is understandable when looking at the structure of the system because the resilience of the system has been, so far, driven by Avebe through market strategies that have allowed the producers in the region to remain competitive.

Our results also highlight the important role of social self-organisation for the resilience of the system. The reinforcing loop linking the farmers and Avebe drives innovation and adaptability and increases resilience. Hence, as shown in this paper, the strategies that enhance the symbiotic relationship between Avebe and the farmers are likely to be more effective than those that focus only on one side of the system.

On the one hand, the cooperative creates a catalytic environment that can be exploited by initiatives aiming to increase resilience and, as shown in the analysis, those strategies that align better with Avebe's feedback loop mechanisms are more effective. However, because Avebe's strategies are mainly focused on economic and market mechanisms, all strategies explored had limited success in increasing resilience to environmental challenges. It can be hypothesised that having other forms of social self-organisation orientated towards dealing with these challenges could potentially be the key to unlock further opportunities to enhance resilience.

Social self-organisation is often identified as an enabler of resilience and the experience in the Veenkoloniën might inspire stakeholders in other farming systems to implement similar structures in their own contexts. The SD model and quantitative results presented in this paper bring it to live by operationalising its causal mechanisms. We think this model, and further modifications of it, can be used for investigating the benefits and drawbacks of social self-organisation to the resilience of farming systems. Understanding the successes and challenges of case studies like the Veenkoloniën is instrumental to develop an environment that enables resilience without compromising the long-term sustainability of the system.

CRediT authorship contribution statement

H Herrera: Conceptualization, Writing – review & editing, Validation, Formal analysis, Resources. **L Schütz:** Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft. **W Paas:** Conceptualization, Writing – review & editing, Supervision, Validation, Formal analysis, Resources. **P Reidsma:** Conceptualization, Writing – review & editing, Supervision. **B Kopainsky:**

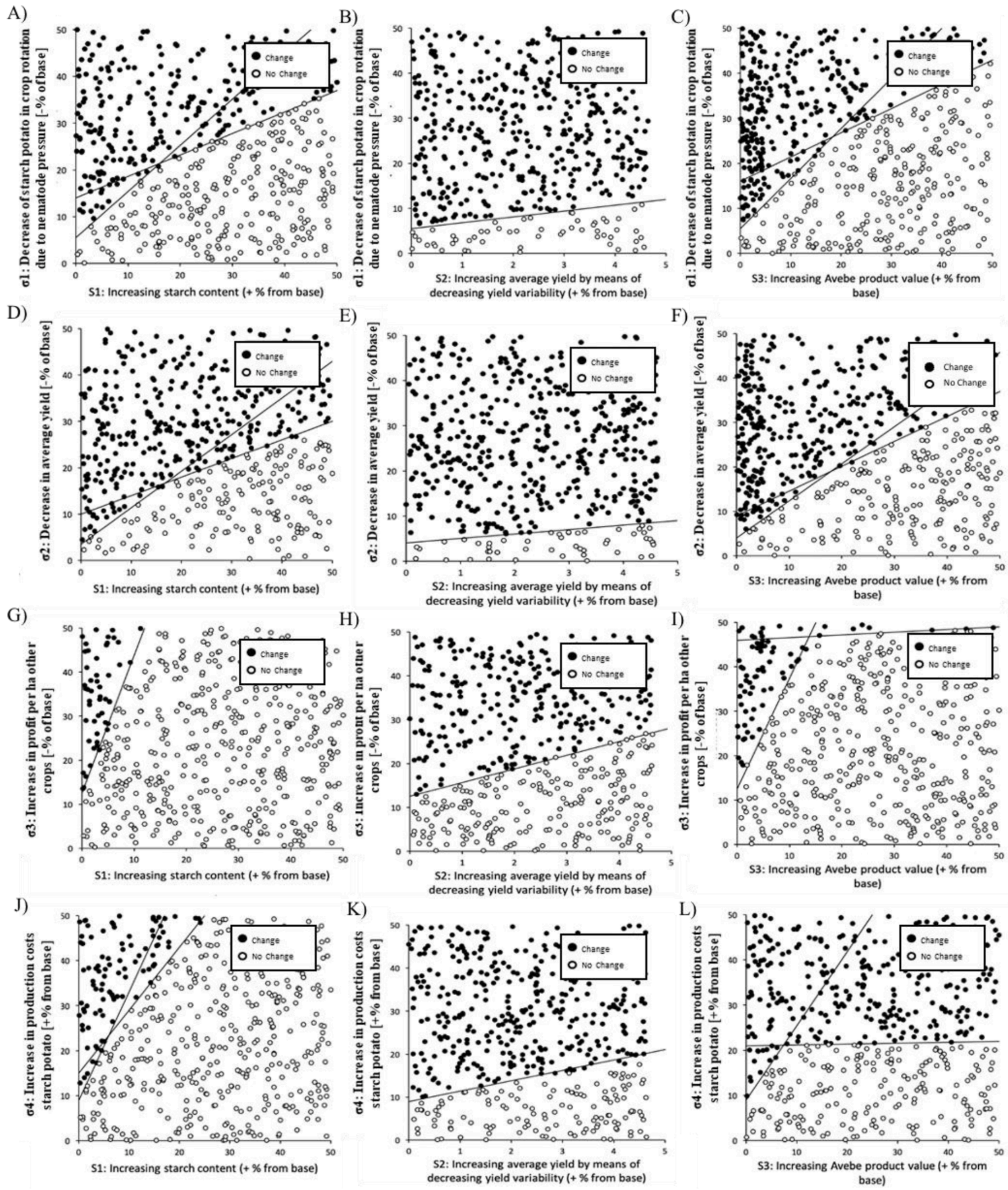

Fig. 8. Simulation results of strategies (S1: Increasing starch content, S2: Increasing average yield by means of decreasing yield variability, S3: Increasing Avebe product value) in combination with different disturbances. The clear dots represent those combinations between strategy and disturbance where the system did not change basin of attraction and the dark dots the combinations in which it did.

Conceptualization, Writing – review & editing, Supervision.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2021.109848.

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