Analysing the resilience of an arable farming system in the Veenkoloniën, NL, using system dynamics modelling

MSc Thesis Plant Production Systems

Lilli Schütz

March 2020

WAGENINGEN
UNIVERSITY & RESEARCH

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Date	March, 2020
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Correct citation: L. Schuetz, 2020, Analysing the resilience of an arable farming system in the Veenkoloniën, NL, using system dynamics modelling, MSc Thesis Wageningen University, xx p.

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Summary

European agriculture is heading towards an uncertain future as climate extremes are escalating, the global competitive landscape is changing, and the growing population is demanding both affordable *and* sustainable food. Highly intensive, climate-exposed, arable farming regions like the Veenkoloniën in the north of the Netherlands are particularly vulnerable to these challenges. Since the turn of the last century, the region has lost half of its small and medium sized family farms, which are specialised in cultivating starch potatoes. Surprisingly, the total volume of starch potatoes grown in the region continues to be stable, as the remaining farms are increasing the size of their operation. This indicates that the efforts of those involved in the starch potato value chain have so far contributed to a relatively robust farming system.

However, many are concerned that the level of resilience in the Veenkoloniën farming system is insufficient in the face of mounting challenges. The system structure and dynamics that may hold some answers about future developments is currently not understood well, and is not yet quantified. The study presented in this thesis demonstrates how a system dynamics approach can be used to provide more insights. This approach was used to uncover the underlying mechanisms that explain the robust production of starch potato production observed in the past. Namely, the starch potato cooperation Avebe, which buys all of the starch potatoes from the region, is one of the major forces that can counteract challenges to starch potato production, through a number of strategies.

A system dynamics model was made, in order to test the relative impacts of challenges in the presence of several strategies. The model confirmed that one of the main drivers of starch potato production in the region is profitability. According to model simulations the number of farms, especially small farms, has been declining due to low profitability in the past. The model also confirmed that starch potato production will decline in the future if Avebe is at some point no longer able to maintain an adequate price of starch potatoes. This could occur when environmental or economic challenges exceed a certain threshold, which was quantified in this study.

The highest impact was found for environmental shocks and stresses, such as several consecutive years with over 20% yield reductions, and the increased presence of potato cyst nematodes in soils. The model simulations also showed that all of the environmental and economic challenges could to some extent be counteracted with a number of strategies, including increasing starch content, decreasing yield variability and increasing Avebe's product value. Implementing these strategies was shown to either prevent or delay a decline of starch potato production.

Importantly, this study provides many points for discussing the resilience of farming systems in general. The model and the results can be used as boundary objects to open up dialogues about the behaviour of farming systems under the studied drivers. A farming system that depends on profit-relationships between system actors may be using strategies to increase robustness in the short-term but diminish resilience in the long term. This study demonstrated that the system dynamics approach can be used as a tool to diagnose such behaviour. This can inform decision makers about how best to intervene and design long-term resilient and sustainable farming systems.

Keywords: system dynamics — resilience — European farming systems — Veenkoloniën — arable farming — agro-industrial cooperative

Acknowledgements

This master's thesis would not have been possible without the input of the many people who have supported me throughout and beyond.

First, I would like to thank Pytrik Reidsma and Wim Paas for introducing me to this project, and for always providing me with excellent support and encouragement. Our joint discussions about my work, the obstacles, and the findings have provided me with guidance and direction, without which this thesis would not have been possible. To everyone at PPS, thank you for your welcoming spirit, and to the students especially, thank you for reviewing my work and giving me valuable feedback.

Many thanks also to Birgit Kopainsky and Hugo Herrera, for helping me gain the necessary skills for a successful system dynamics thesis. Thank you to Birgit, for arranging my stay as a guest student at the University of Bergen and for the excellent lectures in GEO SD 304. To Hugo, thank you for all of your help with the modelling process, and for your reassurance throughout. I would also like to thank Ashish Shrestha for his input and feedback on my model, and together with Anaely Aguiar Rodríguez and Christina Gkini for all the inspiring lectures and hands-on modelling sessions during GEO SD 304.

Thank you all, for pushing me beyond what I thought I could do.

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Chapter 1: Introduction

Most European farmers benefit from good agro-climatic conditions and high quality production factors (DG Agriculture and Rural Development, 2017). Advanced infrastructure, technology and innovation have translated into European farm yields being well above global yields for many crops (DG Agriculture and Rural Development, 2017). Nevertheless, a high degree of uncertainty exists when looking into the future. The average income of the European agricultural sector is low and volatile compared to other sectors (DG Agriculture and Rural Development, 2017). Income pressure is mounting in face of climate change and societal pressure to reduce the use of chemical inputs (Tester and Langridge, 2010). The need to produce more sustainably is in conflict with the capacity of European farmers to compete with ever cheaper exports and imports from other regions of the world (Ricroch et al., 2016). The ability of farmers to cope, depends on their resilience to these challenges (Folke et al., 2016, 2010).

Understanding resilience

Farmers are part of a farming system, i.e. a group of individual farms that produce the main product(s), other system actors, and the joint agro-ecological context in which they interact (Giller, 2013; Meuwissen et al., 2019). Resilience is the capacity of such systems to provide a desired level of environmental, social and economic functions despite challenges, through the resilience capacities robustness, adaptability or transformability (Meuwissen et al., 2019), where:

1. **robustness** is the ability of the system to withstand disturbances and maintain a desired level of a function (Holling, 1973),

2. **adaptability** is the capacity of the system to change the composition of inputs and outputs in response to changing drivers, without changing the system structure (Folke et al., 2010), and

3. **transformability** is the ability of the system to change its fundamental internal processes, thus becoming a new system that can continue to supply a desired level of various (old or new) functions (Folke et al., 2010; Walker et al., 2004).

Resilience can be a means *and* a barrier to achieving sustainability, depending on the level of the three resilience capacities (Marchese et al., 2018). 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 et al., 2018; Robertson and Swinton, 2005; van Apeldoorn et al., 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 et al., 2018). The trade-offs and synergies between short-term productivity and long-term sustainability goals can be revealed through resilience research (Peterson et al., 2018).

Resilience research requires a systems approach

Resilience research of farming systems requires a systems approach. This is because farming systems are classified as having complex interactions between social and ecological sub-systems (Ericksen, 2008; Tendall et al., 2015). Economic challenges (e.g. low income), may affect ecological system components (e.g. soil quality), and vice versa. Likewise, strategies to strengthen one component of a farming systems could have unintended consequences that exacerbate problems in other components (Fiksel, 2006). The often delayed reaction of a system to a disturbance undermines our ability to anticipate these unintended consequences of strategies (Folke et al., 2016). Knowledge about system structure is needed to anticipate these consequences.

Knowledge about system structure as a driver of behaviour can then be used to (1) assess and (2) improve the resilience of farming systems (Schlüter et al., 2014). Assessing resilience is achieved by measuring the effects of challenges on system behaviour. Improving resilience involves designing strategies to increase the three resilience capacities, robustness, adaptability or transformability (Peterson et al., 2018). Studying system structure also provides insights into short-term and long-term dynamics that explain trade-offs between productivity and sustainability goals (Peterson et al., 2018).

Need for case studies

Case studies are often used in resilience research (Allison and Hobbs, 2004; Gunderson and Holling, 2002; Meuwissen et al., 2019). Each farming system is unique (Bijttebier et al., 2018; Meuwissen et al., 2019). Some drivers and challenges may be more important to one farming system than to another, depending on the economic, institutional and cultural context (Naylor, 2009). Therefore, the context-dependent system structure needs to be considered, in order to assess and improve the resilience of a farming system. The results from several case studies can then be used to make hypotheses of how system structure and dynamics determine the resilience of farming systems in a general sense (Allison and Hobbs, 2004; Gunderson and Holling, 2002).

This thesis research involves the detailed analysis of a farming system in the Veenkoloniën, NL, as a case study that is exemplary for a challenged European farming system (Meuwissen et al., 2019; Paas et al., 2019). Specifically, this study uses a system dynamics approach to study how system structure determines the resilience of this specific system. The resilience is determined by quantifying the ability of the system to cope with specific challenges in the presence of coping strategies. The ability to cope with challenges is determined through changes in system indicators. This thesis ends with a reflection about the implications of the resilience assessment of this case study for European farming systems in general.

The following sections provide background information about the Veenkoloniën region and the key challenges facing the region's farmers. This is followed by a description of what is currently known about the resilience of this farming system and the knowledge gap that still exists.

1.1 The Veenkoloniën farming system

The Veenkoloniën (Dutch for Peat Colonies), an agricultural region in the northeast of the Netherlands, are an important example of how a number of challenges are negatively influencing agricultural production in Europe today (Meuwissen et al., 2019; Paas et al., 2019). The region covers parts of the provinces Groningen and Drenthe and is known for the production of starch from potatoes (Strijker, 2008; Fig. 1 A). The removal of peat in the region in the 17th century, led to the mixing of the top layer of bog and the sandy underground, leaving behind fertile soils (Strijker, 2008). This drove the growth of the agricultural industry, with starch potato as one of the main crops (Bijttebier et al., 2018; Strijker, 2008). Since the mid 19th century, the production of starch potatoes has increased significantly (Fig. 1 B).

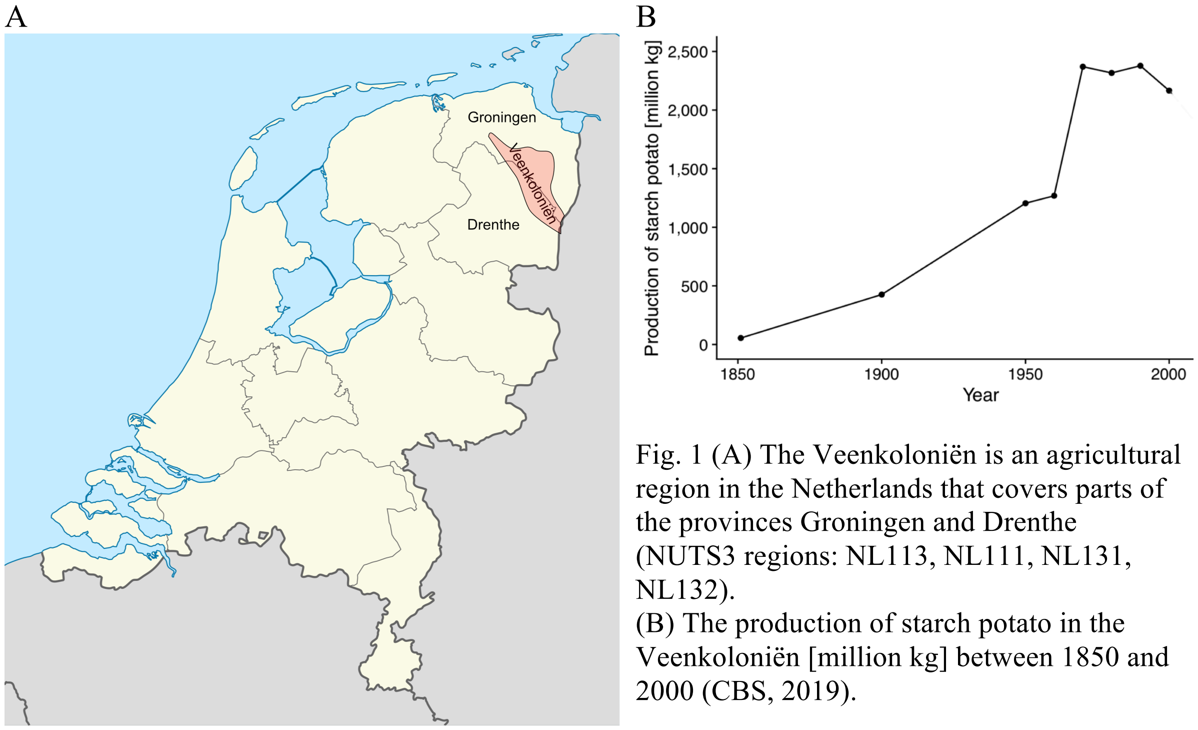


Fig. 1 (A) The Veenkoloniën is an agricultural region in the Netherlands that covers parts of the provinces Groningen and Drenthe (NUTS3 regions: NL113, NL111, NL131, NL132).
(B) The production of starch potato in the Veenkoloniën [million kg] between 1850 and 2000 (CBS, 2019).

The significance of arable farming in the Veenkoloniën region

Today, starch potato production continues to be of great socio-economic importance in the Veenkoloniën (Bont et al., 2007). In 2005, the production of starch from potatoes in the region generated work for more than 7000 working years (Bont et al., 2007). Starch potatoes accounted for up to 50% of the income of arable farms in the region (Bont et al., 2007). Overall, there is a large dependence on arable farming in the region and a large dependence on the cultivation of starch potatoes (Bont et al., 2007).

Consequently, it is alarming that the future of starch potato production in the Veenkoloniën is uncertain. The number of farms cultivating starch potatoes in the Veenkoloniën has decreased significantly since 2000 (Bont et al., 2007; CBS, 2019). Roughly 1100 specialised starch potato farms are present in the Veenkoloniën today, compared to 2000 farms 20 years ago (Fig. 2 dashed line).

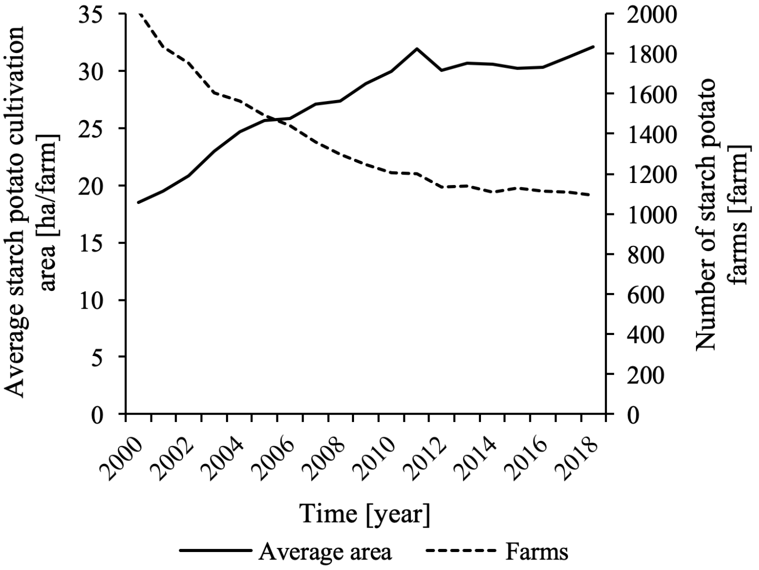


Fig. 2 The number of specialised starch potato farms in the Veenkoloniën [farms] (dashed line – right axis) and the respective average farm size [ha/farm] (solid line – left axis) (CBS, 2019).

The low profitability of starch potato cultivation is likely to be one of the main drivers of the decrease in farm number (Asjes and Munneke, 2007; Paas et al., 2019). The majority of starch potato farm families had an income of less than 25,000 EUR in the year 2005 (Bont et al., 2007). Low profitability is especially problematic for smaller farms, who represent most of the farms that were lost in the past two decades (Bont et al., 2007). This has resulted in an increase of the average farm size (Asjes and Munneke, 2007; Bont et al., 2007; Fig. 2 solid line). However, this also means that there was a significant drop in the number of agricultural jobs in the region (Bont et al., 2007). The unemployment rate in the north of the Netherlands, which is already higher than the national average, could further increase (Bont et al., 2007).

Current resilience assessment of the Veenkoloniën farming system

The low profitability of starch potato cultivation is the result of several challenges to the farming system. A number of research efforts have already been focused on identifying the most important challenges and their impacts on the system (Kuhlman et al., 2014; Meuwissen et al., 2019; Prins, 2011; Vasilev et al., 2012). The SURE Farm project (Towards SUstainable and REsilient EU FARMing systems) is one large-scale resilience research project, that uses the Veenkoloniën as a case study farming system (Meuwissen et al., 2019; SURE Farm project, 2017). Many of the results presented in the deliverables of SURE Farm are used as a point of departure for this study (see Table A.1 in Appendix A, for how this study aligns with the SURE Farm project). Notably, a number of qualitative approaches have been used to identify some of the main challenges facing the region (Paas et al., 2020, 2019). All challenges directly or indirectly influence the profitability of starch potato farms in the region (Paas et al., 2020, 2019). The challenges that are treated within the scope of this study include (Paas et al., 2020, 2019):

(C1) Nematodes in the soil, which are reducing yields and limiting starch potato in crop rotations.
(C2) Decreasing soil quality, which is affecting average yields.
(C3) Low water holding capacity and low drainage capacity, which is making the region sensitive to extreme weather events, such as droughts and extreme rainfall, leading to significant yield losses.
(C4) Increasing profits from other crops relative to the profits of starch potatoes.
(C5) High and rising costs of specialised starch potato farms.

Interestingly, despite the mentioned challenges, the total cultivation area and the total production of starch potato have not significantly changed over the past 20 years (Fig. 3; CBS, 2019). In resilience terms, these trends seem to indicate a high level of robustness (Paas et al., 2019).

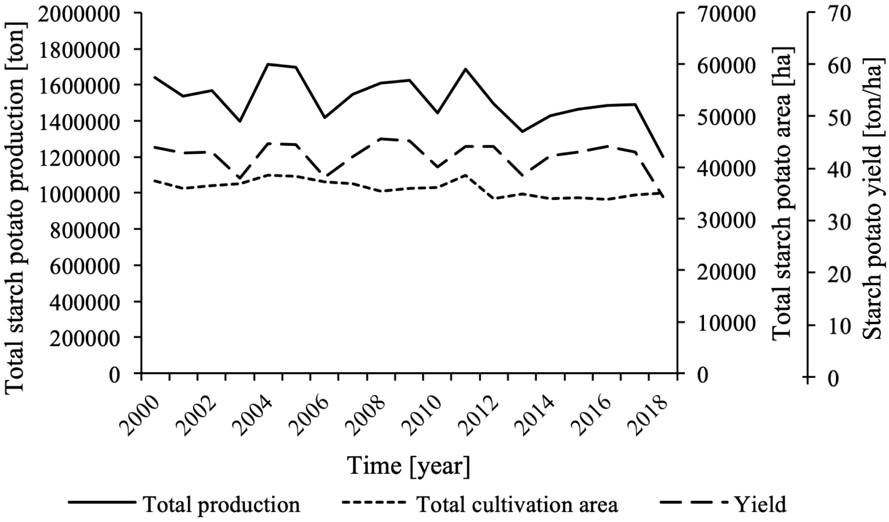


Fig. 3 The total production volume of starch potatoes [ton], total cultivation area of starch potatoes [ha], and yield of starch potatoes [ton/ha] in the Veenkoloniën and Oldambt (CBS, 2019).

One possible explanation for the observed robustness of the Veenkoloniën farming system is the organisation of all starch potato growers into the agro-industrial cooperative called Avebe (Meuwissen et al., 2019). Avebe is the only company in the Netherlands that processes starch from potatoes (Bont et al., 2007). They receive roughly half of all of their starch potato supply from the Veenkoloniën, and represent about one third of the global market share of the starch potato value chain (Strijker, 2008). Starch potato growers own Avebe shares, which come with the obligation to deliver starch potatoes to Avebe (van Dijk et al., 2019). The factories of Avebe process the starch potatoes that are produced by all share-holders 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 members according to the volume and quality of starch potatoes they delivered, and the number of shares they own (Avebe, 2018a).

Avebe and specialized starch potato farmers seem to be responsible for the robustness of the farming system. It is in the interest of Avebe to maintain a steady supply of starch potatoes from the Veenkoloniën farmers, who constitute about 60% of their member pool (Klok, 2019). Likewise, it is of interest to the Veenkoloniën farmers to support Avebe through the production of starch potatoes, in order to receive the added value provided by the cooperative. Members of Avebe receive a higher price for their starch potatoes than the market price (Avebe, 2018a). This co-dependence between starch potato growers and Avebe may explain the robust production of starch potatoes in the Veenkoloniën that was observed in the past (Meuwissen et al., 2019). Many strategies taken by farmers and Avebe were identified in the SURE-Farm project that contribute to maintaining starch potato production (Paas et al., 2019). All strategies address the challenges that impede current levels of starch potato production (Paas et al., 2019). The strategies that are treated within the scope of this study include (Paas et al., 2020, 2019):

(S1): Plant breeding to increase starch content.
(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).
(S3): Increasing value of starch products and also extracting and selling potato protein.

1.2 Knowledge gap

Mostly qualitative methods of the SURE-Farm project have so far contributed to the resilience assessment of the Veenkoloniën farming system (SURE Farm project, 2017; Paas et al., 2020, 2019). Overall, these methods led to the hypotheses that (1) the Veenkoloniën farming system seem to be relatively robust when it comes to starch potato production, that (2) some of the main challenges facing the farming system are those that impede starch potato yield or decrease profitability, and (3) that the strategies that are currently used can at least maintain the current level of starch potato production in the Veenkoloniën (Paas et al., 2020, 2019).

However, quantitative insights into the proximity of the system to challenge thresholds, i.e. the maximum level of a challenge beyond which the system cannot recover, is still missing (Paas et al., 2020). The Veenkoloniën farming system may be less robust than historical trends indicate, if the system is close to challenge thresholds. The degree to which strategies can modify challenge thresholds, or help the system to recover when thresholds are crossed, is also unknown. Such insights can inform system actors about which strategies are most impactful to counteract the effects of specific challenges. In order to gain these insights, a quantitative approach is required that can capture the modes of action of challenges and strategies. In this regard, computer simulations can be used to predict the systems response to challenges and to quantitatively compare the effectiveness of strategies (Carpenter et al., 2005; Herrera, 2017; Schlüter et al., 2014). The chosen modelling approach should be able to integrate the large body of qualitative knowledge that has already been generated about the Veenkoloniën farming system.

All of these requirements are satisfied by a system dynamics approach, which has been used in a number of resilience studies in the past (Bennett et al., 2005; Berkes et al., 2000; Brzezina et al., 2016; Forrester, 1969; Herrera, 2017). System dynamics especially lends itself to study socio-ecological systems as it can be used to study relationships and feedback loops between indicators related to different disciplines (Sterman, 2000). In system dynamics qualitative information can be used to inform model structure and to arrive at quantitative model expressions (Aronson and Angelakis, 2016; Sterman, 2000). Therefore, system dynamics can be used to bridge the gap between the current qualitative understanding about the level of resilience in the Veenkoloniën and a quantitative understanding of how system structure and dynamics can explain this level of resilience.

1.3 Aim, objectives and research questions

The aim of this study is to use system dynamics to study the resilience of the Veenkoloniën starch potato farming system, based on the developments of the main system indicators in the presence of the main challenges and strategies. Specifically, this study aims to identify relative thresholds beyond which each challenge is potentially too large for the current starch potato farming system to continue to function normally without changing. Additionally, the relative ability of several strategies to modify these thresholds will be quantified.

To achieve these aims, this study includes three (research) objectives that are derived from the system dynamics approach (Ford, 1999; Sterman, 2000). Each objective is addressed by answering two research questions. Finally, a fourth (project) objective, is to apply the findings of the first three objectives, for the case of the Veenkoloniën, to other farming systems in Europe.

Objective 1: Model conceptualisation

Developing a conceptual model that represents hypotheses from literature about the causal relationships and feedback mechanisms that play a role in determining the level of starch potato production (and other indicators) in the Veenkoloniën.

RQ1.1 What trends are observed in the Veenkoloniën for the important system indicators?

RQ1.2 Which dynamic structures can explain the underlying mechanisms that give rise to the co-evolution of these trends?

Objective 2: Model formulation

Developing a system dynamics model based on the conceptual model.

RQ2.1 Does the model structure represent the dynamic structures identified under RQ1.2?

RQ2.2 Do the quantitative expressions used in the model adequately capture system behaviour?

Objective 3: Model behaviour analysis

Using the system dynamics model to test the behaviour of the system in the face of challenges and in the presence and absence of strategies.

RQ3.1 What are the thresholds of the main challenges that the system could potentially withstand, in the absence of strategies, before a significant change of the main indicators is observed?

RQ3.2 To what extent can the different strategies modify the thresholds of each of the challenges, to maintain the system in its current state in the face of a challenge?

Objective 4: Resilience of European farming systems

Applying the results of the first three objectives to European farming systems in general, to demonstrate how knowledge of system dynamics can improve our understanding of their resilience.

RQ4 What lessons can be learned about the resilience of European farming systems based on the insights from the system dynamics of this case study?

Chapter 2: Methodology

This study follows an iterative modelling approach adapted from Ford (1999) and Sterman (2000). This approach includes (1) behaviour identification, (2) formulation of a dynamic hypothesis, (3) formulation of a simulation model, (4) model testing and (5) simulations to explore system functioning (Fig. 4). Each step addresses the research questions and research objectives of this study. The objectives are not addressed in isolation from each other. Instead, "Agile SD" principles are followed, in order to address objectives in parallel and to continuously revise and increase confidence in the results (Warren, 2013). The project objective 4 is addressed in the discussion.

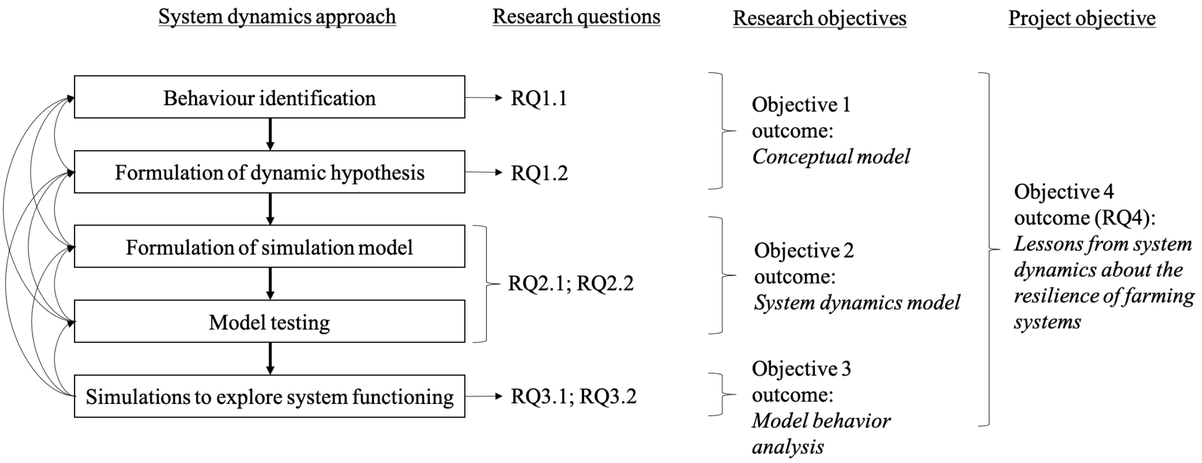


Fig. 4 The methodological framework followed in this study, adapted from Ford (1999) and Sterman, (2000) to address the research objectives of this study, through (1) model conceptualisation, (2) model formulation and (3) model behaviour analysis. The project objective (4) is addressed in the discussion.

Two types of data are consulted in this study (Table 1). Qualitative text data is used for model conceptualisation, model formulation and model testing. Country and region statistic data is used to validate trends identified in literature, to make reference modes of behaviour, to inform model structure and variable choices, for model calibration and for model validation.

Table 1 The data types, data sources, data collection, data processing and data use for this study.

Type of data	Sources	Collection	Processing	Use
Qualitative text data	SURE Farm deliverables (SURE Farm project, 2017); published academic literature (*e.g.* journal articles, conference reports); grey literature (*e.g.* documents published by Avebe, Agenda voor de Veenkoloniën, municipal authorities, newspaper articles)	Finding literature in which the trends of the past 20 years of starch potato production in the Veenkoloniën is discussed (along with explanation of causes for trends); special focus on literature describing farmer behaviour and Avebe strategies to changing environments	Translating Dutch text to English using DeepL (*DeepL*, 2019); open coding of text data according to (Kim and Andersen, 2012) (see Appendix B Table B.1)	Informing model variable selection (stock, flow, parameters), causal relationships, decision rules and drivers; model equations; validation of model structure

Type of data	Sources	Collection	Processing	Use
Quantitative country statistics	Public databases: Centraal Bureau van Statistiek (CBS, 2019); Agro & Food Portal, WUR (Agrimatie, 2019) Requested data: The Farm Accountancy Data Network (FADN, 2019);	Searching databases for the years 2000-2018 at the best regional resolution possible (e.g. CBS: Veenkoloniën & Oldambt; FADN: NUTS3 regions NL111, NL112 , NL131, NL132)	Data processing in R to e.g. disaggregate data by farm type, size, region; aggregate data to mean values; select only relevant indicators; accumulating from different sources in Excel; cross validating between sources; unit conversion (see Appendix F; Table F.1, Table F.2)	Model variable selection; model parameter values and initial values; model calibration; model validation; (see Appendix F; Table F.3, Table F.4)

The focus of this study is on specialised starch potato farms only. These make up most of the arable farms in the region (Bijttebier et al., 2018). Specialised starch potato farms are defined as those that cultivate starch potato in rotation with sugar beet and wheat. This assumption was based on observations in literature and from data that this crop rotation is one of the most common rotations found in the Veenkoloniën (Kuhlman et al., 2014; Paas et al., 2019; Vasilev et al., 2012). The conceptual and formal model boundaries therefore exclude other farm types in the Veenkoloniën.

2.1 Model conceptualisation

A literature study is conducted for model conceptualisation. Literature was chosen in which drivers of important indicators are described (Table 1). The indicators chosen in this study include starch potato production, total starch potato cultivation area, number of starch potato farms, and farm size. These indicators were chosen because they reveal interesting trends over the past 20 years (see Fig. 2, Fig. 3), because they are frequently mentioned in literature, and because of data availability. The historical trends for these indicators are therefore used as the reference modes in this study.

The conceptual model that can explain the historical trends of the system indicators is captured in a causal loop diagram (CLD) (Haraldsson, 2004). In this study, the approach described by Kim and Andersen (2012) is used to translate qualitative text data into a CLD. This process involves the identification of causal structures that are mentioned in each literature source (see Appendix B for an example). The final CLD presented in this study is the result of combining multiple CLDs made with the help of the different literature sources. The CLD and the system dynamics model are created using Stella Architect developed by isee systems inc (*Stella ® Architect*, 2019).

2.2 Model formulation and testing

The CLD is used to guide the development of the system dynamics model. This process involves (Aronson and Angelakis, 2016; Binder et al., 2004):

1. specifying the units of CLD variables
2. determining which CLD variables represent stocks
3. identifying flows

4. connecting flows to stocks and stocks to flows
5. linking non-stock CLD variables as auxiliary variables
6. specifying the equations that define stocks and flows
7. adding any additional variables that are needed and
8. unit analysis.

The model is also built with the help of historical data (Table 1). In iterative cycles, historical trends are modelled one after another. These trends are then linked using the dynamic hypothesis represented in the CLD. Using this approach, initially there may be a high amount of exogenous variables (those that take on the value of historical data at each time step where data is available), which are gradually turned into endogenous variables (those that are calculated by model equations at each time step). The availability of data may therefore also drive the choice of some variables that are included in the model. Ultimately, this process should result in as little exogenous variables, that depend on historical data, as possible. The final model documentation is done according to the reporting guidelines for simulation-based research in social sciences (Rahmandad and Sterman, 2012; model documentation in Appendix E).

Model testing is carried out throughout the process to increase the confidence in the model structure and resulting behaviour, and to identify areas for improvement. Various model tests are used in this study. These tests can be classified into direct structure tests, indirect structure tests and behaviour pattern tests (Table 2).

Table 2 The various tests that are used in this study to assess the system dynamics model that is made (Sterman, 2000).

Type of test	Test	Procedure	Requirements for passing test
Direct structure confirmation test	Structure and boundary assessment tests	Compare model structure with literature and review with experts.	The model structure does not contradict the knowledge about the structure of the real-world system.
	Parameter confirmation test	Compare model parameter values with literature and review with experts.	The parameter values reflect relevant descriptive and numerical knowledge of the system. All parameter values have real world equivalents.
	Direct extreme condition test	Assess the results for flow equations when stocks are given imaginary max and min values.	Each equation makes sense even when inputs take on extreme values.
	Dimensional consistency test	Inspect model equations, and carry out unit analysis.	All equations are dimensionally consistent without the use of parameters with units that have no real world meaning.
Indirect structure confirmation test	Extreme conditions test	Run the model with extreme parameter values and logically evaluate model behaviour.	The model responds plausibly when subjected to extreme parameter values.

	Integration error test	Decreasing the time step and using a different integration method to test for changes in model behaviour.	The results are not sensitive to the choice of time step or numerical integration method.
	Sensitivity analysis	Change model parameters with +/- 25% and +/- 50% observe the range of outputs generated.	The purpose of the sensitivity analysis is to prioritise data collection effort and to identify leverage points.

Type of test	Test	Procedure	Requirements for passing test
Behaviour pattern test	Behaviour reproduction test	Model simulation and historical data is compared quantitatively using the Mean Absolute Error as a fraction of the mean (MAE/Mean) as a robust measure of discrepancy with common units between all variables. $\frac{MAE}{Mean} = \frac{\frac{1}{n}\Sigma\lvert X_m - X_d\rvert}{\bar{X}_d}$ with: $X = value\ of\ observation\ at\ each\ timepoint$ where: $m = modelled\ data$ and $d = historical\ data$	The simulation outcomes for indicators closely resemble historical trends, meaning the MAE/Mean value is low (in this study lower than 10% is defined as adequate).
	Error decomposition	Theil's Inequality Statistics are used to separate mean-squared error into relative contributions of bias (U^B), unequal variation (U^V), and unequal covariation (U^C) (Theil, 1966). $MSE = \frac{1}{n}\sum(X_m - X_d)^2$ $U^B = \frac{\bar{X}_m{}^2 - \bar{X}_d{}^2}{MSE}$ $U^V = \frac{s_m{}^2 - s_d{}^2}{MSE}$ $U^C = \frac{2(1-r)s_m s_d}{MSE}$ $U^M + U^S + U^C = 1$ with: $X = value\ of\ observation\ at\ each\ timepoint$ $s = standard\ deviation$ $r = correlation\ coefficient$ where: $m = modelled\ data$ and $d = historical\ data$	The relative contributions of bias, unequal variation, and covariation reveal what fraction of the error is systematic and unsystematic. On the one hand, bias and unequal variation could indicate systematic errors. Bias shows that simulations and historical data have different means, which may be caused by errors in parameter estimates. Unequal variation indicates that two series have different variances around the mean, which could be caused by differences in long-term trends. On the other hand, unequal covariation is often unsystematic. For the purpose of this study a higher contribution of unequal covariation is desired, as this indicates that long-term trends are followed despite unsystematic errors between individual points (Sterman, 2000).

2.3 Model behaviour analysis

Three types of simulations are analysed in this study:

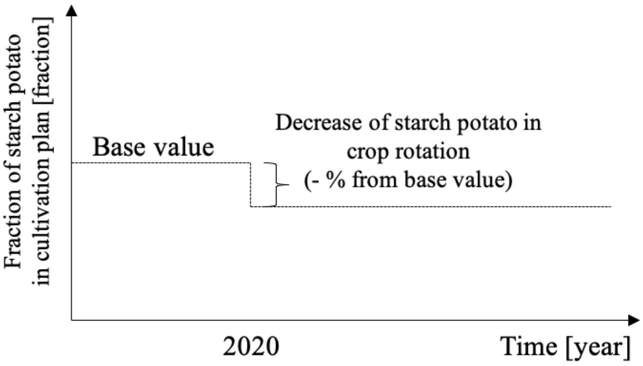
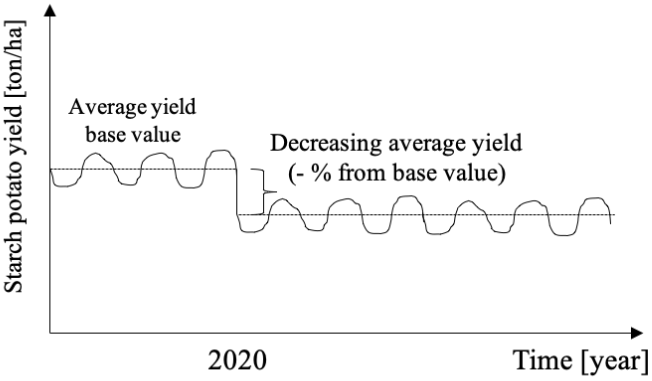
1. Base run simulation
2. Simulations with challenges
3. Simulations with challenges and strategies

Base run simulation

The base run refers to a simulation in which all time series data inputs remain constant going into the future (model simulations between 2020 and 2050). In other words, the trends of exogenous variables are not extrapolated into the future. This results in an equilibrium. In this way, the base run serves as a "negative control". In other words, the equilibrium of the base run is compared to simulations with challenges and strategies that disrupt/restore this equilibrium.

Simulations with challenges

Five challenges are analysed in this study. These include the most important challenges identified for the Veenkoloniën (see section 1.1). All challenges are introduced in the year 2020. The behaviour of the model in the presence of each challenge is tested by conducting a sensitivity analysis on model parameters that represent each challenge (Fig. 5). For this, the Stella Architect feature "Sensitivity" found under "Model analysis tools" is used to change various parameters from their respective base values (until +/- 50%) in the year 2020.

Challenge	Simulation of the challenge
(C1) Decreasing the fraction of starch potato in crop rotation [fraction] due to increased nematode pressure.	
(C2) Decreasing the average yield of starch potato [ton/ha] due to decrease in soil quality.	

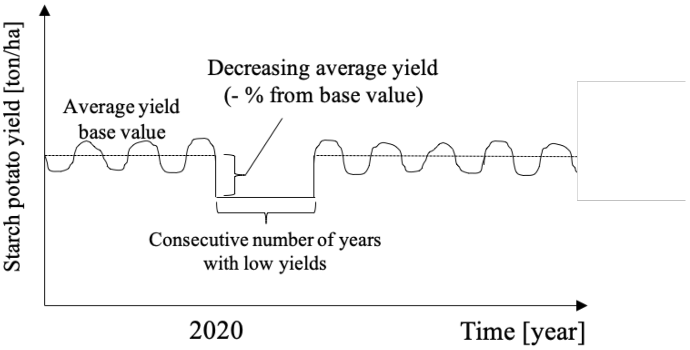
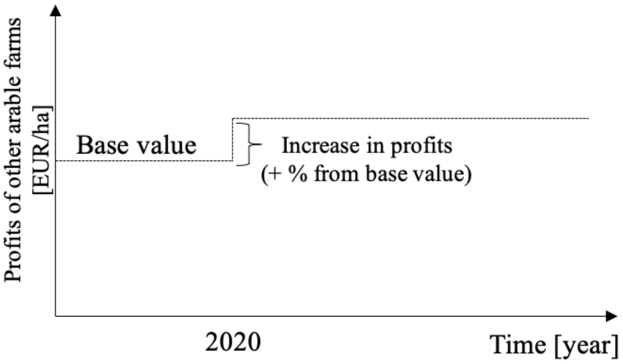
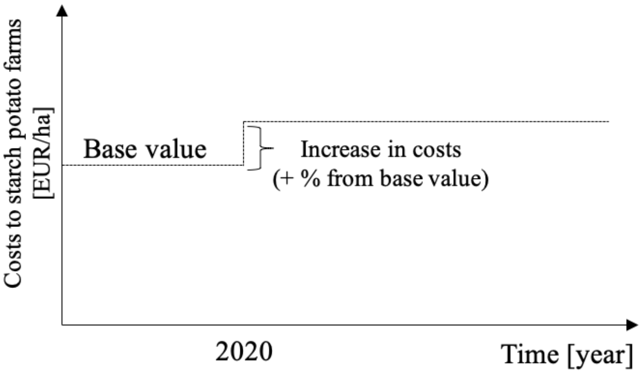
(C3) Decreasing average yield of starch potato [ton/ha] due to extreme weather events for a number of consecutive years	
(C4) Increasing the profits of other arable farms [EUR/ha] relative to the profits of starch potato farms.	
(C5) High and rising costs [EUR/ha] of specialised starch potato farms.	

Fig. 5 The ways in which the five challenges are simulated. A sensitivity analysis is done for each challenge parameter by changing the base value (by up to + or - 50 %). For C3, the average yield is decreased up to -50% for up to 20 consecutive years in a row.

For each challenge, the relative change in the respective parameter (%) is identified that causes a significant decline of the indicator starch potato production. A "significant" decline is defined as a decrease in starch potato production by more than 20% from the 2020 value in the year 2050 (Fig. 6 A). This value was chosen, because preliminary model simulations showed that typically above a 20% decline of starch potato production (Fig. 6 B1), the indicator farm income declined significantly (sometimes to zero) in the year 2050 (Fig. 6 B2). This situation is unsustainable and is therefore assumed to require the system to change (= the system is not robust to the level of the challenge).

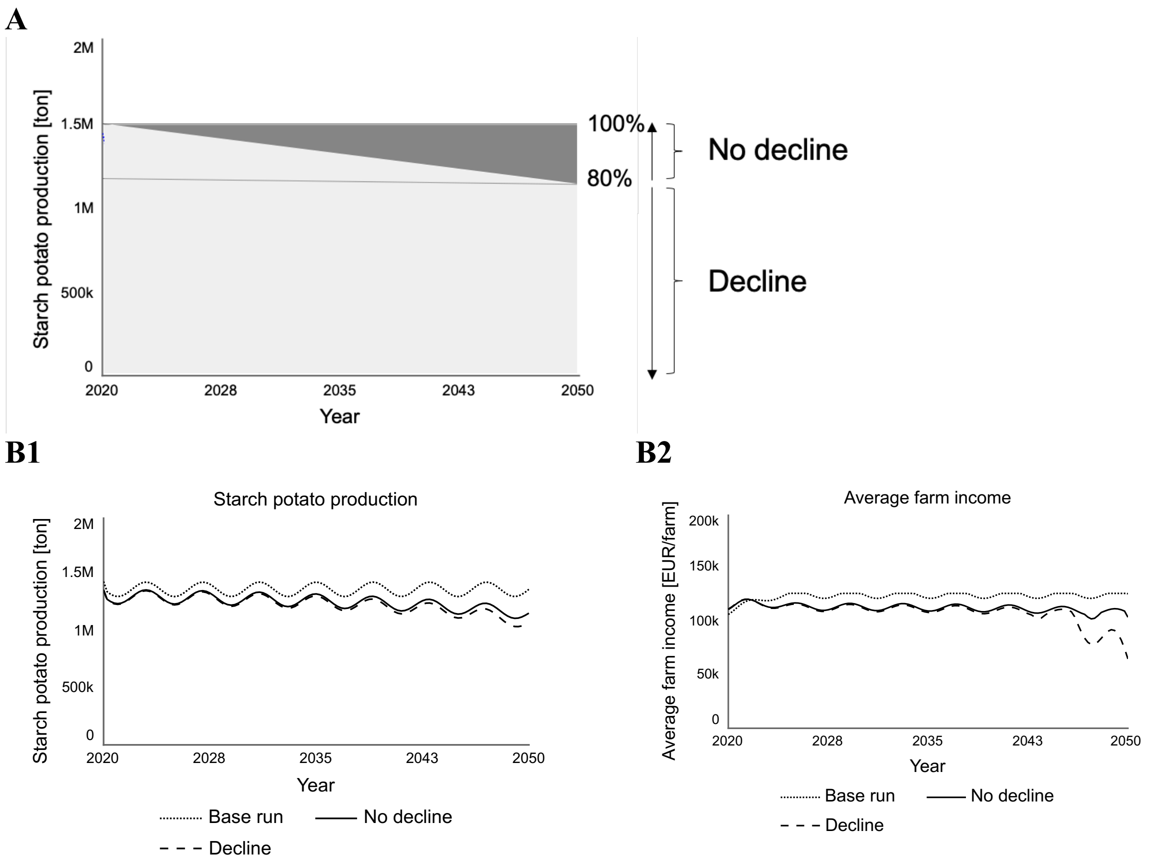


Fig. 6 (A) All simulations where starch potato production is at least 20% lower than the 2020 value in 2050 are labelled "Decline", all others are labelled "No decline". (B1) Example simulations of starch potato production, where one simulation (full line) is labelled "No decline" and another simulation (dashed line) is labelled "Decline". (B2) In the simulation labelled "Decline" in B1, the average farm income is rapidly decreased after the year 2040.

The sensitivity analysis is repeated until the exact threshold for each challenge is found (Fig. 6 B1 shows such a threshold between the solid and the dashed line). The thresholds of each challenge are expressed in relative terms, in order to compare model sensitivities between challenges. Challenges are also tested in combination with each other. For this, at least 200 simulations, with varying degrees of two challenges, are analysed for each challenge pair. The labelled simulations are plotted with one challenge parameter on the x-axis, and the other challenge parameter on the y-axis. This will reveal a threshold line for each challenge pair, above which all parameter combinations lead to a decline of starch potato production. This analysis may also reveal whether two challenges have interacting effects.

Simulations with strategies

Three strategies are analysed in this study. Various model parameters are changed to represent each strategy (Fig. 7). All strategies are introduced in simulations along with a challenge in the year 2020 (5 challenges x 3 strategies = 15 combinations). The simulation results of all challenge-strategy pairs are placed into a so-called "policy space", often used in system dynamics studies (Deegan, 2006). These are tables in which each row represents one challenge and each column represents one policy (= strategy in the case of this study).

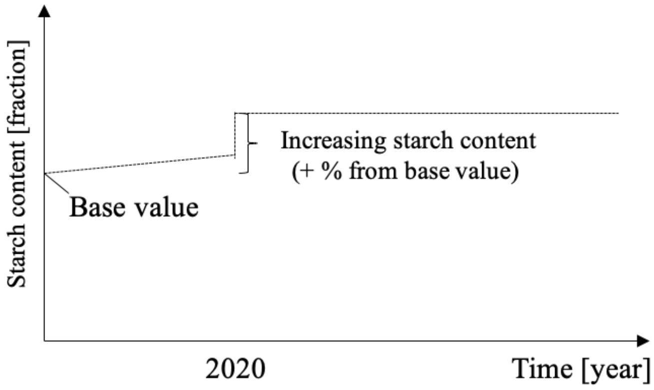
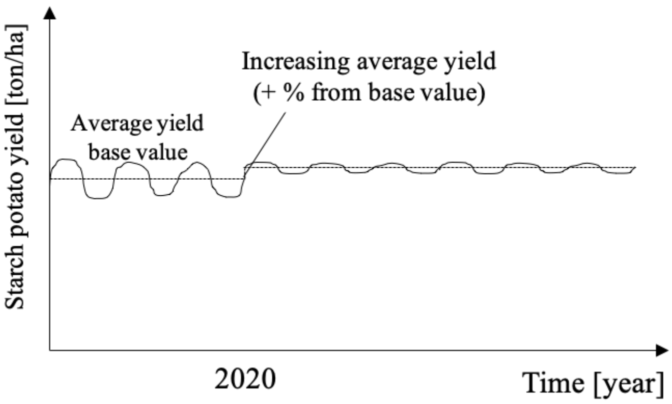
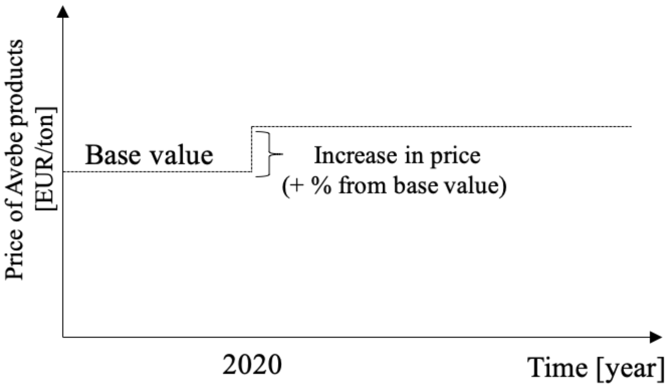
Strategy	Simulation of the strategy
(S1) Increasing the starch content [fraction] through plant breeding	
(S2) Increasing the average yields of starch potato [ton/ha] by means of decreasing yield variability [1]	
(S3) Increasing the price of Avebe products [EUR/ton] e.g. by means of increasing the value of starch products and also extracting and selling potato protein	

Fig. 7 The ways in which various strategies are simulated in the model. A sensitivity analysis is done for each respective parameter by changing the base value (+ 50 %).

[1] In the base run the average starch potato yield is 43 ton/ha, and the yield fluctuates with +/- 2 ton/ha around the average yield. Thus, in S2 the maximum possible average yield increase is 4.6 % (43 + 2 = 45 ton/ha).

For each challenge-strategy pair, at least 500 simulations are run for different parameter value combinations. All simulations in which starch potato production declined by more than 20%, from the 2020 value in the year 2050, are labelled “Decline”, all others are labelled “No decline” (as in Fig. 6). The labelled simulations are plotted with the challenge on the y-axis and the strategy on the x-axis. The resulting point clouds reveal a so-called “safe operating space”, a concept used in resilience literature to describe how strategies can help to stay below thresholds of challenges (Rockström et al., 2009; Scheffer et al., 2015). The safe operating space shows to what extent a strategy needs to be implemented to counteract various degrees of each challenge.

Chapter 3: Results

The following three sections correspond to the three sections in Chapter 2 and address each of the three research objectives separately. First, the final causal loop diagram (CLD) is shown that uses information found in literature to explain the co-evolution of trends of various indicators in the Veenkoloniën farming system. Next, the system dynamics model is described that was made with the help of the CLD. This section includes a model overview, model assumptions and model validation results. Finally, the results from the base run, challenge and strategy simulations are revealed.

3.1 Model conceptualisation

A single CLD can explain the trends of the total starch potato production volume, the total cultivation area, the number of farms and the farm size observed in the Veenkoloniën in the past (Fig. 8).

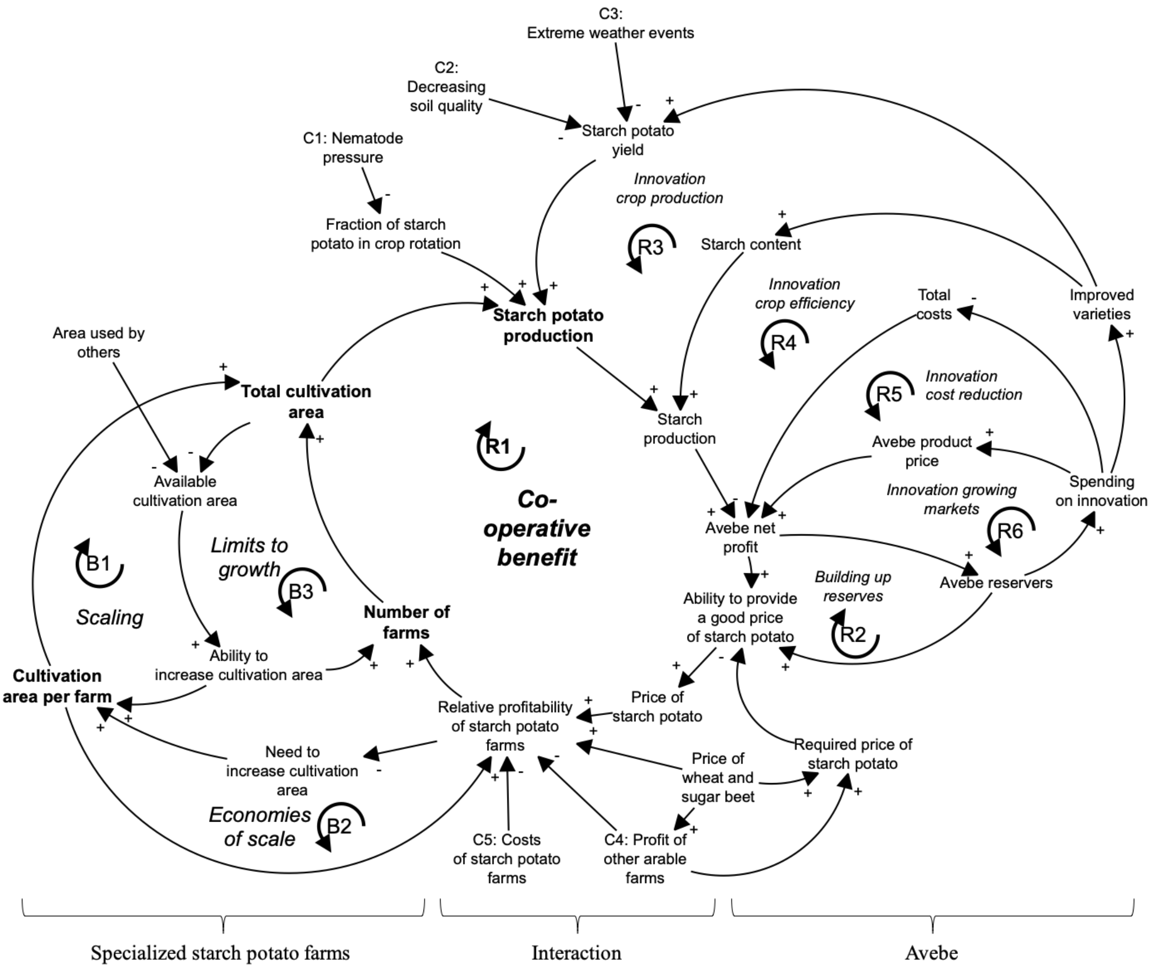


Fig. 8 A causal loop diagram showing the main processes determining starch potato production, cultivation area, number of farms, and farm size in the Veenkoloniën. Positive causalities are indicated by a + and negative causalities by a – next to each arrow head. A central "B" represents a balancing feedback loop and an "R" represents a reinforcing feedback loop.

The main balancing and reinforcing loops of the CLD, can be examined in three parts:

1. The feedback loops **B1**, **B2** and **B3** that represent only starch potato farms.
2. The feedback loops **R1** and **R2** that represent the interaction between starch potato farmers and Avebe.
3. The feedback loops **R3** until **R6** that represent Avebe and its strategies.

The behaviour of specialised starch potato farms

The feedback loops **B1**, **B2** and **B3** capture how total cultivation area can stay constant, as the number of farms decreases but farm size increases (Fig. 9). 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 the majority of farms that have been lost (Bont et al., 2007). Larger farms account for the low profitability of starch potatoes [EUR/ha] by increasing in size [ha/farm] and achieving a higher income through economies of scale (Asjes and Munneke, 2007; Vos, 2019).

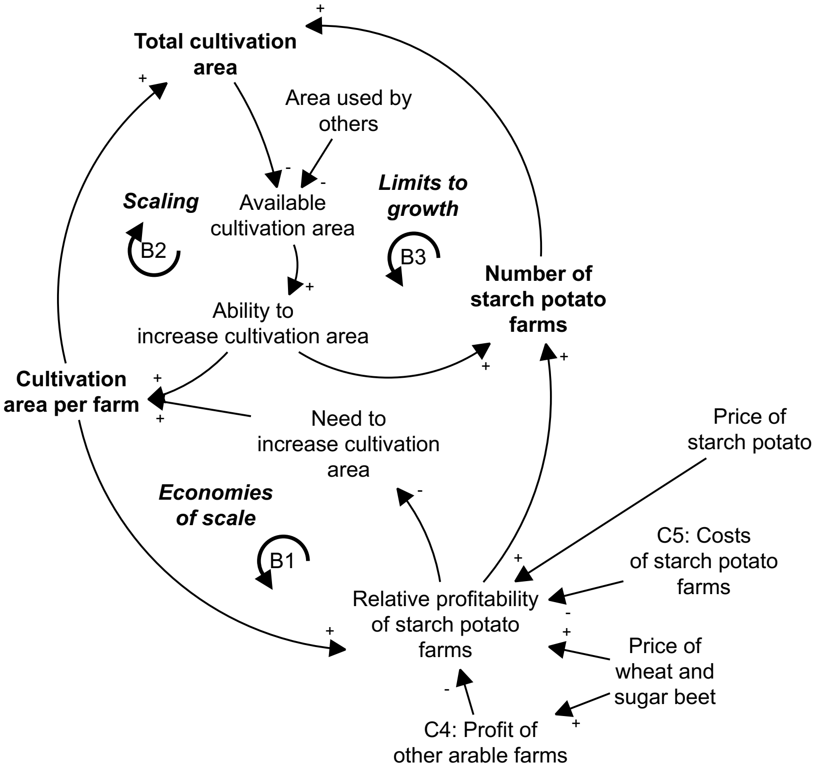


Fig. 9 A causal loop diagram showing the feedback loops **B1**, **B2** and **B3** of Fig. 8. These feedback loops represent the trends observed for total cultivation area, number of farms and farm size. Challenges are labelled "C".

The CLD can be interpreted as follows: A relatively low profitability of starch potato farms can be compensated for by a higher cultivation area per farm (Fig. 9 **B1**: "Economies of scale"). Farms have the ability to increase their cultivation area as long as there is area available (Fig. 9 **B2**: "Scaling"). However, if there is not enough area available for farms to increase in size (or if land prices are too high), starch potato farms may be lost. In this way, the total cultivation area of starch potato farms in the region decreased, when their profitability is low (Fig. 9 **B3**: "Limits to growth").

Fluctuating crop prices and costs of production are challenges to this system. These "external" factors affect the relative profitability of being a specialised starch potato farm in comparison to being another arable farm. Therefore, crop prices and costs ultimately drive the trends for total cultivation area, total number of farms, and cultivation area per farm.

The cooperative benefit enjoyed by members of Avebe

The feedback loops **R1** & **R2** capture how Avebe influences the profitability of starch potato farms by adjusting the starch potato price (Fig. 10). Feedback loop **R1** “Cooperative benefit” is the most important feedback between Avebe and starch potato farms. Avebe depends on the steady flow of starch potatoes from the Veenkoloniën and is thus committed to maintain its member pool, or at least their combined cultivation area (Beldman, 2015; Bont et al., 2007). Avebe therefore aims to offer a reasonable price of starch potato to their members (Avebe, 2014). This price should maintain a relatively high profitability of specialised starch potato farms in comparison to other arable farms (Avebe, 2014).

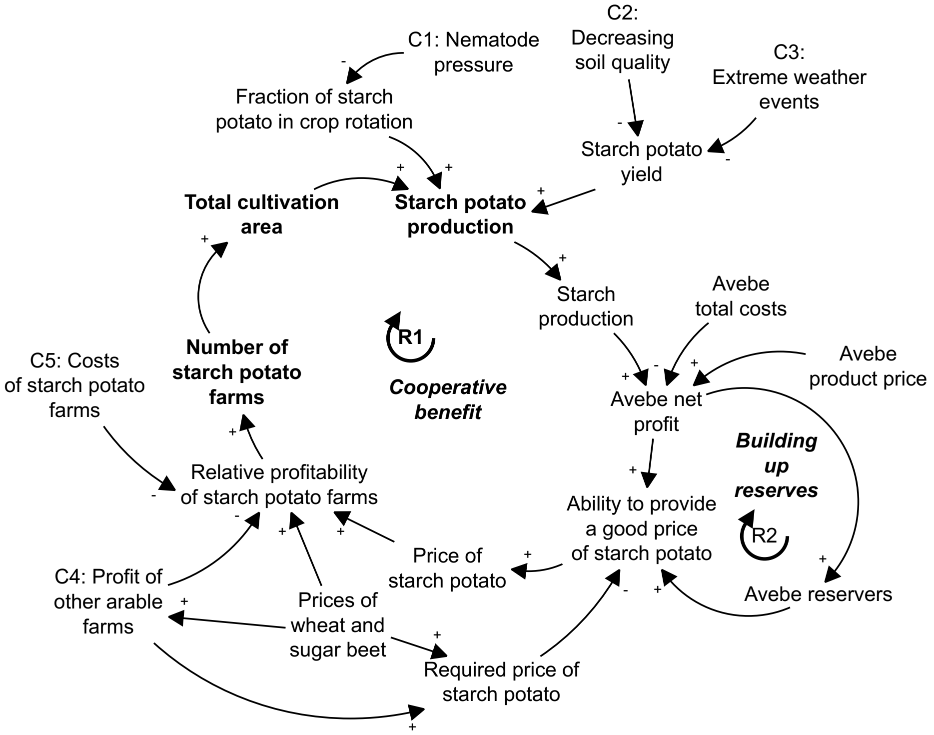


Fig. 10 A causal loop diagram showing the feedback loops **R1** and **R2** of Fig. 8. These feedback loops represent the interaction between starch potato farms and Avebe. Challenges are labelled “C”.

Feedback loop **R1** can be read as follows: The total starch potato production is the product of the total cultivation area, starch potato yield and the fraction of starch potato in the cultivation plan. 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 and their total costs. This net profit is used to pay farmers a price that will maintain a reasonable profit benefit of growing starch potatoes for Avebe compared to if they were only growing other crops.

External challenges to the feedback loop **R1** include nematode pressure (C1), decreasing soil quality (C2), extreme weather events (droughts and flooding) (C3), fluctuating prices of other crops (C4), and costs to starch potato farms (C5). All of these challenges interfere in **R1** in different ways, but all of them ultimately decrease the ability of Avebe to maintain a reasonable starch potato price. However, feedback loop **R2** shows how Avebe can survive a number of years with low profits and still offer a reasonable starch potato price to members. In good financial years Avebe is able to build some reserves to compensate for loss-making years (Fig. 10 **R2**: “Building up reserves”).

Avebe's strategies to maintain a constant supply of starch potatoes

The feedback loops **R3** – **R6** show how Avebe can also use these reserves for spending on innovation, in order to avoid loss-making years (Fig. 11). Especially in recent years Avebe has achieved high returns and has managed to invest heavily in innovation (Avebe, 2014; Beldman, 2015). The goal of this investment is to strengthen the main feedback loop (Fig. 10 **R1**: "Cooperative benefit") by counteracting the challenges (labelled "C" in Fig. 10).

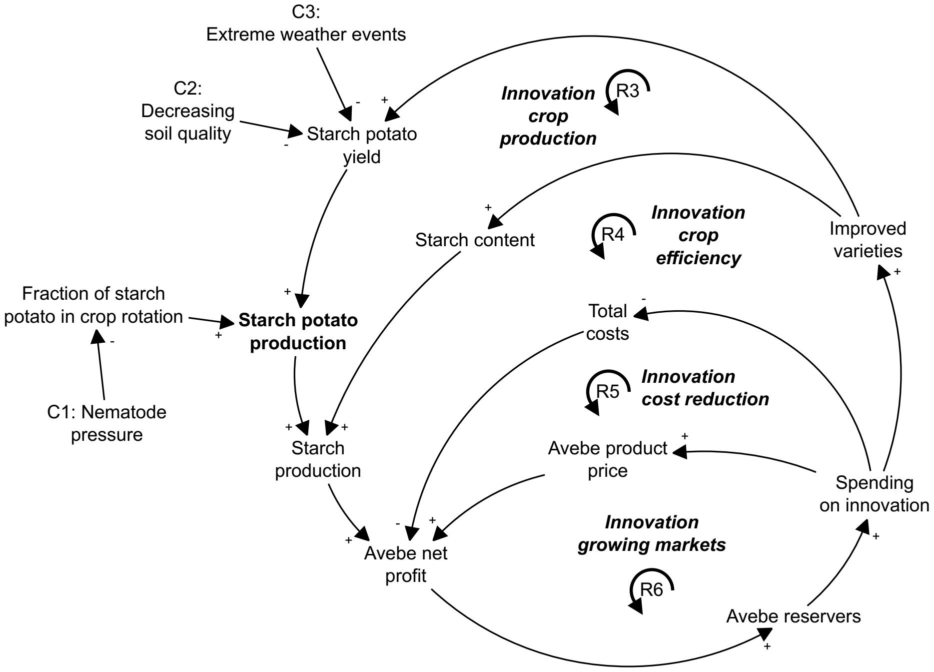


Fig. 11 A causal loop diagram showing the feedback loops **R3**, **R4, R5** and **R6** of Fig. 8. These feedback loops represent the strategies Avebe uses to maintain a steady supply of starch potato production in the face of challenges (labelled "C").

Part of the spending on innovation is reserved for breeding improved starch potato varieties. Specifically, Avebe's own breeding company, Averis in Valthermond, breeds more climate resilient and nematode resistant starch potato varieties (Avebe, 2018a; Fig. 11 **R3**: "Innovation in crop production"). This can make starch potato yield more resilient to extreme weather events and can help to maintain a high fraction of starch potato in the crop rotation respectively. The breeding programs also focus on increasing starch content (Fig. 11 **R4**: "Innovation in crop efficiency). This may maintain starch production and Avebe net profit even if starch potato yields or the cultivated area have decreased.

Apart from breeding programs, Avebe also invests in improving their own operations. Their main focus points are cost reduction and improving product value (Bont et al., 2007; Paas et al., 2019; Fig. 11 **R5**: "Innovation cost reduction" & **R6**: "Innovation growing markets"). The latter has been achieved, for example, by also extracting edible protein from the starch potatoes since 2009 (Paas et al., 2020, 2019).

3.2 Model formulation and testing

The model was built in iterative steps. The following sections describe the most important model components (all model variables are written in `this` font), various model assumptions, and the results of model testing. A full model description and model documentation can be found in Appendix D and Appendix E, respectively.

3.2.1 Model overview

The model is comprised of two modules that each represent one of the two system actors: the "Starch potato farms" and "Avebe" module. The output of one module is an input into the other module and vice versa (Fig. 12).

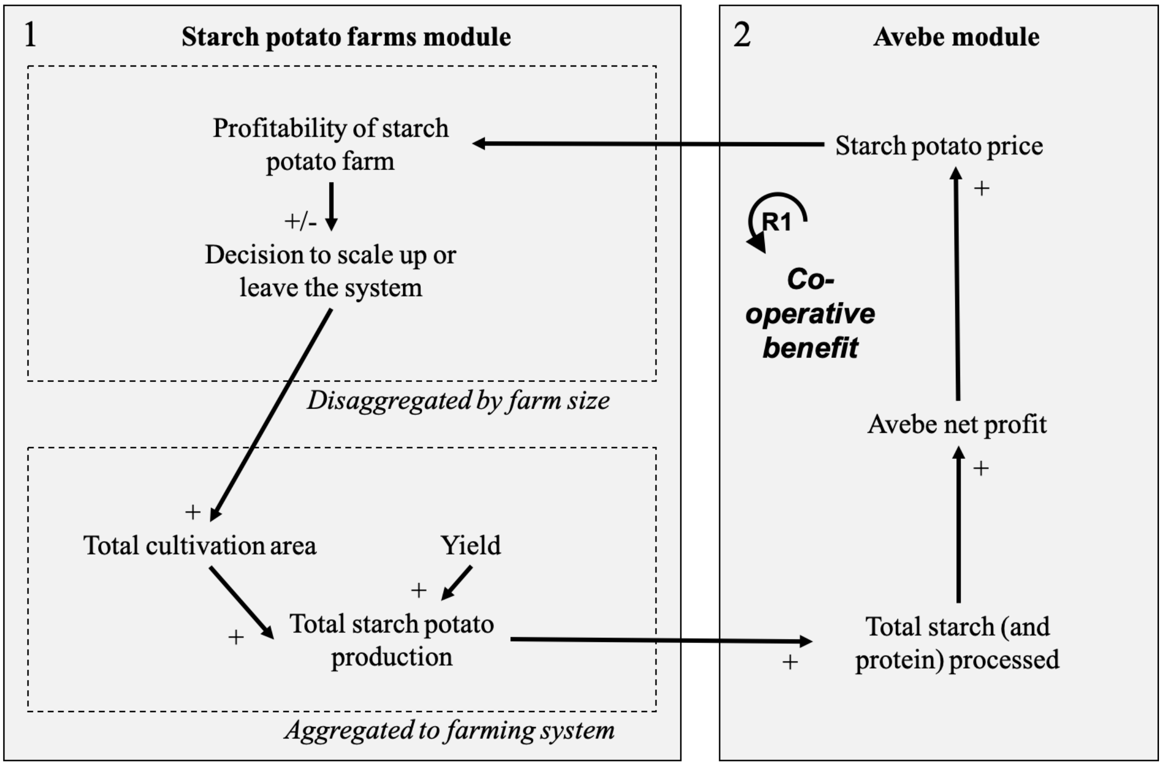


Fig. 12 A model overview showing the two main modules that were included: (1) A module to capture how profitability of starch potato farms (including the entire crop rotation) drives the decisions of farm to either scale up or leave the system. The decisions of the farms influence the total cultivation area and therefore the total starch potato production. (2) The second module calculates Avebe's net profit (before payment to farmers) and uses this net profit to determine the starch potato price. Only if the net profit is high enough can the starch potato price be kept high enough to ensure adequate profitability of starch potato farms.

The starch potato farms module represents farm number and farm size changes, based on the profitability of starch potato cultivation. The main output of this module is total starch potato production. The Avebe module captures how the supply of starch potatoes from the Veenkoloniën determines Avebe's net profits and therefore Avebe's ability to offer a reasonable starch potato price to their members.

Starch potato farms module

The starch potato farms module is split into two parts with different levels of aggregation, i.e. farm (size) level and farming system level. The number of farms are disaggregated by farm size to account for behavioural differences that depend on farm size. The total cultivation area and total starch potato production is aggregated to farming systems level.

An important component in the starch potato farms module is the `Farms` stock. This stock keeps track of the number of specialised starch potato farms in the Veenkoloniën in each year. The `Farms` stock is arrayed to include three farm sizes (Fig. 13). Historical data between the years 2004 and 2013, shared by the Farm Accountancy Data Network (FADN), was used to determine how many farm sizes to include (FADN, 2019). Between 2004 and 2013 only "Class UAA" (an FADN farm classification by utilized agricultural area) labels 4-6 were recorded in the FADN data for the Veenkoloniën region (NUTS3 regions: NL113, NL111, NL131, NL132). In other words, data about outputs, costs and profits are only available for Class UAA labels 4-6 for the Veenkoloniën. Outputs, costs and profits are required model inputs. Therefore, only farms with Class UAA labels 4-6 are taken into account in the model in this study. An average farm size was calculated for each of the Class UAA labels. This was done by taking the average size of all farms for each Class UAA label between the years 2004 and 2013. This procedure resulted in the three farm sizes that were included in the model: small (24 ha/farm), medium (37 ha/farm) and large (130 ha/farm) farms.

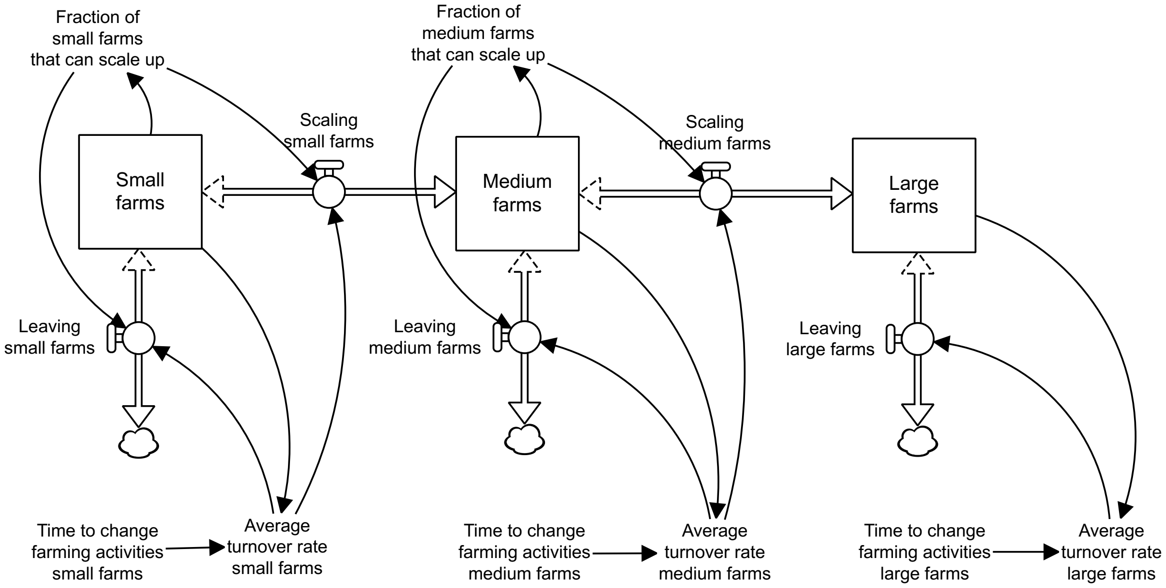


Fig. 13 A disaggregated view of the `Farms` stock in the `Starch potato farms` module, showing one stock for each farm size. Three farm sizes are arrayed in the `Farms` stock [farms], along with their respective rates [farms/year]. All stocks are part of one aging chain, which was adapted from an aging chain structure proposed in Sterman (2000).

Each farm size is represented by one `Farms` stock [farms] with its respective rates (Fig. 13). All three `Farms` stocks are part of one aging chain. Small farms can be transferred into the medium `Farms` stock, and medium farms can be transferred into the large `Farms` stock through their respective `Scaling` rates [farms/year]. Each `Farms` stock also has its own `Leaving` rate [farms/year]. The large `Farms` stock only has a `Leaving` rate but no `Scaling` rate. Thus, the model assumes that large farms have already reached their maximum size and cannot scale up any further. The model also assumes that no new farms can be established in this system. The `Average turnover rate` [farms/year] and the `Fraction of farms that can scale up` [unitless] determine both the `Scaling` rates [farms/year] and the `Leaving` rates:

$$Scaling\ rate\ = Average\ turnover\ rate * (Fraction\ of\ farms\ that\ can\ scale\ up) \tag{Eq. 1}$$

$$Leaving\ rate = Average\ turnover\ rate * (1 - Fraction\ of\ farms\ that\ can\ scale\ up) \tag{Eq. 2}$$

Each farm size has its own `Average turnover rate`. The `Average turnover rate`s are changed according to the profitability of starch potato cultivation (in rotation with wheat and sugar beet) at each point in time for each farm size. The `Average turnover rate` is zero if starch potato farms have a higher profit than other arable farms. In other words, if cultivating starch potato is more profitable than only cultivating other crops, there will be no change to the `Farms` stocks. The model therefore assumes that in this situation the starch potato farms are content with the current situation and will not scale up *or* leave the system.

According to Eq. 1 and Eq. 2, the model assumes that the preferred strategy of farms is to scale up rather than to leave the system. As long as farms have the ability to scale up they will do so. The model does not take into account the cost of scaling up.

The ability to scale up is captured by the `Fraction of farms that can scale up`. This is determined by the `Total available area` [ha] stock and the number of farms that fit into this area. The `Total available area` stock represents the area that is not being used by any farms and is therefore available for scaling farms. The `Total cultivation area` [ha] stock represents the total area used for the entire crop rotation of all starch potato farms (Fig. 14).

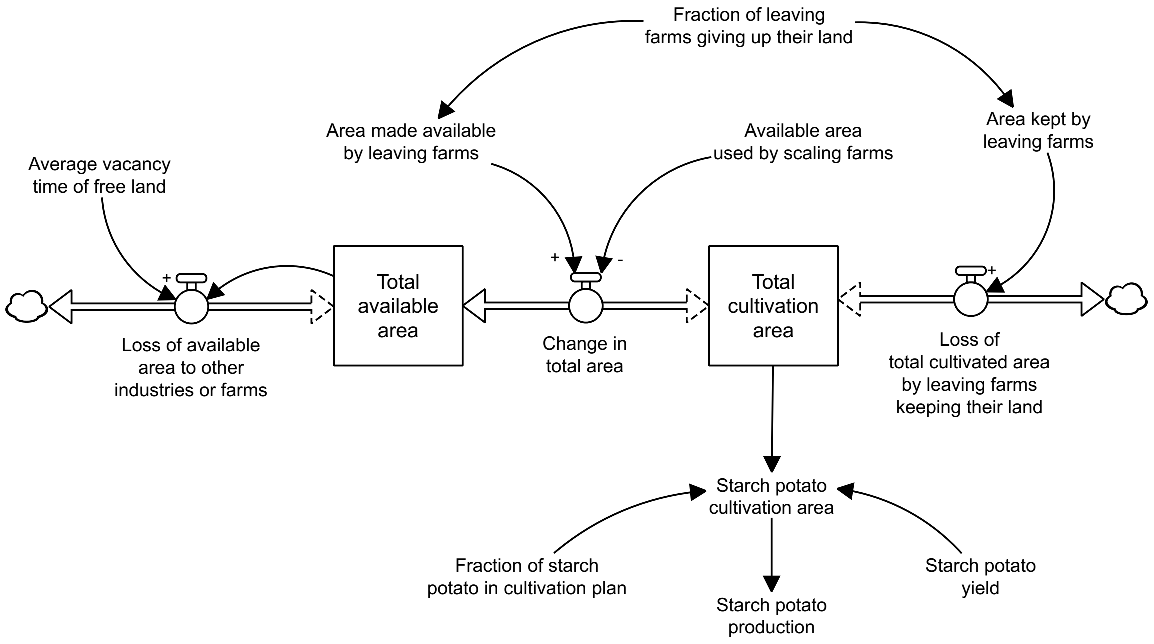


Fig. 14 The `Total available area` [ha] stock and the `Total cultivation area` [ha] stock found in the starch potato farms module, aggregated to farming systems level. The `Total cultivation area` stock is used to calculate `Starch potato cultivation area` [ha] and `Starch potato production` [ton] given the `Starch potato yield` [ton/ha].

The model assumes that if the available area is not used by scaling farms, it will be lost from the system to other industries or farms. This occurs when it is vacant for an `Average vacancy time of free land` [years]. The model also assumes that some farms that leave the system will keep their land, while other farms will make their land available again (`Area made available by leaving farms` [ha] and `Area kept by leaving farms` [ha]). The `Fraction` `of leaving farms giving up their land` [unitless] determines how much area is kept and how much area is lost from the system as farms leave. At every time step the `Total available area` stock and the `Total cultivation area` stock are calculated, given the three rates shown in Fig. 14. The `Total cultivation area` stock is then used to calculate `Starch potato cultivation area` [ha] and `Total starch potato production` [ton].

Avebe module

The Avebe module captures how Avebe sets the starch potato price according to the price desired by farmers, given high enough net profits. The most important assumption in the Avebe module, is that Avebe has some "reserves" to pay farmers an adequate `Starch potato price` [EUR/ton] even if `Net profits` [EUR] in one year are too low. This is possible as long as `Net profits` were high enough in the preceding years. Avebe's reserves are not captured by a stock. Instead, the `Average net profits` [EUR] are calculated for the past 3 years at each time step. These `Average net profits` are used to determine the ability of Avebe to pay farmers the `Price of starch potato desired by farmers`. The `Price of starch potato desired by farmers` is equal to the price that will make the profit of being a specialised starch potato farm (in rotation with sugar beet and wheat) equal to the profit of being another arable farm. Yields of starch potatoes, sugar beet and wheat, prices of sugar beet and wheat, costs of starch potato farms and profits of other arable farms are taken into account in the calculation of the desired starch potato price (calculation in Table E.6).

When the `Average net profits` are below the value needed to pay the `Price of starch potato desired by farmers`, a lower price is offered. This price adjustment does not occur linearly. The degree to which the actual `Price of starch potato` differs from the `Price of starch potato desired by farmers`, is determined by a table function (Appendix D Fig. D.4). In this way, `Payments to farmers` reduce only moderately when `Average net profits` are only slightly below what would be required to pay the full price. Only when `Average net profits` are much less than the full desired payment, will starch potato price reduce significantly.

3.2.3 Model testing

Direct structure confirmation tests

Literature helped to identify the structure that is necessary to describe past trends. The model therefore adequately satisfies the requirements for the structure and boundary assessment test (Table 2). Separating the farms by farm sizes was necessary, as Asjes and Munneke (2007) describe a different behaviour of small and large farms in the Veenkoloniën, in terms of succession and ability to scale. The dependence of farm succession on farm characteristics, such as size was also found in other studies examining European agriculture (Bakker et al., 2015; Breustedt and Glauben, 2007; Zagata and Sutherland, 2015). In the model made in this study, starch potato farms were disaggregated by farm size, in order to account for these differences. However, the total cultivation area and the total production of starch potatoes was aggregated to systems level. One average yield was used to estimate total starch potato production for all farm sizes. This average yield is assumed to be representative for the range of starch potato yields achieved in a given year, by different farmers in the Veenkoloniën (Bont et al., 2007).

The hypothesis, that Avebe can observe some years with low returns and still recover, is confirmed by past events. The financial year 2004/2005 was a loss-making period for Avebe (Bont et al., 2007). The cooperative managed to survive by taking out bank loans and receiving support from its members (Bont et al., 2007). In the model these details are substituted by the assumption of a “buffer time”. The calculation of price, based on the profits of other crops, is in accordance with statements by Avebe (Avebe, 2014).

The parameter confirmation test is also adequately passed. All parameters have real world equivalents. Whenever possible, parameter values used in the model were based on data collected about the Veenkoloniën by the Farm Accountancy Data Network (FADN), by the Centraal Bureau voor de Statistiek (CBS), and by Avebe. Some parameter values were estimated, such as the `Effect of profit on average turnover rates` of each farm type and the `Time to change farming activities`. Estimation of parameters was done by optimising for these parameters during model calibrations with time series data.

Direct and indirect extreme condition tests were carried out by examining equations and substituting extreme values into various parameter values. This confirmed that the model equations are robust and all physical laws are obeyed. A unit analysis confirmed that the model equations are dimensionally consistent and that all parameters have real world equivalents.

Indirect structure confirmation tests

The model was further validated by carrying out integration error tests, sensitivity analyses, and behaviour reproduction tests. The first two tests revealed that the simulation outcomes are consistent between different integration methods (model run in Euler, also tested for Cycle Time, Runge-Kutta (RK) 2 and RK4), as well as when the time step is decreased (from DT = 1/4 to DT = 1/8).

The sensitivity analysis showed that the model is not sensitive to the changes of most parameter values. In other words, the simulation outcomes changed by less than the change in the parameter value (+/- 50% for parameter values). The highest sensitivity was found when changing parameter values that are unique to the medium farms, such as `Size of effect[medium]` and `Time to change farming activities[medium]` (Appendix G; Table G.1). Furthermore, changing the table function for the `Standard effect of relative profitability on average turnover medium farms`, had a large effect on the simulation outcome (Appendix G; Table G.2). These high sensitivities indicate that the reaction of medium sized farms to profit differences are relatively more important for the simulation outcome, than the reactions of small or large farms. This difference may be explained by the higher initial abundance of medium farms, compared to the other two farms. The initial fractions of each farm size were estimated by calibrating the model to historical trends. In future model developments, further data analyses should be carried out to confirm the initial fractions of each farm size.

Behaviour pattern tests

The simulated values for starch potato production, total cultivation area, number of farms, average farm size and farm income approximately follows the historical trends between 2004 and 2013 (Fig. 15, Table 3).

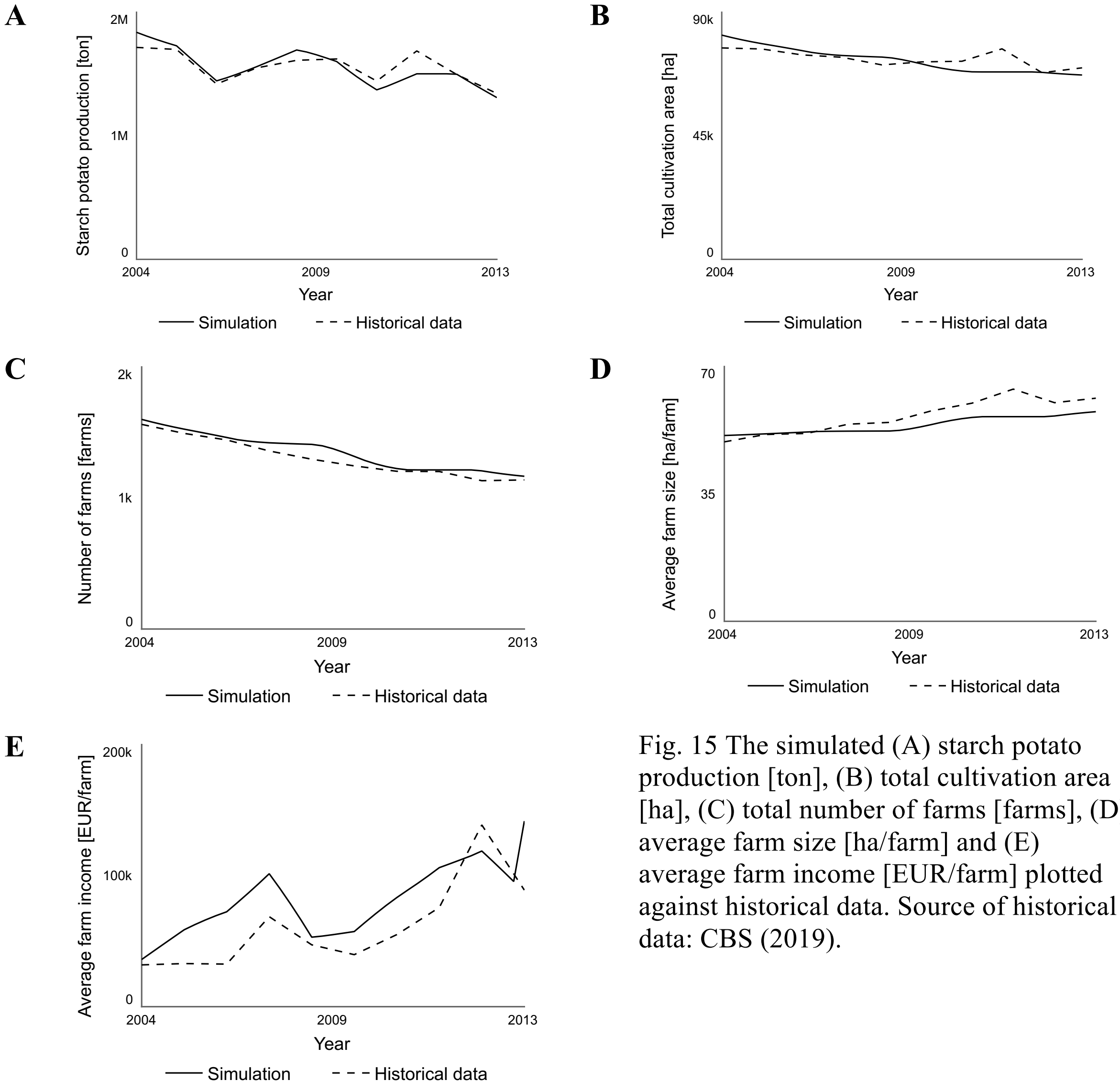
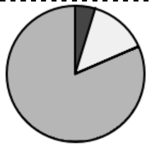


Fig. 15 The simulated (A) starch potato production [ton], (B) total cultivation area [ha], (C) total number of farms [farms], (D) average farm size [ha/farm] and (E) average farm income [EUR/farm] plotted against historical data. Source of historical data: CBS (2019).

Table 3 Simulated model behaviour of various indicators compared against historical data (medium grey: unequal covariation, light grey: unequal variation, dark grey: bias). Source of historical data: CBS (2019)

	Starch potato production [ton]	Total cultivation area [ha]	Total number of farms [farms]	Average farm size [ha/farm]	Average farm income [EUR/farm]
MAE/Mean [%]	3.83	3.83	4.25	4.74	38.19
Theil Inequality Statistics[1]					

▨ Covariation □ Variation ■ Bias

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[1] Stella Architect template by David Wheat.

The MAE/Mean values indicate that the simulated average farm income deviates most from the historical data (MAE/Mean > 10%; Table 3). The best fit between model simulation and historical data was found for total cultivation area and starch potato production, followed by total number of farms and average farm size. For these indicators all MAE/Mean values were below 10%.

Bias contributed the most to the error observed (MSE) between historical data and the simulated total number of farms and average farm income. Unequal variation contributed the most to the MSE of average farm size. This implies that model errors for these indicators are systematic, and that the simulated long-term trends may differ from the historical data.

Unequal covariation contributed the most to the MSE of starch potato production and total cultivation area. This implies that unsystematic errors dominate when simulating these indicators. In other words, long-term trends are followed.

Summary and purpose of model

The purpose of the model is to test the impact of challenges and strategies on the behaviour of important system indicators. The model should therefore capture the modes of action of challenges and strategies, as well as other underlying mechanisms that drive behaviour. Overall, the model fulfils the purpose for which it was built, as it:

1. provides the outputs for the system indicators starch potato production, total cultivation area, farm number, farm size and farm income,
2. is able to capture profitability of starch potato cultivation as the main driver of system behaviour,
3. is able to capture the decisions of farmers to either scale up to improve profitability or to stop cultivating starch potatoes,
4. is able to capture the differences in the behaviour of small farms as opposed to larger farms,
5. includes a feedback between starch potato production and the ability of Avebe to provide a good starch potato price,
6. includes structure that allows the testing of challenges and strategies on model behaviour.

3.3 Model behaviour analysis

The following section describes the results of using the model to explore how starch potato production and other indicators may evolve over time, in the presence and absence of challenges and strategies. This includes an analysis of the base run, an analysis of challenges alone and an analysis of how strategies counteract the effects of challenges.

3.3.1 Base run

The patterns observed in the base run simulation before 2020 are the results of historical trends of exogenous inputs such as yields, costs and prices (Fig. 16). Before 2020, the total cultivation area and total number of farms are decreasing while average farm size is increasing. Starch potato production and average profit per farm are fluctuating in the short term, the first showing a slight decrease and the latter a slight increase in the long term.

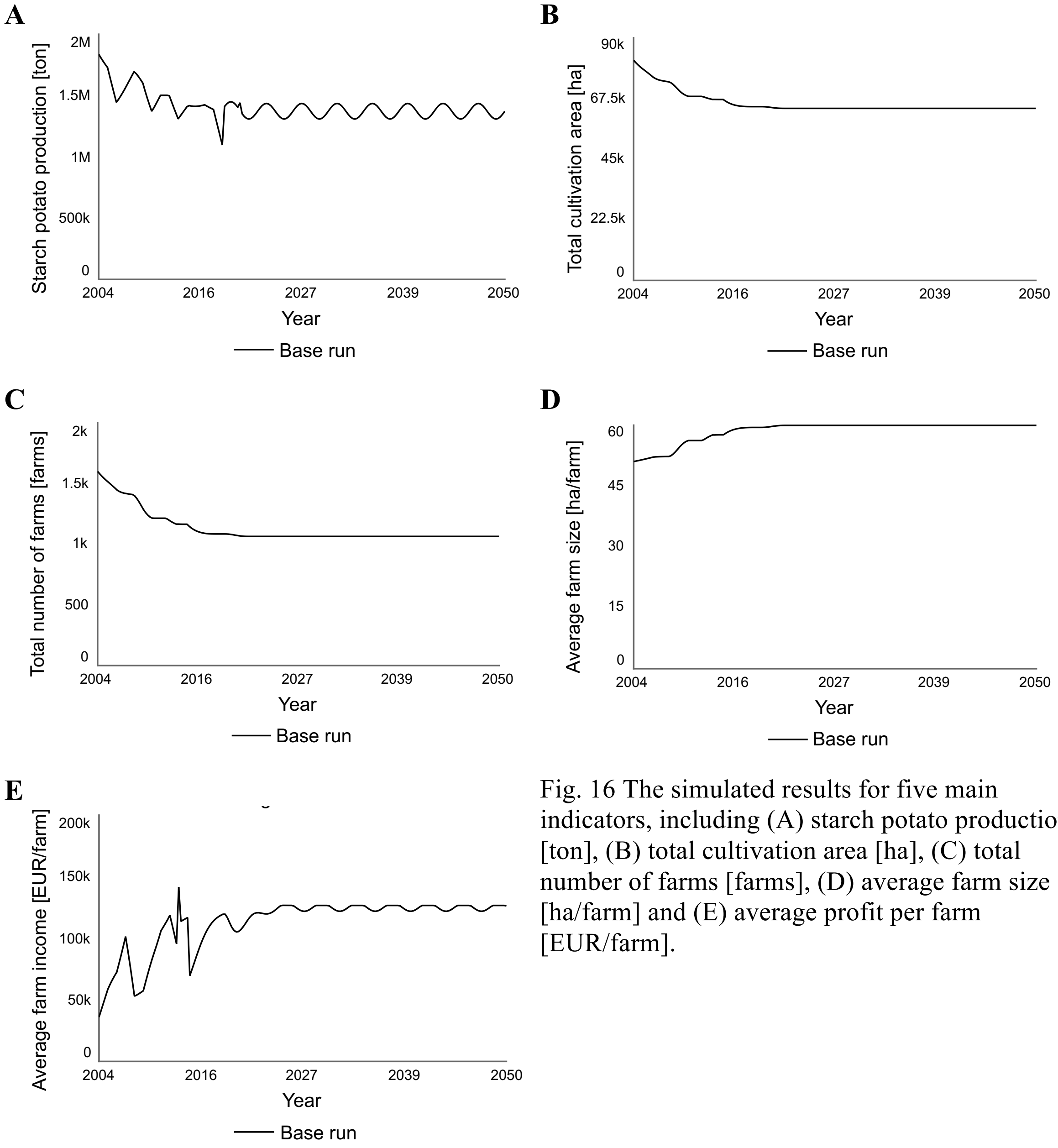

Fig. 16 The simulated results for five main indicators, including (A) starch potato production [ton], (B) total cultivation area [ha], (C) total number of farms [farms], (D) average farm size [ha/farm] and (E) average profit per farm [EUR/farm].

The model behaviour before 2020 can be explained as follows: Before 2020 the profits of other arable farms were on average larger than the profits of starch potato farms. This profit discrepancy is larger the smaller the starch potato farm. Small farms therefore reacted stronger, and either scaled up (stayed in the system), stopped farming, or switched to cultivating other crops (left the system).

As there was not enough area available for all farms to scale up the total number of farms decreased rather than staying constant (Fig. 16 C). The average farm size is increased because the largest decrease is occurring in the small farm stock (Fig. 16 D). This makes the size of larger farms relatively more important in the weighted average calculation. The same reasoning explains the increasing long-term trend of average income per farm (Fig. 16 E). The long-term trends observed for starch potato production are the same as those observed for total cultivation area (Fig. 16 A, B). The short-term trends of starch potato production are the result of fluctuating yields, which are exogenous in the model.

After 2020 the model is run with constant parameter values in the base run. This results in the equilibrium that is observed. This equilibrium is maintained as the profits of starch potato farms are now at least as good or larger than the profits of other arable farms. In other words, Avebe's net profits are high enough to provide a starch potato price that results in this equilibrium. It is important to keep in mind, that in the base run past trends of exogenous inputs (e.g. costs, prices, yields) are not extrapolated into the future. This means that the base run should not be interpreted as a business as usual scenario, to predict what will happen in the future. Instead, the base run serves as a "negative control". In other words, the equilibrium of the base run is compared to simulations with challenges and strategies that disrupt/restore this equilibrium.

3.3.2 Challenges

Single challenge simulation results

The model is very sensitive to all challenges (Table 4). In other words, starch potato production declined by more than 20% (from the 2020 value in 2050) when challenge parameters were changed by less than 20%. The model is slightly more sensitive to environmental challenges affecting starch potato production (C1, C2) in comparison to economic challenges affecting profits (C4, C5). For environmental challenges (C1, C2), if the fraction of starch potato in the cultivation plan decreases by just 5.5%, from 0.5 to 0.4725, or average starch potato yields decrease by just 3.5%, from 43 ton/ha to 41.5%, starch potato production declines. For economic challenges (C4, C5), profits of other arable farms or costs of starch potato farms need to increase by 11.5% or 8.5%, respectively, to cause a decline.

Table 4 The relative change in parameter values representing challenges, above which the simulated total starch potato production declined by more than 20% from the 2020 value in 2050.

Challenge	C1	C2	C4	C5
Model parameter that is changed in each challenge	Fraction of starch potato in cultivation plan	Average yield	Profit per ha other small/medium/large arable farms	Costs per ha small/medium/large farms
Base run value of model parameter	0.5	43 ton/ha	1630 / 1860 / 1900 EUR/ha	2410 / 2120 / 1970 EUR/ha
Relative change in base run value that caused starch potato production to decline by more than 20%	- 5.5 %	- 3.5 %	+ 11.5 %	+ 8.5 %

The system can cope with starch potato yield reductions below 3.5% in the long term (at least for 30 years) (Table 4 C2). Further simulation analyses show that the larger the yield reduction the lower the number of years the system can cope (Fig. 17 C3).

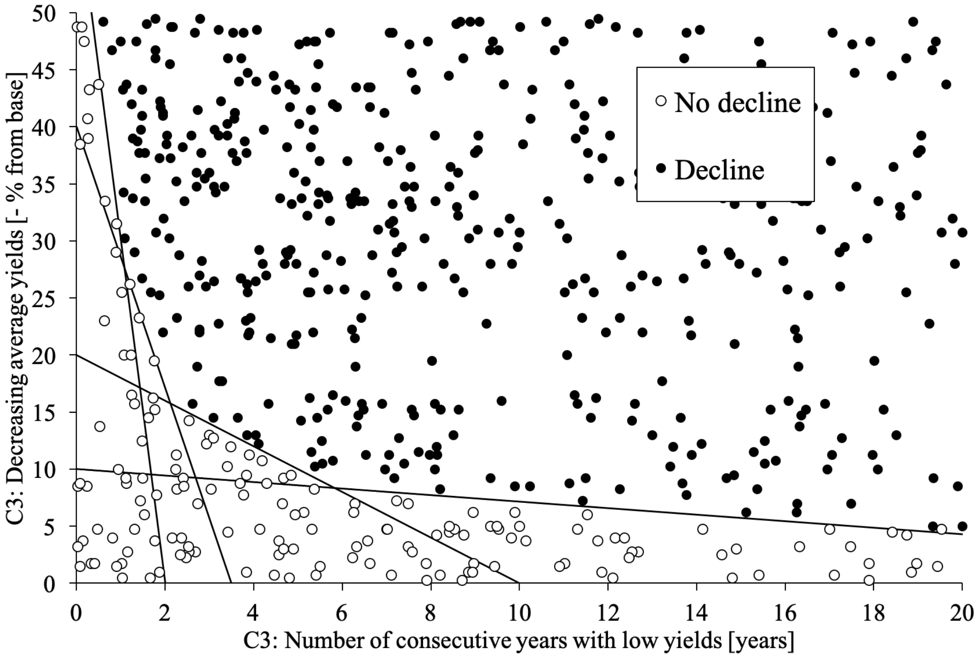

Fig. 17 A safe operating space showing different combinations of decreasing the average yield of starch potato (- % from the average yield base value of 43 ton/ha) and the number of consecutive years of each respective yield, that did or did not cause starch potato production to decline by more than 20% in 2050. Each point represents one simulation.

The simulated relationship between the number of years the system could cope and the decrease of average yields is not linear. In other words, the number of years the system can cope decreases more rapidly the larger the decrease of the average starch potato yields. To illustrate, yield reductions of up to 5% can be withstood for at least 20 years, yield reductions of 10% only for 5 years, and yield reductions of over 20% for less than 1 year. The latter situation is shown in Fig. 18.

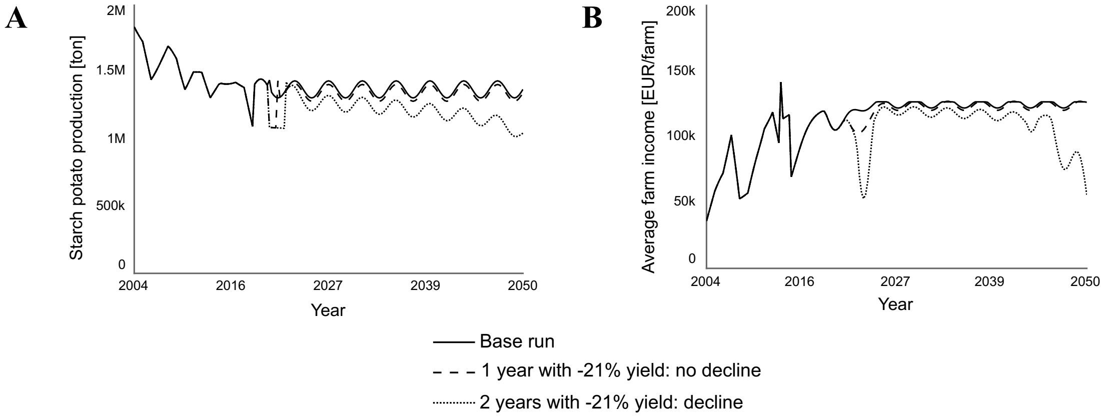

Fig. 18 Model simulations for (A) starch potato production and (B) average farm income, with either 1 (full line) or 2 (dotted line) consecutive years at an average starch potato yield of 34 ton/ha (21% lower than the average yield base value). The simulation with 2 years results in a decline of starch potato production of more than 20% in 2050.

A 21% decrease of the average starch potato yield, means that simulated average starch potato yields are equal to 34 tons/ha. This was the recorded average starch potato yield in 2018, as an extreme drought in the summer significantly reduced the starch potato harvest in the Veenkoloniën (CBS, 2019; Paas et al., 2019). According to the simulation, such a large yield reduction cannot be withstood for even two consecutive years (Fig. 18 A). Interestingly, even with two consecutive years the average farm income seems to recover to almost the same level as the base run within ~5 years (Fig. 18 B). Farm income then starts to decrease again significantly after the year 2040. This occurs as Avebe's reserves are eroded slowly. The decline occurs when Avebe's average net profits of the past 3 years are eventually too low to keep paying an adequate starch potato price.

Multiple challenge simulation results

Different environmental (C1 and C2) and economic (C4) challenges were simulated together to determine their combined threshold values that will cause starch potato production to decline by more than 20% from the 2020 value in 2050 (
Fig. *19*).

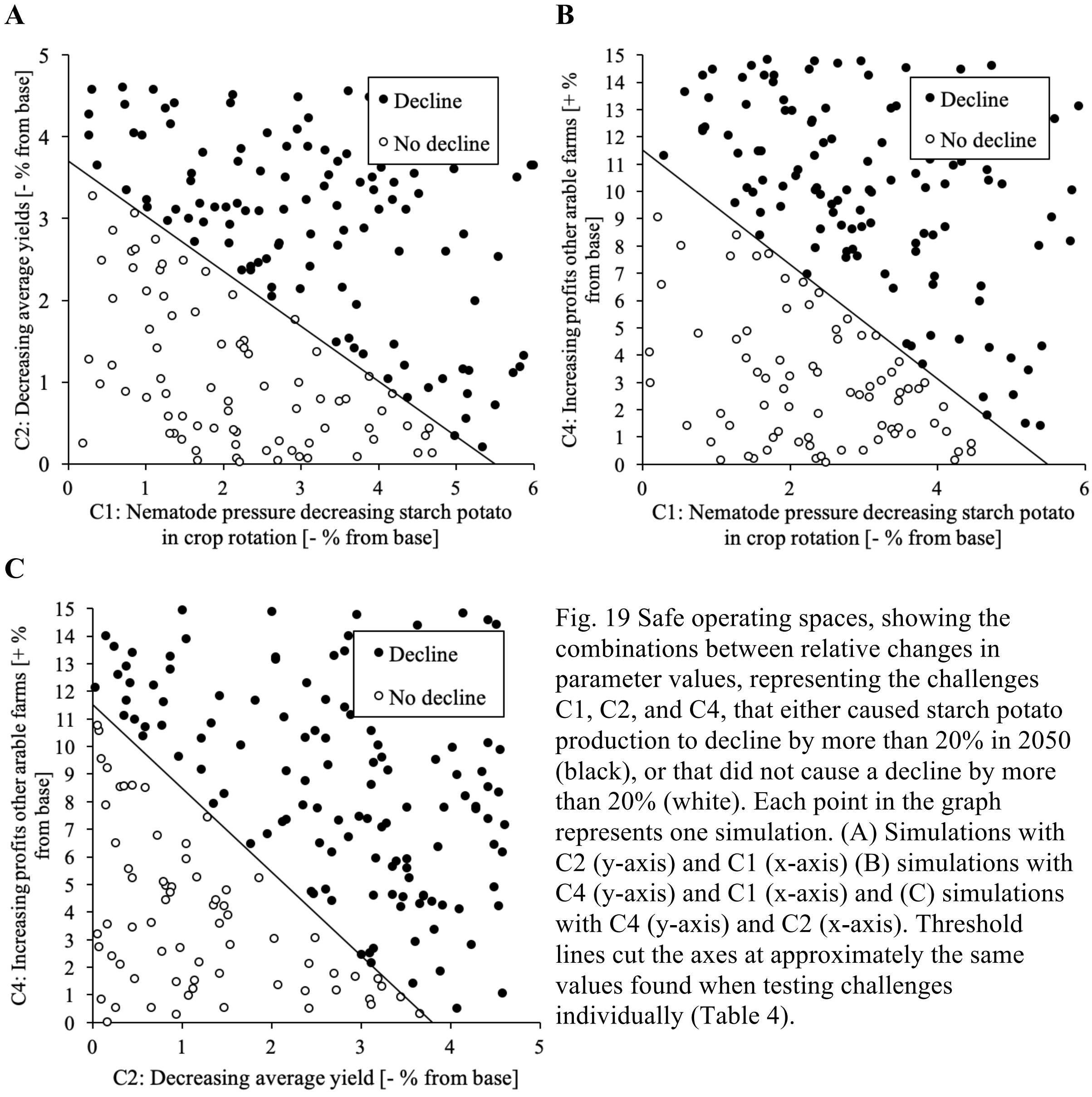

Fig. 19 Safe operating spaces, showing the combinations between relative changes in parameter values, representing the challenges C1, C2, and C4, that either caused starch potato production to decline by more than 20% in 2050 (black), or that did not cause a decline by more than 20% (white). Each point in the graph represents one simulation. (A) Simulations with C2 (y-axis) and C1 (x-axis) (B) simulations with C4 (y-axis) and C1 (x-axis) and (C) simulations with C4 (y-axis) and C2 (x-axis). Threshold lines cut the axes at approximately the same values found when testing challenges individually (Table 4).

The safe operating spaces for all challenge combinations are represented by a single linear threshold line (Fig. 19). This line cuts the axes approximately at the threshold values determined for each individual challenge (Table 4). All combinations to the left of the threshold line caused no system decline (starch potato production declined by less than 20%) and all combinations to the right of the threshold line caused a decline (starch potato production declined by more than 20%). This result indicates that there are no non-linear interacting effects between challenges.

3.3.3 Strategies

The environmental challenges C1 (nematode pressure decreasing starch potato in crop rotation) and C2 (long-term decrease in average yields) were the most difficult challenges to counteract with S1 (increasing starch content) or S3 (increasing Avebe product value) (Fig. 20, rows 1-2). A decrease of starch potato in the crop rotation by over 40%, or a decrease of the average yields by more than 30%, always resulted in a system decline, regardless of the degree of S1 or S3. However, S3 was slightly more effective than S1 for both challenges.

S1 and S3 had very similar effects on all challenges, except for challenge C5 (increasing costs of starch potato farms) (Fig. 20, row 4). Increasing starch content by around 25% was able to stop a system decline for all tested values of C5. However, increasing the costs of starch potato farms by more than 20% led to a system decline, regardless of whether Avebe increased its product value any further than 10%.

A similar result, yet less prominent, was found when comparing the effects of S1 and S3 on C4 (increasing profits of other arable farms) (Fig. 20, row 3). When profits of other arable farms increased by more than 45%, an increase beyond 15% of Avebe’s product value had little strength to stop a system decline. On the other hand, increasing the starch content by more than 10% was able to stop a system decline for all tested values of C4.

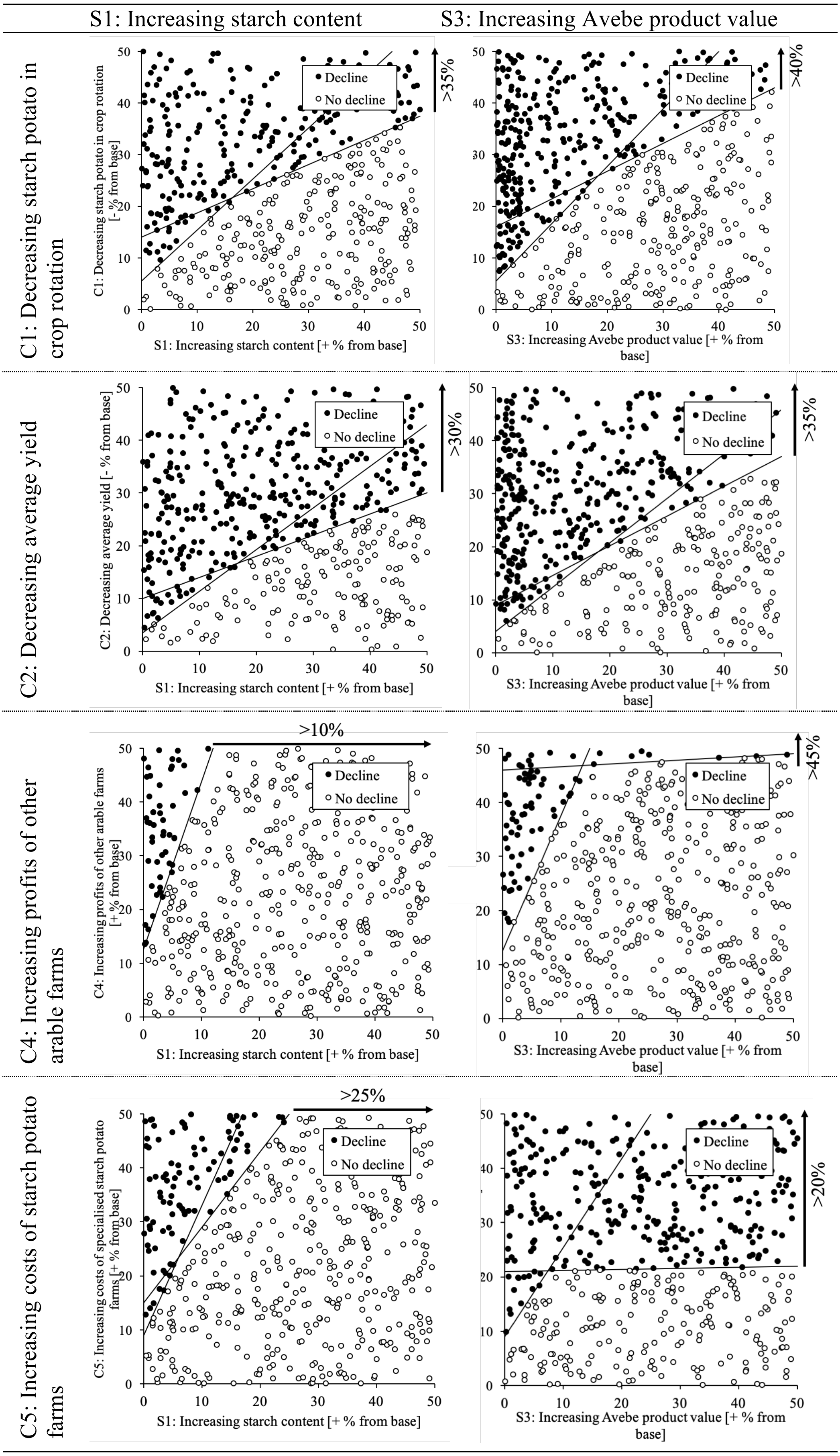

Fig. 20 The safe operating spaces of strategies (S1, S3) in combination with different challenges (C1, C2, C4, C5). A threshold line shows the minimum relative change of a strategy parameter that is required to prevent a system decline, given a relative change of a challenge parameter. A system decline occurs when starch potato production decreases by more than 20% from the 2020 value in 2050. Each point represents one simulation.

S2 (increasing average yield by means of decreasing yield variability) could only be tested for a change of average yields by up to 4.6% (explanation in Fig. 7). Given this constraint and according to simulations, this maximum level of S2 cannot prevent a system decline if starch potato in the crop rotation (C1) or average yields decrease (C2) by more than 10% or 8%, respectively (Fig. 21 A, B). Likewise, S2 cannot prevent a system decline if the profits of other arable farms (C4) or the costs of starch potato farms (C5) increase by more than 25% or 20%, respectively (Fig. 21 C, D).

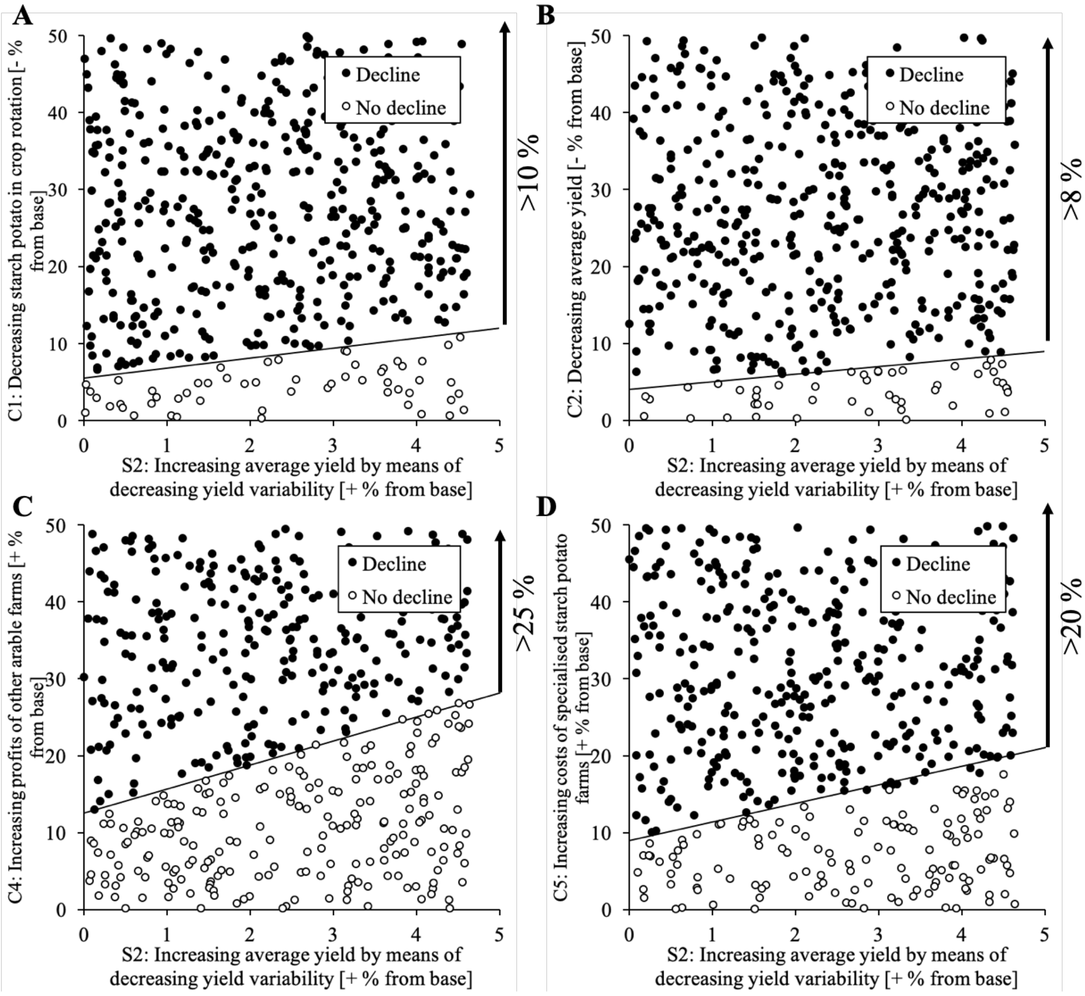

Fig. 21 S2 (increasing average yield by means of decreasing yield variability) in combination with different challenges, including (A) C1 (decreasing starch potato in crop rotation), (B) C2 (decreasing long-term average yields), (C) C4 (increasing profits of other arable farms) and (D) C5 (Increasing costs of starch potato farms). Each point represents one simulation. A threshold line shows the minimum relative change of a strategy parameter that is required to prevent a system decline given a relative change of a challenge parameter. A system decline occurs when starch potato production decreases by more than 20% from the 2020 value in 2050.

S2 is just as effective as S1 or S3 in preventing a system decline below a relative increase of 4.6%. This is shown by the slopes of the threshold lines in Fig. 20 (looking only until +4.6% on x-axis) and Fig. 21. The slopes of the threshold lines are similar between all strategies for all challenges (slope values in Appendix H, Table H.1). In other words, the same relative increase of all strategy parameters (below 4.6%) has the same strength to counteract the effects of each challenge.

Only S1 and S3 were effective to prevent a system decline if average yields decreased by 21% for over 2 years (Fig. 22). S3 was slightly more effective than S1. An increase of only 15% in Avebe product value could prevent a system decline if the low starch potato yields were experienced for 10 consecutive years, whereas an increase of 20% in the starch content was required in the same yield scenario.

S1: Increasing starch content

S2: Increasing average yield by means of decreasing yield variability

S3: Increasing Avebe product value

C3: Decreasing average yield by 21% for a number of consecutive years

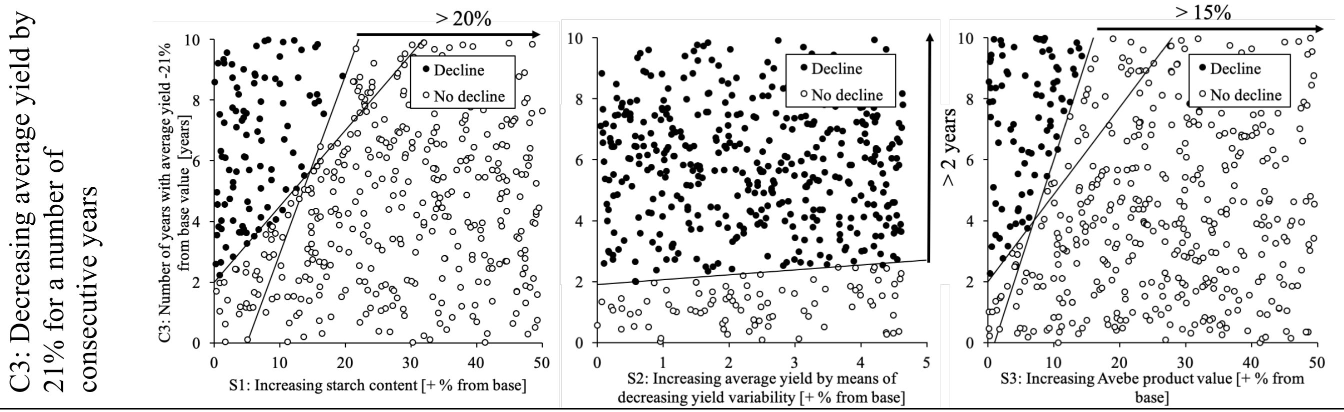

Fig. 22 The safe zones of operation for the three strategies (S1, S2, S3) in combination with C3. A threshold line shows the minimum relative change of a strategy parameter that is required to prevent a system decline given a relative change of a challenge parameter. A system decline occurs when starch potato production decreases by more than 20% from the 2020 value in 2050. Each point represents one simulation

Chapter 4: Discussion

This study used a system dynamics approach, to analyse the resilience of an arable farming system in the Veenkoloniën. In iterative modelling cycles, this study addressed six research questions and three objectives in parallel (Fig. 4). A conceptual model, a formal model and a simulation analysis resulted from this procedure. The results shed insights into the dynamics of the system, and what these mean for the resilience of the Veenkoloniën farming system, and farming systems in general.

4.1 Assessing robustness in the Veenkoloniën

Two player dynamics

The conceptual model and formal model helped to reflect on the trends of system indicators observed in the Veenkoloniën in the past. The starting point of this study was the identified, yet unquantified, co-evolution between these trends. The most important indicator used in this study, starch potato production, has been steady for 20 years. When looking at this indicator alone, the system seems to be "unchanging". However, in the same time period, the number of starch potato farms has drastically decreased and average farm size has increased. This indicates that the farming system is in fact changing.

A literature study showed that the structure of the farming system is one of the most important explanatory factors for the trends that were observed. Specifically, a central structure in Veenkoloniën farming system is that all starch potato farmers are organised and are collaborating with the cooperative Avebe. There is an interdependence between these two players. Avebe depends on a steady supply of starch potatoes, and farmers depend on the extra starch potato price benefit they receive from Avebe's revenues. Therefore, the goal of both players is to maintain their relationship with each other. However, the goal of Avebe is not to keep the same number of members, but to maintain their members' combined cultivation area (which is the main determinant of the total supply of starch potatoes they receive).

The causal loop diagram and a system dynamics model, made in this study, can explain how the actions of both players have resulted in the unchanging level of starch potato production in the Veenkoloniën in the past. The main component of both models is a reinforcing loop that captures the relationship between Avebe and farmers, called R1 "Cooperative benefit" (Fig. 8, Fig. 12). This reinforcing loop can either act as a virtuous cycle that keeps the system stable, or a vicious cycle that causes a system decline. A virtuous cycle is caused by a positive increase in any of the loop variables, which causes the other loop variables to increase and so on. R1 can act as a vicious cycle if any loop variable experiences a large negative change, causing an exponential decline of all variables. Avebe has identified that the profitability of starch potato cultivation is the main turning point in this system. By setting the starch potato price high enough, Avebe can make sure R1 "Cooperative benefit" is a virtuous cycle.

If R1 "Cooperative benefit" acts as a virtuous cycle, starch potato production will be maintained in equilibrium, and is not growing exponentially. This is because the production of starch potato is constrained, and is running at a maximum capacity. In the model, the main constraint is the limited area that is available. In reality, Avebe limits the maximum starch potato supply by offering a limited amount of shares (van Dijk et al., 2019). However, the two constraint concepts are interchangeable. The shares owned by farmers directly determine the maximum starch potato cultivation area they can use. The situation that was observed between 2000 and 2018, indicates that R1 "Cooperative benefit" was acting as a virtuous cycle (or was only minimally vicious). In this time period, many small farms ceased to exist, but their area was taken up by expanding larger farms. Thus, the current farming system seems to operate at a maximum capacity with regards to starch potato production. This production level will be maintained as long as R1 “Cooperative benefit” acts as a virtuous cycle.

A challenging future

Several challenges are influencing the direction of R1 “Cooperative benefit”. Namely, this study analysed environmental and economic challenges that can shift the loop direction of R1 “Cooperative benefit” from a virtuous to a vicious cycle (challenges labelled C in Fig. 8). The more severe the challenges the more vicious the cycle becomes, i.e. the quicker the decline. The model is more sensitive to the environmental challenges (C1, C2) than to the economic challenges (C4, C5) (Table 4). This is because the impact on Avebe is higher. When e.g. starch potato yield is low (C2), Avebe’s net profits are low, and their ability to pay a higher price is diminished. However, according to the model, Avebe will still have to pay a higher price to compensate for the low yields. When e.g. costs of starch potato farms are high (C5), Avebe will also compensate by paying a higher price. However, in this case their net profits are initially higher, because the starch potato supply is adequate. Avebe’s ability to pay a higher price is thus higher initially and is more durable, i.e. the ability to pay a higher price is maintained for a longer time.

The tipping points identified in this study partly correspond to predictions by Veenkoloniën stakeholders, including farmers and other system actors, interviewed in participatory workshops by Paas et al. (2020). For instance, stakeholders predict that nematode pressure should not increase to the point where a 1:2 rotation of starch potatoes is no longer feasible (Paas et al., 2020). This means that most farmers will need to continue to cultivate starch potatoes every two years (average fraction starch potato = 50%). This corresponds to the threshold of C1 identified in this study, which confirms that the average fraction of starch potato will need to stay above 44.5% (Table 4). Stakeholders also determined that the minimum starch potato yields should be above 38 ton/ha (Paas et al., 2020). Assuming that the maximum yield in this scenario remains 45 ton/ha, the average yield would be 41.5 ton/ha. This corresponds to the same threshold determined in this study: a 3.5% decrease from the average yield (43 ton/ha in the base run) (Table 4; C2). Lastly, stakeholders predict that the system will decline, when extreme weather events significantly decrease starch potato yields for 3-4 years in a row, however, the degree of yield decrease was not mentioned (Paas et al., 2020). According to model simulations, the system will decline if average yields fall by 12 – 15% for 3-4 years (Fig. 17). If average yields decline by over 21% (as during the 2018 summer drought), the system will decline if this yield level is experienced for just 2 years in a row (Fig. 18).

Fighting back disturbance

Model simulations showed that thresholds of the different challenges can be modified by different strategies (Fig. 20, Fig. 21, Fig. 22). In other words, the strategies decrease the degree to which the challenges can turn R1 “Cooperative benefit” into a vicious loop (Fig. 8). The mode of action of the strategies is to increase starch potato production (S2), starch production (S1) or Avebe net profit (S3) directly (Fig. 11).

The effectiveness of each strategy was found to depend on the nature of the challenge and the nature of the strategy. One result seems counter intuitive at first. According to model simulations, a strategy that directly influences crop productivity (S1) is more effective against economic challenges (C4 and C5), while a strategy that directly influences economic return (S3) is slightly more effective against crop productivity (= environmental) challenges (C1 and C2) (Fig. 20). This may be explained by the pricing calculation and delays in the model. Avebe adjusts the starch potato price depending on starch content. When varieties with higher starch content (S1) are used, farmers receive a higher starch potato price. Economic challenges instantly decrease the profitability of starch potato farms, but the price calculation also instantly takes into account the higher starch content. Therefore, the price offered to farmers is higher in S1 than in S3 (where Avebe's product value is increased). Due to the higher price offer, less farmers, and ultimately less cultivation area, is lost when S1 is implemented along with large degrees of C4 or C5. However, this also means that S1 puts more pressure on Avebe to pay a higher price. Therefore, S1 slightly diminishes the ability of Avebe to absorb the impact of environmental challenges (C1 and C2) in comparison to S3. In the case of C1 and C2, it is more important to increase Avebe's revenues directly, in order to have a buffer for the decreased starch potato supply. Overall, this shows that no single strategy is effective against all challenges, and that staying robust requires different types of strategies with different modes of action.

The effectiveness of three strategies also needs to be discussed in terms of feasibility. This is because the ability to implement the three strategies depends on many factors outside of the control of the system actors. Improving starch potato varieties through plant breeding depends on future developments in plant breeding policies in the EU (Callaway, 2018). Plant breeding could potentially become faster and cheaper, but the current GMO directive is a strong barrier for applications of new plant breeding techniques (Callaway, 2018). If legislations change, sustainable intensification through plant breeding could become one of the main strategies to maintain the level of starch potato production in the Veenkoloniën. Nevertheless, biological limits may be reached in starch content and other plant characteristics. Therefore, plant breeding strategies may not be able to keep up with the increasing frequency, and severity, of environmental challenges. Furthermore, the ability of Avebe to increase their product value depends on the developments in the starch market, and the activities of Avebe's competitors (Emmann et al., 2012). Until now, Avebe has managed to stay ahead of competition, but this may change in the future.

The willingness of Avebe to implement the strategies also needs to be taken into account. The model assumes that Avebe is only receiving starch potatoes from the Veenkoloniën region, but in reality about 40% of shares are held by members in other parts of the Netherlands and Germany. Avebe may decide to gradually move away from the Veenkoloniën, if the Veenkoloniën region becomes more unsuitable for starch potato production in the future relative to these other areas. This would mean that Avebe may not be willing to spend heavily on innovation, in order to prevent a decline of starch potato production in the Veenkoloniën region alone.

Overall, this study can conclude that given the ability *and* willingness to implement strategies, Avebe is able to absorb most of the impact of environmental and economic challenges, leaving farmers less exposed to disturbance. This relationship between farmers and Avebe provides income stability to farmers and improves farm succession rates. Only if this relationship is maintained, will the supply of starch potatoes from the region remain stable.

Symptoms of a rigidity or lock-in trap

One hypothesis that results from applying the findings of this study (the lack of change and the high level of connectivity between system actors) to other studies of resilience, is that the Veenkoloniën farming system may have fallen into a rigidity or lock-in trap (Allison and Hobbs, 2004; Holling et al., 2002). Rigidity traps occur in agro-industries were management is focused on controlling fluctuations, in order to achieve stable economic targets, and where profits within the agro-industry are reinforcing one another (Allison and Hobbs, 2004; Holling et al., 2002). In a lock-in trap, the agricultural system is under pressure to produce more, while at the same time the economic return from the land is decreased due to depletion of natural resources (Allison and Hobbs, 2004). The rigidity and robustness in such systems is increased, as system actors become more and more dependent on each other (Allison and Hobbs, 2004). The economic system is strengthened, but decoupled from the ecological system on which it depends (Naylor, 2009; Robertson and Swinton, 2005). This has consequences for the system's adaptive and transformative capacities. If this is the case, the Veenkoloniën region is at risk that the continued effort to maintain the high level of starch potato production will erode natural resources and decrease biodiversity.

Understanding these phenomena, and identifying them in farming systems like the Veenkoloniën, is the first step to making systemic changes that can help a trapped system. In the Veenkoloniën, systemic changes might include decreasing the dependence of farmers on Avebe and vice versa. For instance, specialised starch potato farms could diversify and add crops to their rotation that do not fall under a contract with a cooperative (Paas et al., 2019, 2020). Avebe could either expand their member pool in further regions, or turn to other sources of starch and protein in the future.

4.2 Model limitations and suggestions for improvement

A model is a simplification of reality, which can be used to study important factors separately. This study showed that it was useful to isolate profitability, as an explanatory factor, from other drivers of change. Model simulations between 2000 and 2018 show that using profitability of starch potato farms as the main driver is enough to explain the trends that were observed (Fig. 15). Nevertheless, the model could be expanded to include more drivers, by adding components and more feedback loops. This may further improve confidence in the model results, by addressing uncertainty in model structure, model equations and the resilience assessment.

Uncertainty in model structure

The model structure could be further improved by adding missing links and feedback between components that are already included in the model, or by adding new components. Adding missing links between old and new components will make the model more endogenously driven. For example, there is a negative feedback between the frequency of starch potato in the crop rotation and starch potato yield. This is caused by an increase of nematode pressure and a decrease of soil quality (see Appendix C, Fig. C.1, CLD adapted from Paas et al. (2020)). Furthermore, a positive relationship exists between costs and yields, because costs are determined by inputs that increase yields (e.g. irrigation; Fig. C.1). Moreover, the choice of crop rotation will depend on the profits and yields of the various crops, as well as the individual crop constraints for maximum fraction in the rotation.

A larger change to the model would be to analyse and include further trends that are observed in the Veenkoloniën, in order to control for their confounding effects. An important trend, that was not included, is the increase of the average age of farmers, which is caused by a decrease in farm succession rate (Asjes and Munneke, 2007; Bijttebier et al., 2018; Paas et al., 2019). Especially small family farms are not finding successors (Asjes and Munneke, 2007; Bont and Everdingen, 2010). There may be an interaction between the aging farmer trend and the trends included in this study. For instance, it could be that the maintained starch potato production is a result of farmers who are "too old to change". Thus, a large decrease in starch potato production may occur, if there is a sudden generation shift in the future where many farms do not find successors in a short period of time. The age of the farmer also determines the minimum income that the farmer wants to receive, which drives the farmer's choice to keep farming or to choose a different occupation (Breustedt and Glauben, 2007). A possible adjustment to the model could be to make minimum required income, and its effect on average turnover rate, endogenous, as a function of average farmer age and average income in the Netherlands (see proposed CLD in Appendix C, Fig C.1).

Uncertainty in model equations

To a large extent, the model simulations for various indicators showed behaviour that resembles historical trends between 2004 and 2013 (Fig. 15 E). For all indicators except farm income, the MAE/mean was below 10%, suggesting a reasonable fit between simulated and historical data (Table 3). However, farm income showed a high contribution of bias to the already large MSE/mean. This indicates a large systematic error, caused by errors in parameter estimates (Sterman, 2000). Farm income is a variable that is pivotal to the behaviour of the simulated farms in the model. Errors in this variable may therefore influence the outcome of the resilience analysis. Future model developments should include a re-parameterisation of variables needed to calculate farm income.

The error in simulated farm size is mostly explained by unequal variation, suggesting differences in long-term trends (Table 3). According to the data, the average farm size increased more quickly than the simulated values (Fig. 15 D). This discrepancy could be the result of including only three farm sizes, and limiting the maximum farm size to 130 ha/farm cultivated area. In future work on the model, exogenous inputs for e.g. costs of inputs and yield could be made endogenous, so that all necessary values can be generated for any farm size.

Uncertainty in resilience assessment

The simulation analysis was focused on determining the robustness, rather than the adaptability or transformability of the farming system. However, certain model simplifications could lead to an over- or underestimation of the level of robustness. These simplifications include the dependence of Avebe on the Veenkoloniën and vice versa.

The dependence of Avebe on the Veenkoloniën was overestimated. In reality, 40% of Avebe's members are from other regions in the Netherlands and northern Germany (Klok, 2019). It can be argued, that this assumption could both overestimate *or* underestimate the simulated level of robustness (of starch potato production) in the Veenkoloniën. An overestimation of robustness may result, as the current decision rules imply that Avebe will always try to satisfy the price requirement of its members from the Veenkoloniën. This decision does not change, even if e.g. starch potato yields in the region have dropped significantly. In reality, in this scenario Avebe may gradually move its member pool to more viable regions, that do not suffer from such low yields. Another possibility is that Avebe would close down some production branches and focus on only the members that still have adequate yields (Bont et al. 2007). An underestimation of robustness may result, if e.g. Avebe still receives adequate supply from other regions, and is able to maintain at least 40% of its net profits at their normal level. Avebe's member diversity could compensate for lower net profits from one region if net profits in another region are adequate. In other words, Avebe's ability to offer adequate prices is buffered by member diversity.

The dependence of the Veenkoloniën farmers on Avebe is also overestimated. The model assumes that starch potato farms will only sell their starch potatoes to Avebe. In reality, members are free to sell some starch potatoes to other buyers (Reindsen, 2019). This model assumption is likely to overestimate the level of robustness in the region. A number of consecutive low starch potato price offers from Avebe may result in decreased loyalty to the cooperative. Members will gradually sell their shares, and sell a proportion of their starch potatoes elsewhere, provided that elsewhere the prices are maintained. This may accelerate the decline of Avebe, as less members are now supporting Avebe and the remaining members will suffer from even lower price offers.

This list of "uncertainties" of the assessment of robustness gives further insights into the decisions of system actors that may influence the resilience of the Veenkoloniën farming system. This insight provides an opportunity for future studies to test further strategies. System dynamics lends itself well to study changes to decision rules, which often represent more effective leverage points in a system (Meadows, 1999). Future studies could thus unveil important leverage points that have not been considered in this study.

4.3 Resilience of farming systems in Europe

So what can we learn about the resilience of farming systems, from a modelling exercise focused on one very specific case in the Veenkoloniën? A large diversity of farming systems exists in Europe that may differ significantly from the studied system. The drivers, and the responses of the system actors, that were identified in this study, may not apply directly to e.g. organic farming systems in Europe. However, many factors influence all types of farming systems, including climate change, changes to legislation, developments in the world market, and technological improvements. Europe is a small and tight-knit continent, and in a broad sense European farming systems share one social-environmental context.

The results of this study show that the Veenkoloniën farming system is operating very close to the thresholds of various challenges (Table 4). It is likely that many farming systems across Europe are faced with a similar situation, because they are influenced by the same climate, economic and policy changes. The pressure to stay below thresholds is therefore common to all. This is challenging in an uncertain future. Already one single extreme event can alter the structure of the farming system (Fig. 17). Interestingly, simulations showed that the observed change can occur many years after the event that triggered this change (Fig. 18). A system may recover from a shock in the short term, but the effects of the shock (or the intervention that was used) may continue to alter the system slowly, through reinforcing loops that only become evident much later. In the case of this study, this effect occurred as Avebe's reserves were eroded, and their buffer capacity reduced slowly over time. This could be applied to other slow moving variables that represent buffer capacities, such as the ecological buffering capacity of the soil (Bowman et al., 2008). The phenomenon, that resilience in the short term reduces resilience in the long term, is described in other studies of resilience (Allison and Hobbs, 2004; Carpenter et al., 2001; van Apeldoorn et al., 2011). This has implications for other farming systems, where system actors are focused on managing the fast-changing variables, while neglecting the variables that change slowly in the short term, but have significant impacts in the long term.

This study showed that long-term planning is also possible by observing short-term trends. In all simulations of challenges, the effects increased over time (Fig. 6). This results from the dominant reinforcing loop R1 "Cooperative benefit". The thresholds identified in this study are defined by van Nes et al. (2016) as the type of tipping points, where changing external conditions erode the resilience of the current state until a bifurcation is reached, that results in a so-called critical transition. However, these critical transitions can be anticipated (Scheffer et al., 2009). In this study, a downward trend of starch potato production was already visible in the short term for all challenges. Such short-term diagnostics can be used to identify similar vicious cycles in other farming systems. This may help to anticipate a sudden change of the system of interest in the future. Armed with this knowledge, system actors can adequately prepare for or prevent a change.

One of the main findings of this study, is that the structure of the Veenkoloniën farming system has prevented change in the past. The collaboration of farmers with Avebe helped to stabilise the system, because farmers were less exposed to disturbance. The same thinking can be applied to other farming systems in Europe. Farmers, as single actors, cannot control all of the factors that pose challenges to their livelihoods, especially when there is little ecological buffering capacity (Folke et al., 2003). In this situation, collaboration with industry and with policy makers is required, in order to protect farmers from the full impact of challenges. An important tool for this type of system management are technological improvements, such as the plant breeding strategies employed by Avebe. In fact, the yield gaps of several other crops grown in the Netherlands may be closed with technological and efficiency improvements (Silva et al., 2017). However, such innovation strategies may also reinforce unsustainable development pathways (Westley et al., 2011). This occurs if innovation strategies focus on treating single system variables, without considering the impacts on other (particularly slow-moving) variables (Westley et al., 2011). This may lead to continued depletion of natural resources, and rigidity or lock-in traps (Allison and Hobbs, 2004; Boonstra and de Boer, 2014). The high dependence on (and intervention in) one feedback loop, as exemplified by this Veenkoloniën case study, may be used as a diagnostic tool to identify such traps in other farming systems.

In “trapped” systems, change could be recognised as an opportunity. A balance between stopping unwanted change and allowing desirable change is needed. This study focused largely on robustness, and the efforts of farmers and Avebe to prevent a change of the system. This is because system actors fear that a decline of starch potato production will lead to a less desirable system (Paas et al., 2020). However, these efforts may have trade-offs with the capacity of the system to adapt or transform (Paas et al., 2019), and alternative systems may be more sustainable (Paas et al., 2020). The current system is not providing adequate levels of other system functions, such as the maintenance of natural resources and the attractiveness of the area (Paas et al., 2019). Less dependence on starch potato could improve the ability of the system to provide these other functions. For instance, a decline of agriculture, and a shift to other sources of income, may lead to an increased maintenance of natural resources and biodiversity. In the long run, this may improve the attractiveness of the area for residents and increase work opportunities in more lucrative industries. This thinking should be applied to all regions in Europe, with a high degree of dependence on agriculture, that is combined with a relatively low economic performance.

Chapter 5: Conclusions

This study has demonstrated the usefulness of a system dynamics approach to improve our understanding of how challenges and strategies affect the Veenkoloniën farming system. Model simulations showed that the past behaviour can be explained by one main driver, the profitability of starch potato cultivation. Simulations also showed that the farming system is operating close to many challenge thresholds. A change beyond 3.5% - 11.5% of various environmental or economic challenges resulted in a system decline, a situation in which the system will need to change. The system is especially close to environmental challenge thresholds, including nematode pressure, and declining soil quality or extreme weather events that are reducing starch potato yields. An analysis of strategies revealed that challenge thresholds can be modified, depending on the nature of the challenge and the nature of the strategy. Different strategies are needed to be robust against diverse challenges. However, the safe operating spaces identified for the challenge-strategy combinations are in some cases relatively narrow.

Overall, the results of this study indicate that the Veenkoloniën starch potato farming system will continue to be robust, only as long as the current structure of the system is able absorb environmental and economic shocks. In this situation, starch potato farms in the region are less exposed to disturbance because of the buffering capacity of the agro-industrial cooperation Avebe. However, the profit-driven nature of this relationship may indicate that the Veenkoloniën has fallen into a rigidity or lock-in trap. This phenomenon might reduce the capacity of the system to adapt or transform. Therefore, the current and future resilience of the Veenkoloniën farming system are at risk.

The results of this particular case study also revealed learning opportunities for studying the resilience of farming systems in general. The presence of reinforcing feedback loops in farming systems means that small short-term changes can help to anticipate a significant and sudden change in the level of system functions in the long term. When strategies are mainly focused on strengthening one main reinforcing loop, with a profit-driven goal, this may lead to high levels of robustness, at the expense of adaptability or transformability. Strategies with the goal to achieve quick effects, without taking into account the consequences for slow-reacting system components, should be scrutinised. These strategies may work in the short term but they may strengthen unsustainable future trajectories and ultimately lead to a worse off system.

In light of climate change, globalisation and the rising demand for food, decision makers will need to make many choices in the future, in order to improve the resilience and sustainability of farming systems. Knowledge of system structure – the links between system components and the presence of feedback loops – should be taken into account by these decision makers. Farming systems are complex social-ecological systems, and insights from system dynamics can help to successfully navigate these systems through a changing world.

Chapter 6: Recommendations for further research

Future research about the resilience of the Veenkoloniën farming system can either build on the model and resilience-assessment approach adopted in this study, or use the model but adopt another approach. The resilience-assessment approach that was used in this study, was to quantify the proximity to challenge thresholds (with and without strategies) as a proxy for robustness. This provided insight into the safe-operating-spaces, but it did not account for the likelihood that thresholds will be crossed in the future. Another approach would be to use the designed future scenarios of other studies (e.g. the Shared Socioeconomic Pathways proposed by Mitter et al. (2019) for agricultural systems in Europe) and test the path-dependent development of the system depending on each scenario. This approach would benefit from the work already done by other studies, especially those that determined the likelihoods of certain developments coinciding with each other. If instead, the approach of this study is used in future research, further challenges and strategies could be designed. New strategies should also include changes to decision rules in the model. Finally, the method used in this study could be applied to more case study farming systems. Differences and similarities between case studies will further inform the overall assessment of the resilience of European farming systems. The explorative and flexible nature of the system dynamics approach is likely to uncover many nuances of resilience and foster an engaging discussion between the policy, society and industry angles on sustainable agriculture.

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Appendices

Appendix A: Concepts and background information

SURE Farm theoretical framework

Meuwissen et al. (2019) describes the framework used in the SURE-Farm project and this study to assess the resilience of farming systems. The authors define resilience of a farming system as the ability of the system to provide system functions in the face of shocks and stresses, through three different resilience capacities (Meuwissen et al., 2019):

4. **Robustness**: the ability of the system to withstand disturbances and maintain a desired level of output (Holling, 1973).

5. **Adaptability**: the capacity of the system to change the composition of inputs and outputs in response to changing drivers, without changing the system structure or resulting feedback mechanisms (Folke et al., 2010).

6. **Transformability**: the ability of the system to change its fundamental internal processes, thus becoming a new system that can continue to supply a desired level of various functions (Folke et al., 2010; Walker et al., 2004).

The framework also distinguishes between resilience to specific disturbances (termed specific resilience), and general resilience to unknown challenges (termed general resilience) (Meuwissen et al., 2019). Several other important concepts found in resilience literature form the basis of the SURE-Farm theoretical framework:

1. Farming system: The **farming system** is characterised by internal and external players. Internal players mutually influence each other and include the farms that produce the main product(s) and other non-farm actors. External players have a unilateral influence on the farming system, meaning they are influencers but are not influenced. Farming systems are also characterised by different nested scales, including fields, farm households and other collectives (Meuwissen et al., 2019).

2. Challenges: The farming system is faced with **challenges**, distinguished as having environmental, economic, social or institutional character. These challenges can either be shocks or long-term stresses. The impact of a shock is felt at a particular point in time, and the effects of the shock may or may not be reversible. Long-term stresses are felt over a certain time interval, and have an accumulating effect on the system by gradually changing the system's environment. The pressure of multiple shocks and stresses can change the behaviour and structure of the system over time (Meuwissen et al., 2019).

3. Functions: The key to distinguish a resilient from a non-resilient system is to determine whether the system can continue to provide certain system **functions** when it is faced with a challenge. System functions can be divided into those delivering private and those delivering public goods. Private goods include the production of food and non-food products, the provision of capital to farm households and other actors and the quality of their lives. Public goods include the maintenance of natural-resources,

protection of biodiversity and animal welfare and a balanced social structure (Meuwissen et al., 2019).

4. Resilience capacities: The challenges and functions of farming systems are not static. Therefore, resilience of the farming system requires the capacity of the system to maintain *and* change its character. This is achieved through three **resilience capacities** defined above, namely robustness, adaptability, and transformability (Meuwissen et al., 2019).

5. Resilience attributes: A particular farming system may exhibit certain levels of each of the three resilience capacities (robustness, adaptability and transformability). The level to which a resilience capacity contributes to the overall resilience of the system is determined by the system's **resilience attributes**. As defined by the Resilience Alliance (2010), these attributes include diversity, modularity, openness, tightness, and system reserves.

This study in the context of SURE Farm

The aim of this study addresses the objectives of SURE Farm work package 5 (Table A.1). The focus of this study is on the most important system functions, challenges and strategies that were identified for the Veenkoloniën.

Table A.1 The objectives of the SURE Farm work package 5 next to details about the focus of this study in addressing these objectives.

Objectives of WP5	"Assess the current resilience and delivery of private and public goods for selected farming systems across the EU."	"Assess the impact of future challenges."	"Assess the expected impact of resilience-enhancing strategies (and combinations of resilience-enhancing strategies)."
The focus in this study	This study is focused on the functions **food production** and **economic viability**, through the analysis of the indicators **starch potato production (ton)** and **farm income (EUR)** respectively.	This study is focused on some of the main challenges: **Environmental challenges** (*e.g.* droughts, flooding, and potato cyst nematode infections) **Economic challenges** (*e.g.* low and fluctuating economic performance per hectare of land)	Strategies by the main system actors will be analysed: **Strategies by farmers**: Scaling **Strategies by Avebe:** Investing in plant breeding programs (Increasing starch content, increasing drought and nematode resilience) Increasing product value

Appendix B: Methods

Model conceptualisation

Kim and Andersen (2012) describe a systematic way to translate qualitative text data into causal loop diagrams. The identified causal structures are recorded and presented in a tables. The following example text, taken from Paas et al. (2019), illustrates how qualitative text data is recorded in Table B.1.

"The general stability of starch production in the period from 2000-2018 in the area can be explained by a steady increase in starch production per hectare (around 2% increase per year, due to increased starch content and nematode resistance of potatoes) on the one hand and a slow decrease in area with starch potatoes on the other hand, except for the last 5-6 years where the area with starch potatoes is stable according to participants." (Paas et al., 2019)

Table B.1 How causal structures and variable behaviour is recorded from a text excerpt from Paas et al. (2019). Table structure adapted from Kim and Andersen (2012).

Document: Paas et al. (2019)
Main argument: Starch production was stable between 2000-2018

Causal structures	*Cause variable:*	Starch content (%)	Nematode resistance	Starch production per hectare (ton/ha)	Cultivation area (ha)
	Effect variable:	Starch production per hectare (ton/ha)	Starch production per hectare (ton/ha)	Starch production (ton)	Starch production (ton)
	Relationship type:	Positive	Positive	Positive	Positive
Variable behaviour	*Cause variable:*	Increased	Increased	Increased (2%/year)	Decreased
	Effect variable:	Increased (2%/year)	Increased (2%/year)	Stable	Stable

Various causal structures are then combined to create CLDs that represent all dependencies mentioned in a text. An example for a CLD made after transcribing a section of Paas et al. (2019) is shown in Fig. B.1. Arrows connect pairs of cause and effect variables. The polarity at the arrow head indicates whether the variables are positively (+) or negatively (-) correlated. A delay in the effect is indicated by double crossed out arrows. When a sequence of arrows forms a circle a feedback loop is created. Feedback loops are either balancing (B) or reinforcing (R). A balancing loop results in goal seeking behaviour while a reinforcing loop results in exponential growth or decay. The example illustrates that an increased nematode pressure decreases starch production per hectare which is compensated by increased spending on innovation and the development of new potato varieties with increased nematode resistance (Fig. B.1, loop B). However, after some time nematodes may break the resistance of new varieties increasing nematode pressure again (Fig. B.1, loop R). Together these two loops represent one dynamic hypothesis about the pattern of nematode pressure and resistance observed in the Veenkoloniën.

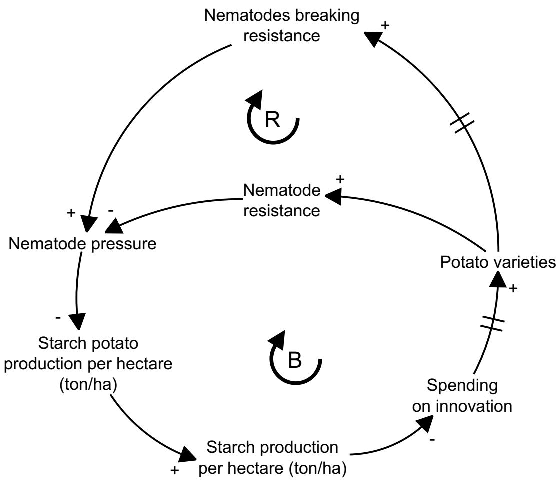


Fig. B.1 A CLD made after transcribing (Paas et al., 2019) using the approach outlined in (Kim and Andersen, 2012). The arrows connect variables with causal dependencies, where the arrow points from the cause variable to the effect variable. The polarity symbol next to an arrow head indicates whether the two variables are positively (+) or negatively (-) correlated. A delay in the effect is indicated by double crossed out arrows. A balancing (goal-seeking) feedback loop is indicated by a B, while a reinforcing (exponential) feedback loop is indicated by an R.

Appendix C: More on model conceptualisation

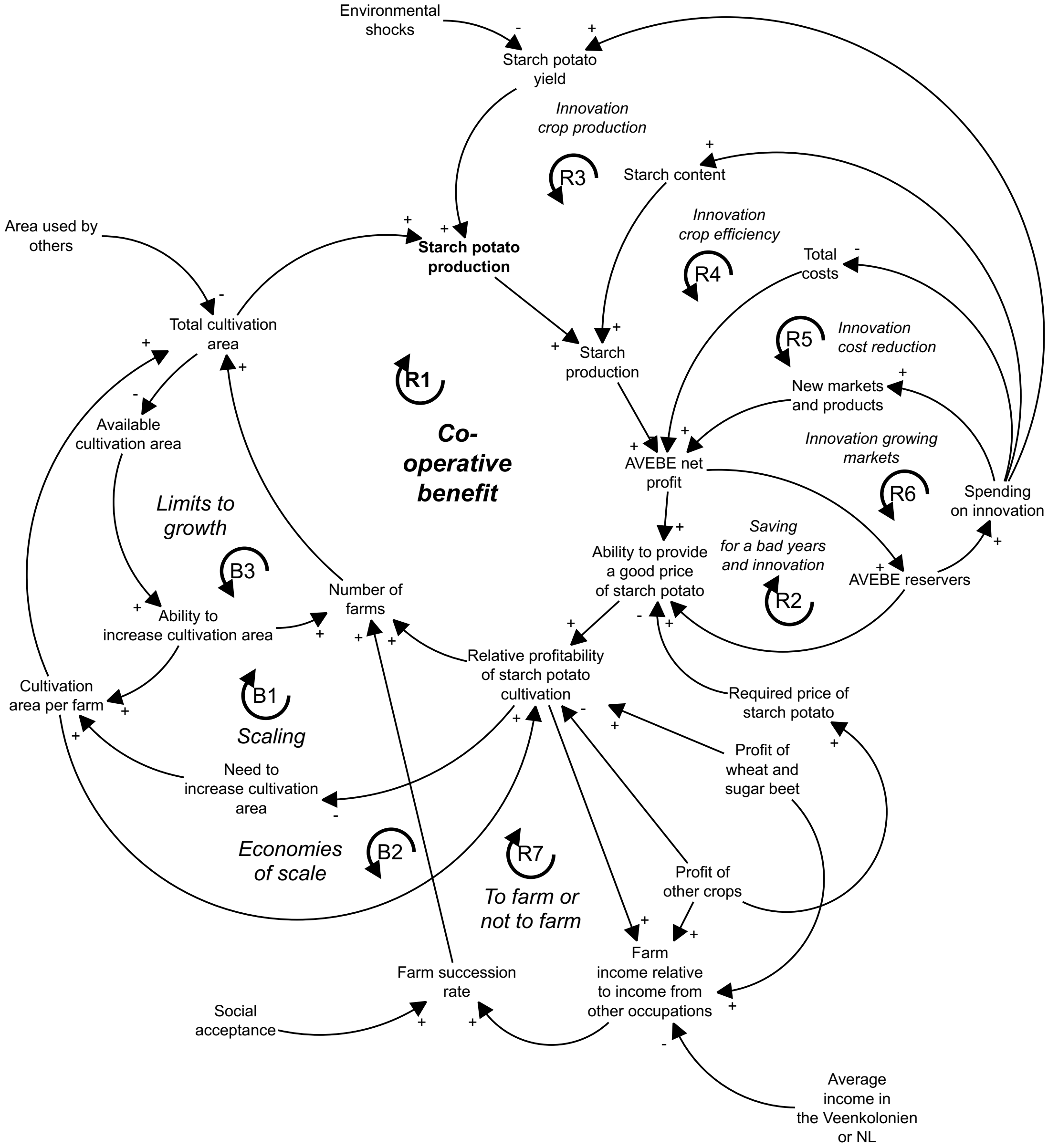


Fig. C.1 The CLD in Fig. 8 expanded to include R7 “To farm or not to farm”, that represents how farm succession rate depends on the relative income of farming in comparison to the average income in the Veenkoloniën or NL.

The farm succession rate depends on whether farming as an occupation remains attractive. Farming will likely remain attractive if it is at least as profitable as other occupations in the region or NL. The rate of succession will also depend on the degree of social acceptance of farming.

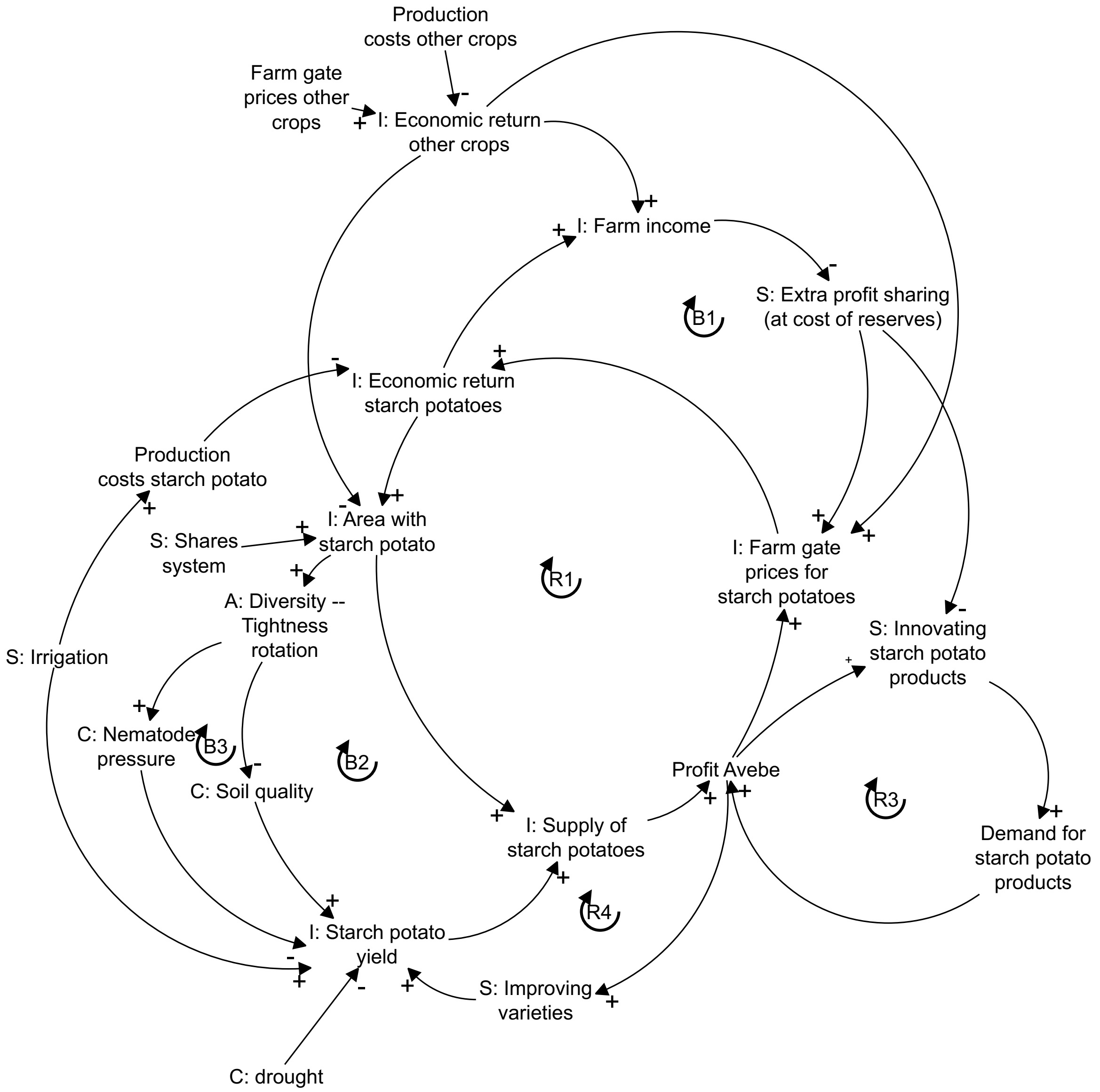


Fig. C.2 A CLD of the farming system in the Veenkoloniën adapted from Paas et al. (2020).

The CLD presented in this study mostly aligns with the CLD of Paas et al. (2020). The feedback loop in Fig. 8, R1 “Cooperative benefit”, aligns with the feedback loop in Fig. C.2, R1. In the latter, a higher “Profit Avebe” leads to a higher “Farm gate price for starch potatoes” and “Economic return starch potatoes”. This results in a higher “Area with starch potatoes” and thus a higher “Supply of starch potatoes” and “Profit Avebe”. The authors propose the “S: Shares system” to be a constraint on this reinforcing loop as opposed to the limited land availability proposed in this study. However, the two ideas are interchangeable and will not significantly affect the interpretation.

The effects of challenges and strategies on starch potato yield (in this case “C: drought”, “C: nematode pressure”, “I: soil quality”, “S: improved varieties”, “S: irrigation”) also align to the CLD presented in this study. Paas et al. (2020) also identified that Avebe may use its reserves at the cost of spending on innovation, in order to increase the farm gate price of starch potatoes (Fig. C.2, B1; Fig. 8, R2).

Appendix D: Model description

The `Starch potato farms` module sub-section in which the system is disaggregated by farm size is shown in Fig. D.1. The most important component in this sub-section is the `Farms` stock. This stock keeps track of the number of starch potato farms in the Veenkoloniën in each year. The `Farms` stock is arrayed to include three farm sizes. The model equations belonging to this structure are listed in Table E.1.

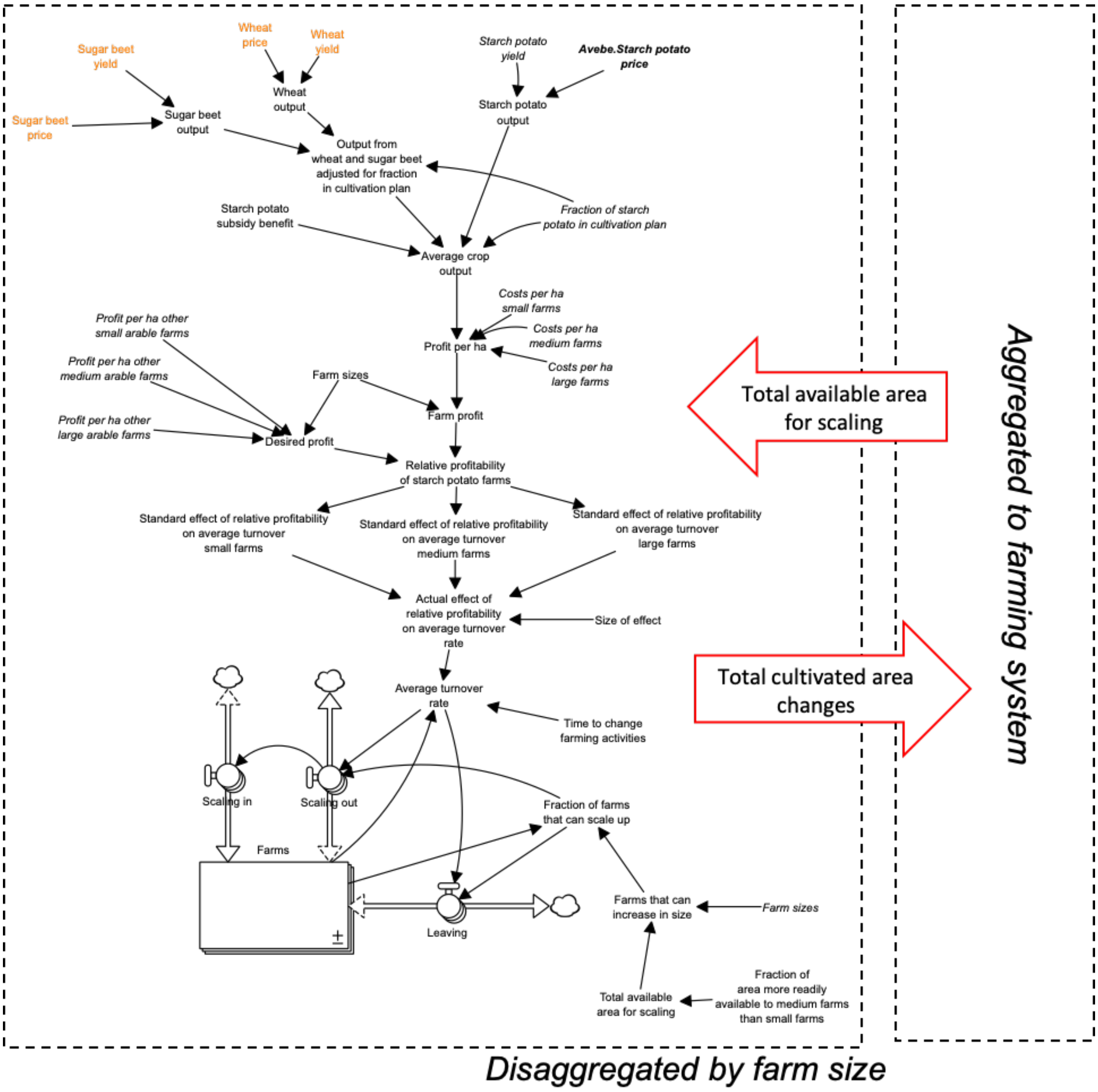


Fig. D.1 Snapshot of the sub-section of the `Starch potato farms` module disaggregated by farm size. The number of farms are captured by the stock `Farms`, which is arrayed to include small (24 ha/farm), medium (37 ha/farm) and large (130 ha/farm) farms.

The change in the number of `Farms` is determined by two types of rates. The `Scaling in`/`Scaling out` rates and the `Leaving` rates. These two rates capture the decision by farmers to either scale up or leave the system. The `Scaling in`/`Scaling out` rates allow small farms to become a medium farm, or medium farm to become a large farm. The `Scaling in`/`Scaling out` rates thus represent flows between the arrayed `Farms` stocks. The model assumes that only small and medium farms have the ability to increase in scale, while large farms have already reached a maximum size.

The `Leaving` rates drain each `Farms` stock separately. Each rate is determined by the `Average turnover rate` variable and the `Fraction of farms that can increase in size` variable. The higher the `Fraction of farms that can increase in size` the higher the `Scaling in`/`Scaling out` rates and the lower the `Leaving` rates. The model therefore assumes that the preferred strategy of farms is to scale up rather than to leave the system.

The `Average turnover rate` determines the change in the `Farms` stock based on profitability differences between starch potato farms and other arable farms. The model assumes that when profitability of starch potato farms is higher than of other arable farms the `Average turnover rate` is zero. In other words, only if other arable farms are more profitable than starch potato farms will starch potato farms either scale up or leave the system. If starch potato farm profitability is higher than other arable farm profitability, then starch potato farmers will be content to stay in their current situation.

The profitability difference between starch potato farms and other arable farms is given by the variable `Profit benefit`. The `Profit benefit` of starch potato farms is the relative profit of starch potato farms of each size (`Profit of farm`) compared to the profit of other arable farms of the same size (`Desired profit`). The profit of starch potato farms is determined by the output of the crop rotation with starch potato, sugar beet and wheat (`Starch potato output`, `Sugar beet output`, `Wheat output`) minus the costs (`Costs per ha small farms`, `Costs per ha medium farms`, `Costs per ha large farms`). The profit of other arable farms is exogenous data from the FADN (2019).

The `Fraction of farms that can increase in size` is determined by the `Total available area`. The `Total available area` stock is found in the `Starch potato farms` module sub-section that is aggregated to farming system level (Fig. D.2). The model equations belonging to this structure can be found in Table E.2.

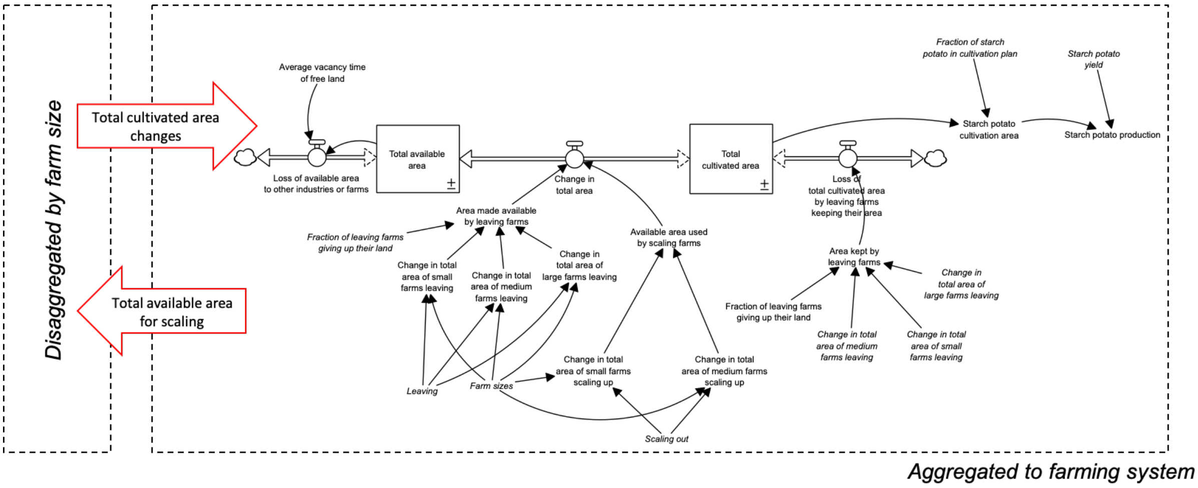


Fig. D.2 Snapshot of the sub-section of the `Starch potato farms` module aggregated to farming system level. This section includes the aggregated `Total cultivation area` belonging to all farms and the `Total available area` that can still be used.

The `Fraction of farms that can increase in size` is the relative number of small and medium farms that "fit" into their respective `Total available area for scaling`. The model assumes that more area is available to the medium farms to scale up than it is available to small farms (`Fraction of area more readily available to medium farms than small farms`). Medium farms have a higher disposable income they could potentially spend on increasing farm size, especially given the fact that land prices have been rising (Asjes and Munneke, 2007).

The `Scaling in/Scaling out` rates and the `Leaving` rates of the `Farms` stock influence the rates of the `Total available area` and `Total cultivated area` stocks. The `Change in total cultivation area` rate keeps track of the cultivation area gained through scaling farms and lost through leaving farms. Leaving farms either make their area available again for others or keep their area. The farms keeping their area represent those that continue farming, but stop cultivating starch potatoes. The `Fraction of farms stopping farming completely` parameter determines how much of the `Leaving` rate cultivation area is lost from the system and how much stays in the system. The area that stays in the system is moved from the `Total cultivation area` stock to the `Total available area` stock.

The `Loss of total cultivation area by leaving farms keeping their area` rate keeps track of all leaving farms that do not return their area to the `Total available area` stock. The model assumes that this lost area cannot be recovered again in the future. The model also assumes that free area in the `Total available area` stock will not stay available forever. The `Loss of land to other industries or farms` rate drains the `Total available area` stock that has a specific `Average vacancy time of free land`.

The `Total cultivation area` at any given time point determines the total `Starch potato production` given a certain `Starch potato yield`. The total volume of starch potatoes is input for the `Avebe` module (Fig. D.3). The equations of this module can be found in Table E.5.

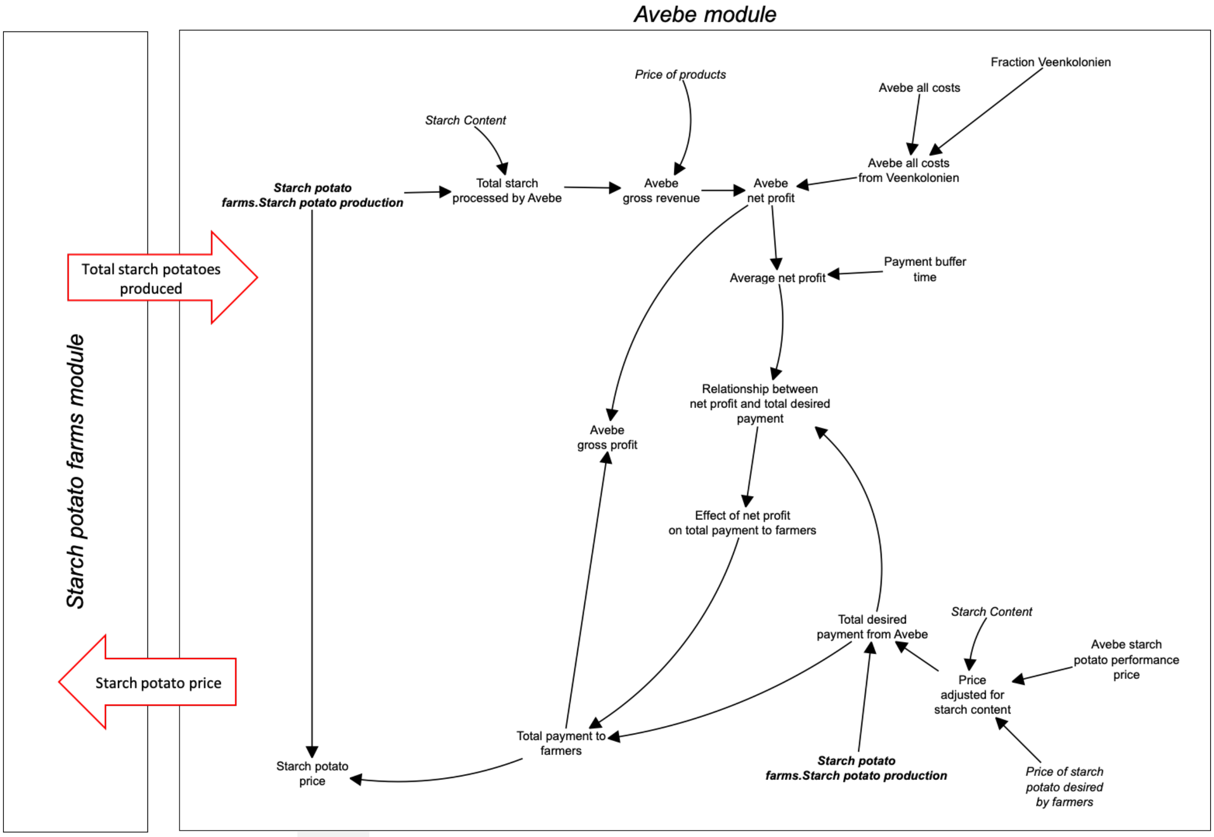


Fig. D.3 Snapshot of the `Avebe` module. The number of farms are captured by the stock "Farms", which is arrayed to include small (24 ha/farm), medium (37 ha/farm) and large (130 ha/farm) farms.

The total starch potato volume (`Starch potato production`) is processed into starch given a certain `Starch content`. The `Avebe net profit` is calculated with the `Price of products` and `Avebe all costs from Veenkolonien`.

The `Price of starch potato desired by farmers` is assumed to be equal to the price farmers would need so that starch potato cultivation is at least as profitable as the cultivation of other crops. The calculation of this price also takes into account profits from the cultivation of sugar beet and wheat in any given year.

Avebe will be able to meet the `Total desired payment from Avebe` if the `Avebe net profit` can cover this payment. However, the model assumes that in years where `Avebe net profit` is not high enough, Avebe does not immediately stop paying farmers. Instead, it is likely that Avebe has a number of "bad" financial years it can observe before this drop in payment would occur. For this, Avebe's reserves were not formally included in the model (for example as a stock). Instead, a `Payment buffer time` of three years was estimated to account for the number of years that Avebe can still pay farmers even if their revenues do not fully cover the required payment. The `Payment buffer time` is used to calculate the `Average net profit` of only the last few years.

The `Average net profit` is then compared to the `Total desired payment from Avebe`, i.e. the `Starch potato price adjusted for starch content` times the total volume of starch potatoes delivered that year. If the `Average net profit` is only slightly below the `Total desired payment from Avebe`, then most of this payment will still be covered. The degree to which the `Total payment from Avebe` is lower than the `Total desired payment from Avebe` is given by the variable `Effect of net profit on total payment to farmers`. This variable contains the lookup table (Fig. D.4).

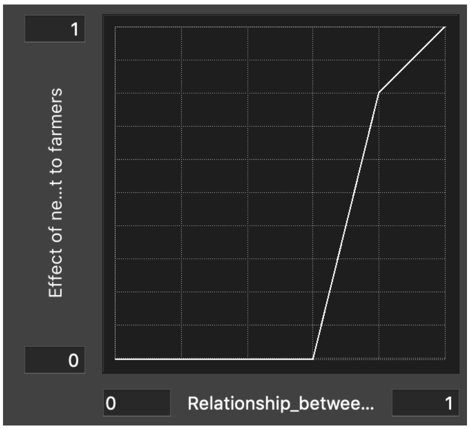


Fig. D.4 The lookup table used by the `Effect of net profit on total payment to farmers` variable in the Avebe module. The payment to farmers reduces linearly as net profit reduces until average net profit is 80% of the desired payment. Between 60% - 80% the payment decreases more rapidly. When net profits are lower than 60% of the desired payment, the total payment to farmers is equal to zero.

The `Total payment from Avebe` is then used to determine the `Avebe gross profit` and the actual `Starch potato price` in a given year.

The `Starch potato price` is the main output from the `Avebe` module that is an input for the `Starch potato farms` module. The `Starch potato production` and `Starch potato price` model calculations therefore complete the feedback between the `Starch potato farms` module and the `Avebe` module.

Further model structure

Apart from the model structure outline in the above sections, further model structure was required. This includes structures for carrying out side calculations (e.g. calculation of `Farm income`) and conversions and structure that allows the testing of the effect of challenges and strategies on model behaviour. All model structures for carrying out side calculations is are shown in Fig. D.5. The equations for these structures are documented in Table E.3 and Table E.6.

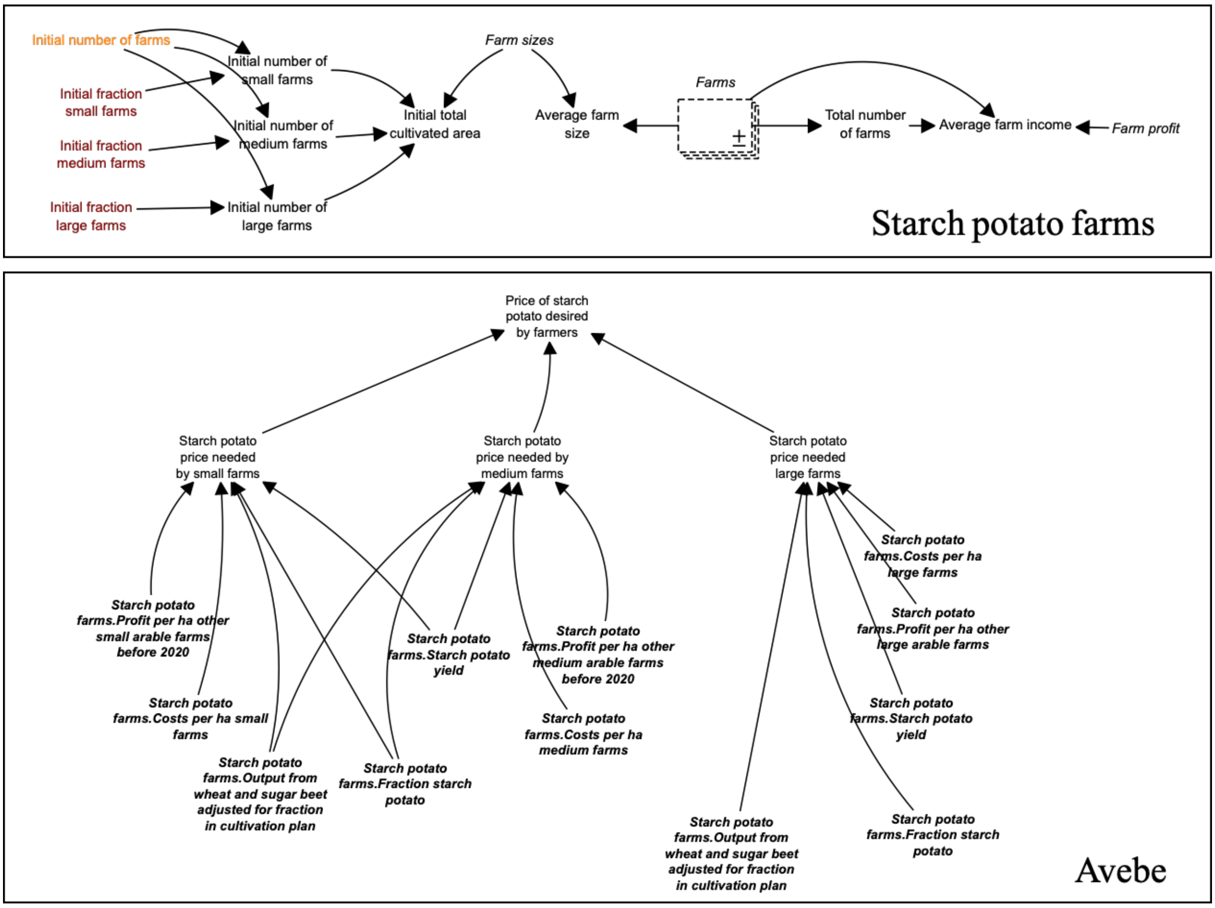


Fig. D.5 Snapshot of the side calculations in the `Starch potato farms` module and the `Avebe` module. In the `Starch potato farms` module side calculations, the initial values for the `Farms` stocks, the resulting `Initial cultivation area`, the `Average farm size`, `Total number of farms`, and `Average farm income` is calculated. In the `Avebe` module the `Price of starch potato desired by farmers` is calculated as the average starch potato price desired by the three farm sizes that would make each farm size at least as profitable as other arable farms of the same size.

The initial values for the `Farms` stocks are calculated by taking the number of starch potato farms observed in the Veenkoloniën and Oldambt in 2004 (CBS, 2019) by multiplying this by the estimated fraction of each farm size class (FADN, 2019). The initial number of farms determines the `Initial total cultivated area` by taking into account `Farm sizes`. The `Average farm size` is calculated as a weighted average of the number of farms in each `Farms` stocks and the respective `Farm sizes`. Likewise, the `Average farm income` is calculated as a weighted average of the `Farm profit` of each farm size. The equations for these structures are listed in Table E.3.

The `Price of starch potato desired by farmers` is the average price desired by each farm size. The price desired by each farm size is equal to the price that would make starch potato cultivation in rotation with sugar beet and wheat just as profitable as cultivating other crops. The profit per ha of other arable farms is used as a proxy for the profitability of cultivating other crops. The equations for these structures are listed in Table E.6.

Challenge model structure

To test the various challenges further model structure was made (Fig. D.6; see Table E.4 for equations). This structure allows for testing of individual challenges or challenges in combination with each other. Each challenge is introduced in the simulation in the year 2020.

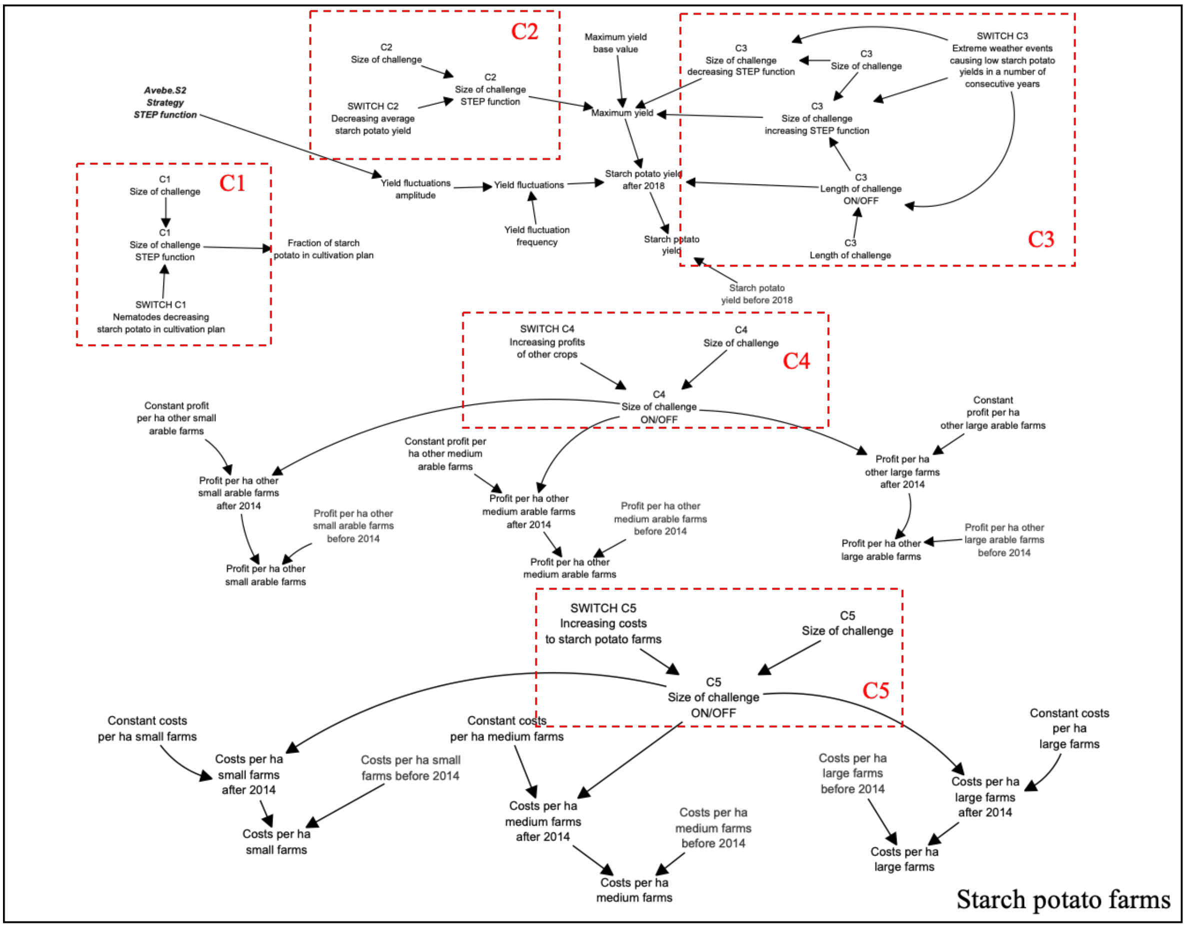


Fig. D.6 Snapshot of how challenges were included as structures in the model. Five challenges are represented in the model: (C1) nematode pressure decreasing fraction of starch potato in cultivation plan, (C2) average yields decreasing in 2020 OR average yields decreasing at a constant slope as of 2020, (C3) low yields for a number of consecutive years due to weather extremes, (C4) increase in profits of other crops, and (C5) increase in costs of starch potato farms.

Two challenges were designed that influence the starch potato yield (C2 and C3). Starch potato yield is exogenous in the model. Between 2004 and 2018 the average starch potato yield in the Netherlands is used as input (Fig. 3; data CBS (2019); processed data shown in Table F.3). The maximum and average yields observed in this time period were 45 ton/ha and 43 ton/ha respectively. Low yields between 38 and 40 ton/ha were observed roughly every 4 years. In the base run, this yield trend observed between 2004 and 2018 is extrapolated into the future using the SINWAVE function in Stella Architect. The SINWAVE function simulates yield fluctuations with the amplitude `Yield fluctuation amplitude` and frequency `Yield fluctuations frequency`.

(C1) To simulate an increase in nematode pressure after 2020, the `Fraction starch potato` parameter (base run = 0.5) is decreased in 2020 with the `C1 Size of challenge` variable. C1 can be turned on by setting the `SWITCH C1` value from 0 to 1.

(C2) To simulate a decrease of average yields in after 2020, the `Maximum yield` parameter (base run = 45 ton/ha) is decreased in 2020 with the `C2 Size of challenge` variable. C2 can be turned on by setting the `SWITCH C2` value from 0 to 1.

(C3) To simulate a decrease of average yields in after 2020 for a set period of time, the `Maximum yield` parameter (base run = 45 ton/ha) is decreased in 2020 with the `C3 Size of challenge` variable for until 2020+`C3 Length of challenge`. During this time the fluctuations are also removed. C3 can be turned on by setting the `SWITCH C3` value from 0 to 1.

(C4) To simulate an increase in profits of other crops in after 2020, the `Profit per ha other arable farms` parameters (different for each farm size) is increased in 2020 by multiplying this with the `C4 Size of challenge` variable. C4 can be turned on by setting the `SWITCH C4` value from 0 to 1.

(C5) To simulate an increase in costs of starch potato farms in after 2020, the `Costs per ha` parameters (different for each farm size) is increased in 2020 by multiplying this with the `C5 Size of challenge` variable. C5 can be turned on by setting the `SWITCH C5` value from 0 to 1.

Strategy model structure

Some extra model structure was required to test the impact of strategies on model behaviour (Fig. D.7).

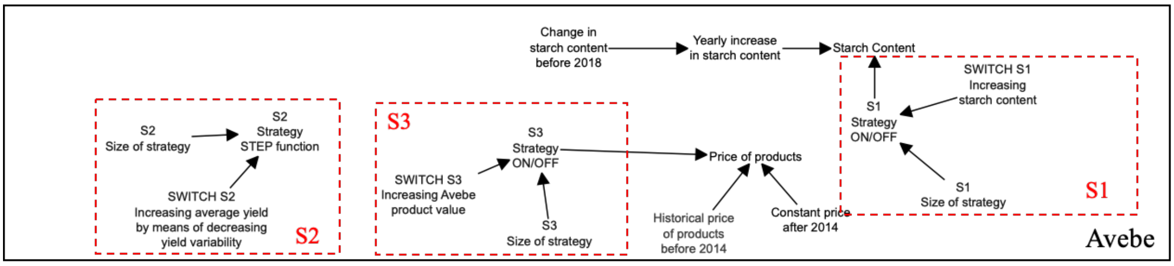


Fig. D.7 Snapshot of how strategies were included as structures in the model. Three strategies are represented in the model: (S1) increasing starch content, (S2) decreasing yield variability and (S3) increasing Avebe product value.

(S1) Starch content is instantly increased to a final value in 2020. The final starch content is given by `S1 Size of strategy`. When `SWITCH S1` has the value 1, S1 is turned on.

(S2) The yield variability is decreased by changing the amplitude of the fluctuations in the SINWAVE function (`Yield fluctuations`; see). The new yield fluctuations are calculated by decreasing `Yield fluctuations amplitude` with the value of `S2 Size of strategy`. Thus, the minimum yields are increased in S2 but the maximum yields stay constant. Overall, the average yields are increased. When `SWITCH S2` has the value 1, S2 is turned on.

(S3) The `Price of products` is increased by multiplying it with the factor `S3 Size of strategy`. When `SWITCH S3` has the value 1, S3 is turned on.

Appendix E: Model documentation

Table E.0 A list of the model documentation tables, their content, and the corresponding figure showing the model diagram.

Table	Content	Figure
Table E.1	Model documentation for the starch potato farms module; disaggregated by farm size	Fig. D.1
Table E.2	Model documentation for the starch potato farms module; aggregated to systems level	Fig. D.2
Table E.3	Model documentation of side calculations in the Starch potato farms module.	Fig. D.5
Table E.4	Model documentation calculating starch potato yield and challenges.	Fig. D.6
Table E.5	Model documentation for the Avebe module.	Fig. D.3
Table E.6	Model documentation of side calculations in the Avebe module.	Fig. D.5
Table E.7	Model documentation for strategies.	Fig. D.7

Table E.1 Model documentation for the starch potato farms module; disaggregated by farm size (corresponding model structure in Fig. D.1).

Units

Formulation and comments

FARMS STOCK:

1. Farms[small](t) = Farms[small](t - dt) + (Scaling_in[small] - Leaving[small] - Scaling_out[small]) * dt
   INIT Farms[small] = Initial_number_of_small_farms
2. Farms[medium](t) = Farms[medium](t - dt) + (Scaling_in[medium] - Leaving[medium] - Scaling_out[medium]) * dt
   INIT Farms[medium] = Initial_number_of_medium_farms
3. Farms[large](t) = Farms[large](t - dt) + (Scaling_in[large] - Leaving[large] - Scaling_out[large]) * dt
   INIT Farms[large] = Initial_number_of_large_farms

[farm]

A stock exists to count the number of farms of each farm size class. These stocks are depleted by farms leaving (leaving completely or scaling up to the next size) and filled by farms scaling up from a smaller size class. It is assumed that no new farms will be established and that large farms cannot scale up further.

Total_number_of_farms = Small_farms+Medium_farms+Large_farms

[farm]

The total number of farms is the sum of the three farm number stocks. This is one of the main indicators of the model that is compared to data from CBS (2019).

FLOWS FARM STOCKS:

INFLOWS:

1. Scaling_in[small] = 0
2. Scaling_in[medium] = Scaling_out[small]
3. Scaling_in[large] = Scaling_out[medium]

OUTFLOWS:

1. Leaving[small] = Average_turnover_rate[small]*(1-Fraction_of_farms_that_can_scale_up[small])
2. Leaving[medium] = Average_turnover_rate[medium]*(1-Fraction_of_farms_that_can_scale_up[medium])
3. Leaving[large] = Average_turnover_rate[large]*(1-Fraction_of_farms_that_can_scale_up[large])

[farm/year]

4. Scaling_out[small] =
   Fraction_of_farms_that_can_scale_up[small]*Average_turnover_rate[small]
5. Scaling_out[medium] =
   Fraction_of_farms_that_can_scale_up[medium]*Average_turnover_rate[medium]
6. Scaling_out[large] =
   Fraction_of_farms_that_can_scale_up[large]*Average_turnover_rate[large]

INFLOWS:
The scaling in rates of each farm size is equal to the scaling out rate of each respective smaller farm size.

OUTFLOWS:
The scaling out rates of farms is determined by the average turnover rate and the fraction of farms able to scale up.
The leaving rate of farms in each farm size class is the average turnover rate. In the case of small and medium sized farms this rate is multiplied by the fraction of farms not able to scale up to the next farm size class.

CROP OUTPUTS

1. Starch_potato_output = Starch_potato_yield*AVEBE.Starch_potato_price
2. Sugar_beet_output = Sugar_beet_price*Sugar_beet_yield
3. Wheat_output = Wheat_price*Wheat_yield
4. Output_from_wheat_and_sugar_beet_adjusted_for_fraction_in_cultivation_plan =
   (Wheat_output+Sugar_beet_output)*(1-Fraction_starch_potato/2)
5. Average_crop_output =
   Fraction_starch_potato*Starch_potato_output+Output_from_wheat_and_sugar_beet_adjusted_for_fraction_in_cultivation_plan+Starch_potato_subsidy_benefit

[EUR/ha]

The crop output is the total amount of revenue per ha for growing each crop, given a particular price and yield.
The combined output (revenue/ha) of sugar beet and wheat that farmers expect to get is adjusted for the fraction of these two crops in the cultivation plan (based on the fraction of starch potato in the cultivation plan).
The average output of all three crops is the output of each individual crop multiplied by the respective share in the cultivation plan (0.5 starch potato, 0.25 wheat and 0.25 sugar beet). On top of this output a starch potato subsidy is added.

REQUIRED PARAMETERS FOR CROP OUTPUTS

1. *starch potato price calculation in model documentation of Avebe module
   *starch potato yield calculation in model documentation of challenges
2. Sugar_beet_price = GRAPH(TIME)
   Sugar_beet_yield = GRAPH(TIME)
3. Wheat_price = GRAPH(TIME)
   Wheat_yield = GRAPH(TIME)
4. Fraction_starch_potato = 0.5
5. Starch_potato_subsidy_benefit = IF TIME <= 2013 THEN 500 ELSE 0

Prices: [EUR/ton]
Yields: [ton/ha]
Subsidy: [EUR/ha]
Fraction: [unitless]

Source of historical crop prices: CBS (2019)
Source of historical crop yields: CBS (2019)
Of the total cultivated area half is used to grow starch potatoes and the other half is used to grow sugar beet and wheat. This assumption is based on historical trends in the Veenkolonien and Oldambt recorded by CBS (2019). In reality this fraction may change slightly from year to year.
Until 2013 and the reform of the CAP, farmers received relatively more subsidy per ha for growing starch potato than for growing other crops. 500 EUR/ha more subsidy is a rough estimate based on reports (Bont et al., 2007; Vasilev et al., 2012)

FARM COSTS PER HA

1. Costs_per_ha_small_farms = IF TIME <= 2014 THEN Costs_per_ha_small_farms_before_2014 ELSE Costs_per_ha_small_farms_after_2014
    a. Costs_per_ha_small_farms_before_2014 = GRAPH(TIME)
    b. Costs_per_ha_small_farms_after_2014 = Constant_costs_per_ha_small_farms*"C5_Size_of_challenge_ON/OFF"
        i. * For C variables see Table E.4.
        ii. Constant_costs_per_ha_large_farms = 1970
2. Costs_per_ha_medium_farms = IF TIME <= 2014 THEN Costs_per_ha_medium_farms_before_2014 ELSE Costs_per_ha_medium_farms_after_2014
    a. Costs_per_ha_medium_farms_before_2014 = GRAPH(TIME)
    b. Costs_per_ha_medium_farms_after_2014 = Constant_costs_per_ha_medium_farms*"C5_Size_of_challenge_ON/OFF"
        i. Constant_costs_per_ha_medium_farms = 2120
3. Costs_per_ha_large_farms = IF TIME <= 2014 THEN Costs_per_ha_large_farms_before_2014 ELSE Costs_per_ha_large_farms_after_2014
    a. Costs_per_ha_large_farms_before_2014 = GRAPH(TIME)
    b. Costs_per_ha_large_farms_after_2014 = Constant_costs_per_ha_large_farms*"C5_Size_of_challenge_ON/OFF"
    c. Constant_costs_per_ha_small_farms = 2410

[EUR/ha]

The values for costs per ha of different sized farms between the years 2003 and 2014 were derived from data about starch potato farmers in the Veenkoloniën recorded by FADN (2019). After 2014 costs per ha are kept constant using the last value for each farm size.

FARM PROFIT PER HA

1. Profit_per_ha[small] = Average_crop_output-Costs_per_ha_small_farms
2. Profit_per_ha[medium] = Average_crop_output-Costs_per_ha_medium_farms
3. Profit_per_ha[large] = Average_crop_output-Costs_per_ha_large_farms

[EUR/ha]

The profit of each farm size class farms is the product of profit per ha and farm size.

FARM PROFIT / INCOME

1. Farm_profit[small] = Profit_per_ha[small]*Farm_sizes[small]
2. Farm_profit[medium] = Profit_per_ha[medium]*Farm_sizes[medium]
3. Farm_profit[large] = Profit_per_ha[large]*Farm_sizes[large]
4. Average_farm_income = ((Farm_profit[small]*Farms[small])+(Farm_profit[medium]*Farms[medium])+(Farm_profit[large]*Farms[large]))/Total_number_of_farms

[EUR/farm]

The profit of each farm size class farms is the product of profit per ha and farm size. The average profit per farm is the weighted average between the number of farms of each farm size class and the profit of each farm size at any given time.

REQUIRED PARAMTERS FOR FARM PROFIT

1. Farm_sizes[small] = 24
2. Farm_sizes[medium] = 37
3. Farm_sizes[large] = 130

[ha/farm]

The average farm size of the three different farm size classes is the average size of specialised starch potato farms of the FADN Class UAA labels 4-6 in the Veenkoloniën between the years 2004-2013 as recorded by FADN (2019).

PROFIT PER HA OTHER ARABLE FARMS:

1. Profit_per_ha_other_small_arable_farms = IF TIME <= 2014 THEN Profit_per_ha_other_small_arable_farms_before_2014 ELSE Profit_per_ha_other_small_arable_farms_after_2014
    a. Profit_per_ha_other_small_arable_farms_before_2014 = GRAPH(TIME)
    b. Profit_per_ha_other_small_arable_farms_after_2014 = Constant_profit_per_ha_other_small_arable_farms*"C4_Size_of_challenge_ON/OFF"
        i. * For C variables see Table E.4.
2. Profit_per_ha_other_medium_arable_farms = IF TIME <= 2014 THEN Profit_per_ha_other_medium_arable_farms_before_2014 ELSE Profit_per_ha_other_medium_arable_farms_after_2014
    a. Profit_per_ha_other_medium_arable_farms_before_2014 = GRAPH(TIME)
    b. Profit_per_ha_other_medium_arable_farms_after_2014 = Constant_profit_per_ha_other_medium_arable_farms*"C4_Size_of_challenge_ON/OFF"
3. Profit_per_ha_other_large_arable_farms = IF TIME <= 2014 THEN Profit_per_ha_other_large_arable_farms_before_2014 ELSE Profit_per_ha_other_large_farms_after_2014
    a. Profit_per_ha_other_large_arable_farms_before_2014 = GRAPH(TIME)
    b. Profit_per_ha_other_large_arable_farms_after_2014 = Constant_profit_per_ha_other_large_arable_farms*"C4_Size_of_challenge_ON/OFF"

[EUR/ha]

The profit per ha of each farm size class between the years 2003-2014 was taken from data recorded by FADN (2019) about all arable farms in the Veenkolonien. After 2014 the profit per ha is kept constant using the 2014 value. This value is adjusted based on possible scenarios of future profits of other crops.

DESIRED FARM PROFIT:

1. Desired_profit[small] = Profit_per_ha_other_small_arable_farms*Farm_sizes[small]
2. Desired_profit[medium] = Profit_per_ha_other_medium_arable_farms*Farm_sizes[medium]
3. Desired_profit[large] = Profit_per_ha_other_large_arable_farms*Farm_sizes[large]

[EUR/farm]

It is assumed that starch potato farms will want to receive at least as much profit as they could if they were another arable farm of the same size class.

RELATIVE PROFITABILITY OF STARCH POTATO

1. Relative_profitability_of_starch_potato_farms[small] = Farm_profit[small]/(Farm_profit[small]+Desired_profit[small])
2. Relative_profitability_of_starch_potato_farms[medium] = Farm_profit[medium]/(Farm_profit[medium]+Desired_profit[medium])
3. Relative_profitability_of_starch_potato_farms[large] = Farm_profit[medium]/(Farm_profit[medium]+Desired_profit[medium])

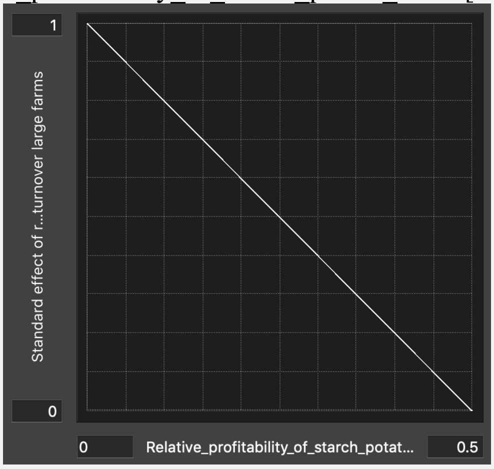
[unitless]

The relative profitability of being a starch potato farm is the profit of starch potato farms divided by the sum of the profit of starch potato farms and other arable farms. If this value is between 0.5 and 1 starch potato farms have a higher profit than other arable farms and if it is below 0.5 starch potato farms have a lower profit than other arable farms.

EFFECT OF RELATIVE PROFITABILITY ON AVERAGE TURNOVER RATE

STANDARD EFFECT

1. Standard_effect_of_relative_profitability_on_average_turnover_small_farms = GRAPH(Relative_profitability_of_starch_potato_farms[small])
2. Standard_effect_of_relative_profitability_on_average_turnover_medium_farms = GRAPH(Relative_profitability_of_starch_potato_farms[medium])
3. Standard_effect_of_relative_profitability_on_average_turnover_large_farms = GRAPH(Relative_profitability_of_starch_potato_farms[large])



ACTUAL EFFECT

1. Actual_effect_of_profit_benefit_on_average_turnover_rate[small] = Size_of_effect[small]*Standard_effect_of_relative_profitability_on_average_turnover_small_farms
    a. Size_of_effect[small] = 1
2. Actual_effect_of_profit_benefit_on_average_turnover_rate[medium] = Size_of_effect[medium]*Standard_effect_of_relative_profitability_on_average_turnover_medium_farms
    a. Size_of_effect[medium] = 0.5
3. Actual_effect_of_profit_benefit_on_average_turnover_rate[large] = Size_of_effect[large]*Standard_effect_of_relative_profitability_on_average_turnover_large_farms
    a. Size_of_effect[large] = 0.25

[unitless]

The standard effect of relative profitability on average turnover rate is an assumption about the reaction of starch potato farms when they compare their profit to that of other arable farms. As long as starch potato farms have a higher profit the standard effect is 0 and average turnover rate will be 0. Average turnover rate is only increased when the profit of starch potato farms is lower than that of other arable farms. The shape of the standard effect curve of all farm size classes is assumed to be the same.

The size of effect is multiplied by the standard effect to get the actual effect depending on farm class size. It is assumed that small farms have the highest effect size and large farms have the lowest effect size. This assumption is based on the observation that large farms have a higher successor rate than small farms, and are more likely to remain stable despite changes. The values were obtained through calibration using historical data.

AVERAGE TURNOVER RATE FARMS STOCKS

1. Average_turnover_rate[small] = (Farms[small]/Time_to_change_farming_activities[small])*Actual_effect_of_relative_profitability _on_average_turnover_rate[small]
    a. Time_to_change_farming_activities[small] = 2

[farm/year]

2. Average_turnover_rate[medium] = (Farms[medium]/Time_to_change_farming_activities[medium])*Actual_effect_of_relative_profitability_on_average_turnover_rate[medium]
    a. Time_to_change_farming_activities[medium] = 3
3. Average_turnover_rate[large] = (Farms[large]/Time_to_change_farming_activities[large])*Actual_effect_of_relative_profitability _on_average_turnover_rate[large]
    a. Time_to_change_farming_activities[large] = 5

The average turnover rate is the number farms of each farm size class divided by the time to change farming activities, multiplied by the effect of profit benefit. As a result, average turnover rate will be 0 if starch potato farms have a higher profit than other arable farms. The time to change farming activities is assumed to be less for small farms than for large farms. The values were obtained through calibration with historical data.

FARMS ABILITY TO SCALE UP

1. Farms_that_can_increase_in_size[small] = Total_available_area_for_scaling[small]/(Farm_sizes[medium]-Farm_sizes[small])
    a. Total_available_area_for_scaling[small] = Total_available_area*(1-Fraction_of_area_more_readily_available_to_medium_farms_than_small_farms)
    b. Fraction_of_area_more_readily_available_to_medium_farms_than_small_farms = 0.7
2. Farms_that_can_increase_in_size[medium] = Total_available_area_for_scaling[medium]/(Farm_sizes[large]-Farm_sizes[medium])
    a. Total_available_area_for_scaling[medium] = Total_available_area*Fraction_of_area_more_readily_available_to_medium_farms_than_small_farms
3. Farms_that_can_increase_in_size[large] = 0

1. Fraction_of_farms_that_can_scale_up[small] = MIN(MAX(Farms_that_can_increase_in_size[small]/Farms[small], 0), 1)
2. Fraction_of_farms_that_can_scale_up[medium] = MIN(MAX(Farms_that_can_increase_in_size[medium]/Farms[medium], 0), 1)
3. Fraction_of_farms_that_can_scale_up[large] = 0

Farms that can increase in size: [farm]

Total available area for scaling: [ha]

Fractions: [unitless]

The fraction of farms able to scale up is determined by the number of farms able to scale up and the number of farms in the respective stock. The number of farms able to scale up is determined by the average size needed to scale up and the number of farms that can receive this needed area given the total available area. It is assumed that medium farms have a higher access to the total available area for scaling, as they have more disposable income.

Table E.2 Model documentation for the starch potato farms module; aggregated to systems level (corresponding model structure in Fig. D.2).

Formulations and comments **Units**

AREA STOCKS:

1. Total_available_area(t) = Total_available_area(t - dt) + (Change_in_total_area - Loss_of_available_area_to_other_industries_or_farms) * dt
   a. INIT Total_available_area = 0.00001
2. Total_cultivated_area(t) = Total_cultivated_area(t - dt) + (- Change_in_total_area - Loss_of_total_cultivated_area_by_leaving_farms_keeping_their_area) * dt
   a. INIT Total_cultivated_area = Initial_total_cultivated_area

[ha]

The total cultivation area is the sum of the total area that is currently in use by all farm size classes. It is used to determine the total production of starch potatoes. The total cultivation area is increased when farms scale up and it is decreased when farms leave the system.
The total available area a stock that can be used by farms that want to scale up to the next size class. It is increased when farms that stop cultivating starch potatoes stop farming completely and give up their land. It is decreased as other industries or farms may buy this land or when farms in the system scale up to the next size class. It is assumed that the initial total available area is 0 (or 0.00001 to avoid model error).

LOSS OF AVAILABLE AREA RATE
(OUTFLOW Total_available_area):

1. Loss_of_available_area_to_other_industries_or_farms = (Total_available_area/Average_vacancy_time_of_free_land)
   a. Average_vacancy_time_of_free_land = 2

[ha/year]

If available area is not used quickly it may be lost to other industries or other farms. The Veenkoloniën has been experiencing an increase in land bought by other industries or land used as nature areas. Land not currently in use is therefore assumed to be lost given an average vacancy time of free land. Two years was estimated based on model calibration to historical data.

CHANGE IN TOTAL AREA RATE
(OUTFLOW Total_cultivated_area INFLOW Total_available_area):

1. Change_in_total_area = Area_made_available_by_leaving_farms-Available_area_used_by_scaling_farms

[ha/year]

This flow keeps track of the movement between the total cultivated area and the total available area that is not currently in use and free to anyone who needs it. When the flow is negative area from the total available area is moved to the total cultivated area and vice versa.

LOSS OF CULTIVATION AREA RATE
(OUTFLOW Total_cultivated_area):

1. Loss_of_total_cultivated_area_by_leaving_farms_keeping_their_area = Area_kept_by_leaving_farms
   a. Area_kept_by_leaving_farms = (1-Fraction_of_leaving_farms_giving_up_their_land)*(Change_in_total_area_of_small_farms_leaving+Change_in_total_area_of_medium_farms_leaving+Change_in_total_area_of_large_farms_leaving)

[ha/year]

Cultivated area is lost when farms that are leaving are retaining their cultivation area for other purposes than starch potato production.

RATE EQUATIONS REQUIRED VARIABLES

1. Area_made_available_by_leaving_farms = (Fraction_of_leaving_farms_giving_up_their_land*(Change_in_total_area_of_small_farms_leaving+Change_in_total_area_of_medium_farms_leaving+Change_in_total_area_of_large_farms_leaving))
    a. Fraction_of_leaving_farms_giving_up_their_land = 0.5
    b. Change_in_total_area_of_small_farms_leaving = (Farm_sizes[small]*Leaving[small])
    c. Change_in_total_area_of_medium_farms_leaving = (Farm_sizes[medium]*Leaving[medium])
    d. Change_in_total_area_of_large_farms_leaving = (Farm_sizes[large]*Leaving[large])
2. Available_area_used_by_scaling_farms = (Change_in_total_area_of_small_farms_scaling_up+Change_in_total_area_of_medium_farms_scaling_up)
    a. Change_in_total_area_of_small_farms_scaling_up = (Farm_sizes[medium]-Farm_sizes[small])*Scaling_out[small]
    b. Change_in_total_area_of_medium_farms_scaling_up = (Farm_sizes[large]-Farm_sizes[medium])*Scaling_out[medium]

All except fractions: [ha/year]

Fraction: [unitless]

The area made available when farms are leaving the system is the determined by the rate at which farms are leaving, the farm sizes and the fraction of farms that stop farming completely. This fraction was estimated based on model calibration. The total cultivation area is increased as farms are scaling up to the next farm size class.

STARCH POTATO AREA / PRODUCTION

1. Starch_potato_cultivation_area = Total_cultivated_area*Fraction_of_starch_potato_in_cultivation_plan
2. Starch_potato_production = Starch_potato_cultivation_area*Starch_potato_yield
    a. *starch potato yield calculation in model documentation of challenges

Area: [ha]

Production: [ton]

The total starch potato volume produced (ton) is determined by the yield and the fraction of the total cultivation area that is used to grow starch potatoes.

Table E.3 Model documentation of side calculations in the Starch potato farms module (corresponding model structure in Fig. D.5).

Formulation and comments	**Units**
INITIAL NUMBER OF FARMS AND CULTIVATION AREA 1. Initial_number_of_farms = 1600 2. Initial_number_of_small_farms = Initial_number_of_farms*Initial_fraction_small_farms a. Initial_fraction_small_farms = 0.35 3. Initial_number_of_medium_farms = Initial_number_of_farms*Initial_fraction_medium_farms a. Initial_fraction_small_farms = 0.45 4. Initial_number_of_large_farms = Initial_number_of_farms*Initial_fraction_large_farms a. Initial_fraction_small_farms = 0.2 5. Initial_total_cultivated_area = (Initial_number_of_small_farms*Farm_sizes[small])+Initial_number_of_medium_farms*Farm_sizes[medium]+Initial_number_of_large_farms*Farm_sizes[large]	Number of farms: [farm] Fractions: [unitless] Area: [ha]
The initial number of starch potato farms in 2004 is based on data collected by (CBS, 2019) about the Veenkolonien and Odlambt . The initial fraction of the different farm size classes is estimated based on data collected by FADN (2019) about starch potato farms between the years 2003 and 2014 and model calibration. The initial total cultivation area is calculated by taking the average farm sizes and the initial number of farms for each farm size class. This value was validated using data collected by CBS (2019) about the Veenkolonien and Oldambt.	
FARM INCOME 1. Average_farm_income = ((Farm_profit[small]*Farms[small])+(Farm_profit[medium]*Farms[medium])+(Farm_profit[large]*Farms[large]))/Total_number_of_farms	All variables: [EUR/farm]
The average profit per farm is the weighted average between the number of farms of each farm size class and the profit of each farm size at any given time.	

Table E.4 Model documentation calculating starch potato yield and challenges (corresponding model structure in Fig. D.6).

Formulation and comments	**Units**

STARCH POTATO YIELD
1. Starch_potato_yield = IF TIME <= 2018 THEN Starch_potato_yield_before_2018 ELSE Starch_potato_yield_after_2018
  a. Starch_potato_yield_before_2018 = GRAPH(TIME)
  b. Starch_potato_yield_after_2018 = IF TIME < 2020 OR TIME > 2020+"C3_Length_of_challenge_ON/OFF" THEN Maximum_yield-Yield_fluctuations ELSE Maximum_yield
    i. *all C variables are explained below.
    ii. Maximum_yield = (Maximum_yield_base_value-C3_Size_of_challenge_decreasing_STEP_function+C3_Size_of_challenge_increasing_STEP_function)-C2_Size_of_challenge_STEP_function
      1. Maximum_yield_base_value = 45
    iii. Yield_fluctuations = SINWAVE(Yield_fluctuations_amplitude, Yield_fluctuation_frequency)+Yield_fluctuations_amplitude
    iv. Yield_fluctuations_amplitude = 2-Avebe.S2_Strategy_STEP_function
      1. S variables are explained in Table E.7
	All variables: [ton/ha]

The starch potato yield is a combination between historical data and projected trends until 2050. Until 2018 the historical starch potato yield for the Veenkoloniën and Oldambt, recorded by CBS (2019), are used. After 2018 the yield is simulated using a sine wave that shows approximately the same pattern as the years 2003-2014. This trend is modified in various future yield challenges. The starch potato yield after 2018 is simulated using a maximum yield and yield fluctuations based on a sine function. The actual maximum yield is the maximum yield observed in historical data (CBS, 2019) and any adjustments given different yield challenges after 2020. It is assumed that yields will fluctuate from year to year given the observed past trends. The amplitude and length of the sine function is based on historical trends (CBS, 2019).	
CHALLENGE 1 (C1): 1. SWITCH_C1_Nematodes_decreasing_starch_potato_in_cultivation_plan = 0 2. C1_Size_of_challenge = 0.1 {variable used for challenge sensitivity analysis} 3. C1_Size_of_challenge_STEP_function = (1-SWITCH_C1_Nematodes_decreasing_starch_potato_in_cultivation_plan)*0+(SWITCH_C1_Nematodes_decreasing_starch_potato_in_cultivation_plan)*STEP(C1_Size_of_challenge, 2020)	All variables: [unitless]
The structure for challenge 1 ultimately influences the variable Fraction_of_starch_potato_in_cultivation_plan. A SWITCH can be used to turn on C1 when this is turned to 1 instead of 0. When C1 is turned on then the fraction of starch potato in the cultivation plan is decreased with the variable C1_Size_of_challenge. This occurs only after 2020 with the help of the variable C1_Size_of_challenge_STEP_function.	
CHALLENGE 2 (C2): 1. SWITCH_C2_Decreasing_average_starch_potato_yield = 0 2. C2_Size_of_challenge = 1.72 {variable used for challenge sensitivity analysis} 3. C2_Size_of_challenge_STEP_function = (1-SWITCH_C2_Decreasing_average_starch_potato_yield)*0+(SWITCH_C2_Decreasing_average_starch_potato_yield)*STEP(C2_Size_of_challenge, 2020)	SWITCH: [unitless] Size of challenge: [ton/ha]

The structure for challenge 2 ultimately influences the variable Maximum_yield. A SWITCH can be used to turn on C2 when this is turned to 1 instead of 0. When C2 is turned on then the maximum yield decreases with the C2_Size_of_challenge variable. This occurs only after 2020 with the help of the variable C2_Size_of_challenge_STEP_function.	
CHALLENGE 3 (C3): 1. SWITCH_C3_Extreme_weather_events_causing_low_starch_potato_yields_in_a_number_of_consecutive_years = 0 a. "C3_Length_of_challenge_ON/OFF" = (1-SWITCH_C3_Extreme_weather_events_causing_low_starch_potato_yields_in_a_number_of_consecutive_years)*0+(SWITCH_C3_Extreme_weather_events_causing_low_starch_potato_yields_in_a_number_of_consecutive_years)*C3_Length_of_challenge 2. C3_Length_of_challenge = 2 {1.72/1.8 = Threshold with a yield change amplitude of 11} 4. C3_Size_of_challenge = 11 {variable used for challenge sensitivity analysis} 3. C3_Size_of_challenge_decreasing_STEP_function = (1-SWITCH_C3_Extreme_weather_events_causing_low_starch_potato_yields_in_a_number_of_consecutive_years)*0+SWITCH_C3_Extreme_weather_events_causing_low_starch_potato_yields_in_a_number_of_consecutive_years*STEP(C3_Size_of_challenge, 2020)	SWITCH: [unitless] Size of challenge: [ton/ha] Length of challenge: [year]
The structure for challenge 3 ultimately influences the variable Starch_potato_yield variable between a chosen number of consecutive years by lowing the maximum yield value between those years and removing the fluctuations. A SWITCH can be used to turn on C3 when this is turned to 1 instead of 0.	
CHALLENGE 4 (C4): 1. SWITCH_C4_Increasing_profits_of_other_crops = 0 5. C4_Size_of_challenge = 1.11 {variable used for challenge sensitivity analysis} 2. "C4_Size_of_challenge_ON/OFF" = (1-SWITCH_C4_Increasing_profits_of_other_crops)*1+(SWITCH_C4_Increasing_profits_of_other_crops)*C4_Size_of_challenge	[unitless]
The structure for challenge 4 ultimately influences the variables for the profits of other arable farms. A SWITCH can be used to turn on C4 when this is turned to 1 instead of 0.	
CHALLENGE 5 (C5): 1. SWITCH_C5_Increasing_costs_to_starch_potato_farms = 0 6. C5_Size_of_challenge = 1.095 {variable used for challenge sensitivity analysis} 2. "C5_Size_of_challenge_ON/OFF" = (1-SWITCH_C5_Increasing_costs_to_starch_potato_farms)*1+SWITCH_C5_Increasing_costs_to_starch_potato_farms*STEP(C5_Size_of_challenge, 2020)	[unitless]
The structure for challenge 5 ultimately influences the variables costs to starch potato farms. A SWITCH can be used to turn on C5 when this is turned to 1 instead of 0.	

Table E.5 Model documentation for the Avebe module (corresponding model structure in Fig. D.3).

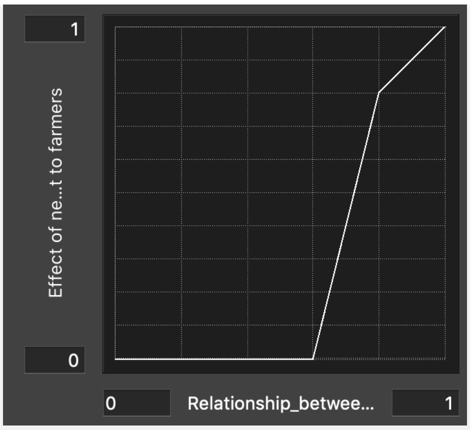
Formulation and comments	**Units**

AVEBE STARCH PROCESSING
1. Total_starch_processed_by_AVEBE = Starch_potato_farms.Starch_potato_production*Starch_Content
    a. Starch_content = IF TIME < 2020 THEN (0.19+Yearly_increase_in_starch_content) ELSE 0.206+"S1_Strategy_ON/OFF"Yearly_increase_in_starch_content = RAMP(Change_in_starch_content_before_2018, 2004)
        i. Change_in_starch_content_before_2018 = 0.001
        ii. *all S variables explained in Table E.7
	Total starch: [ton]
	Starch content: [untiless]
	Change in starch content: [1/year]

It is assumed that Avebe processes all the starch potatoes they receive from the Veenkoloniën farmers into starch. The starch content in 2004 is based on the standard starch content of starch potatoes. Based on reports this starch content has been increasing in the past 20 years and is now roughly at 20%. From this a yearly increase of 0.001 was estimated between 2004 and 2018. In 2020 the simulated starch content is 0.206 and is kept constant from then on.	

AVEBE GROSS REVENUE, NET PROFIT, GROSS PROFIT
1. Avebe_gross_revenue = Total_starch_processed_by_AVEBE*Price_of_starch_products
2. Avebe_net_profit = Avebe_gross_revenue-Avebe_all_costs_from_Veenkolonien
    a. Avebe_all_costs_from_Veenkolonien = Avebe_all_costs*Fraction_Veenkolonien
    b. Avebe_all_costs = GRAPH(TIME)
    c. Fraction_Veenkolonien = 0.4
    d. Average_net_profit = SMTH3(AVEBE_net_profit, Payment_buffer_time)
        i. Payment_buffer_time = 3
3. Avebe_gross_profit = Avebe_net_profit – Total_payment_to_farmers
    a. MAX(Total_desired_payment_from_Avebe*Effect_of_net_profit_on_total_payment_to_farmers, 0)
    b. Total_payment_to_farmers = MAX(Total_desired_payment_from_Avebe*Effect_of_net_profit_on_total_payment_to_farmers, 0)
	[EUR]

The net profit of Avebe is the gross revenue minus the costs of production. These costs do not include the price Avebe has paid to the farmers. The average net profit is the profit of Avebe averaged over 3 years (the payment buffer time). The total costs of Avebe are based on the total costs recorded in Avebe's annual reports (Avebe, 2018b) and the fraction of costs assumed to come from the processing and selling of starch potatoes from the Veenkoloniën. This fraction was based in part on reports and in part on calibration. It may deviate from the 0.6 (Klok, 2019) as the values found and processed for Avebe’s finances may be inaccurate. The gross profit is determined by the net profit minus the total payment to farmers.	
TOTAL PAYMENT TO FARMERS 1. Relationship_between_net_profit_and_total_desired_payment = Average_net_profit/Total_desired_payment_from_Avebe 2. Effect_of_net_profit_on_total _payment_to_farmers	Total payment [EUR] Other [unitless]



3. Total_payment_to_farmers = MAX(Total_desired_payment_from_Avebe*Effect_of_net_profit_on_total_payment_to_farmers, 0)

The relationship between net profit and the total desired payment will be above 1 if the total desired payment is below the average net profit and vice versa. This variable is used in the assumption that Avebe can still keep paying farmers even if the relationship is slightly below 1. Avebe will only stop paying farmers if the relationship falls very far below 1. This is determined by the lookup table shown above. The total payment to farmers is decreased slightly when the relationship is between 0.6 and 1. Below 0.6 no payment can be made to farmers.

STARCH POTATO PRICE AND DESIRED PAYMENT

1. Starch_potato_price = Total_payment_to_farmers/Starch_potato_farms.Starch_potato_production
2. Price_adjusted_for_starch_content = IF TIME <= 2013 THEN (Avebe_starch_potato_performance_price/0.19)*Starch_Content ELSE (Price_of_starch_potato_desired_by_farmers/0.19)*Starch_Content
   a. Avebe_starch_potato_performance_price = GRAPH(TIME)
   b. * Desired price explained in Table E.6

EUR/ton

The starch potato price is the price that the farmers receive for selling their potatoes to Avebe. Until 2014 the historical starch potato price recorded by Avebe is used. After 2014 the price is calculated by the average price farmers want to receive, given a certain profit of other crops. This assumption is based on statements by Avebe that they want to ensure a reasonable income benefit of growing starch potatoes rather than another crop (Avebe, 2018a).

The price of starch potatoes is adjusted for starch content. Standard starch potatoes have a starch content of 0.19. Potatoes with a higher starch content receive a higher price. Before 2014 this price is determined by the historical price Avebe has paid. After 2014 this price is determined by the desired price if starch potato cultivation receives at least as much income as cultivating other types of crops (desired price).

Table E.6 Model documentation of side calculations in the Avebe module (corresponding model structure in Fig. D.5).

Formulation and comments	**Units**
DESIRED STARCH POTATO PRICE 1. Price_of_starch_potato_desired_by_farmers = MEAN(Starch_potato_price_needed_by_small_farms, Starch_potato_price_needed_by_medium_farms, Starch_potato_price_needed_large_farms) a. Starch_potato_price_needed_by_small_farms = (Starch_potato_farms.Profit_per_ha_other_small_arable_farms_before_2014+Starch_potato_farms.Costs_per_ha_small_farms_before_2014-Starch_potato_farms.Output_from_wheat_and_sugar_beet_adjusted_for_fraction_in_cultivation_plan)/(Starch_potato_farms.Starch_potato_yield*Starch_potato_farms.Fraction_of_starch_potato_in_cultivation_plan) i. *Same calculation for medium and large farms with respective variables	EUR/ton
The starch potato price that is desired by farmers is average total desired price between the different size classes. The starch potato price required by each size class is determined by calculating the price that would be necessary if the profit of starch potato cultivation is the same as the profit of other crops per size class.	

Table E.7 Model documentation for strategies (corresponding model structure in Fig. D.7).

Formulation and comments	**Units**
STRATEGY 1 (S1) 1. SWITCH_S1_Increasing_starch_content = 0 2. S1_Size_of_strategy = 0.1 {Variable used for strategy sensitivity analysis} 3. "S1_Strategy_ON/OFF" = (1-SWITCH_S1_Increasing_starch_content)*0+(SWITCH_S1_Increasing_starch_content)*S1_Size_of_strategy	[unitless]
The structure for strategy 1 ultimately influences the variable Starch_content. A SWITCH can be used to turn on S1 when this is turned to 1 instead of 0. When S1 is turned on then the starch content increases with the S1_Size_of_strategy variable.	
STRATEGY 2 (S2) 1. SWITCH_S2_Increasing_average_yield_by_means_of_decreasing_yield_variability = 0 2. S2_Size_of_strategy = 0.6 {Variable used for strategy sensitivity analysis} 3. S2_Strategy_STEP_function = (1-SWITCH_S2_Increasing_average_yield_by_means_of_decreasing_yield_variability)*0+SWITCH_S2_Increasing_average_yield_by_means_of_decreasing_yield_variability*STEP(S2_Size_of_strategy, 2020)	SWITCH: [unitless] Size of strategy and STEP function: [ton/ha]
The structure for strategy 2 ultimately influences the variable Yield_fluctuations_amplitude. A SWITCH can be used to turn on S2 when this is turned to 1 instead of 0. When S2 is turned on then the yield fluctuations decrease with the S2_Size_of_strategy variable. This means that the average yield is ultimately increased. This only occurs after 2020 with the help of the STEP function.	

STRATEGY 3 (S3)

1. SWITCH_S3_Increasing_Avebe_product_value = 0
2. S3_Size_of_strategy = 0 {Variable used for strategy sensitivity analysis}
3. "S3_Strategy_ON/OFF" = (1-SWITCH_S3_Increasing_Avebe_product_value)*1+(SWITCH_S3_Increasing_Avebe_product_value)*S3_Size_of_strategy

[unitless]

The structure for strategy 3 ultimately influences the variable Price_of_products. A SWITCH can be used to turn on S3 when this is turned to 1 instead of 0. When S3 is turned on then the price of products increase with the S3_Size_of_strategy variable.

Appendix F: Model data

Table F.1 The data requirements and processing steps for all required data inputs for the `Starch potato farms` module. The data is found in Table F.3.

Data input	Data source	Further explanation and data processing

Costs per hectare of starch potato farms between the years 2004 and 2013[1]
[EUR/ha]
Model variables:
`Costs per ha small farms`
`Costs per ha medium farms`
`Costs per ha large farms`
	FADN (2019)[2]	The FADN data was 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. Fixed costs per hectare were calculated by dividing the “Total farming overheads“ by the “Total crops area“. Variable costs are already given as “Specific crop costs per ha“. Averages were calculated for each year for each farm size class[3].

Profit per hectare of other arable farms between the years 2004 and 2013[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 was 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 year for 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`
`Wheat 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.

[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).

Table F.2 The data requirements and processing steps for all required data inputs for the `Avebe` module. The data is found in Table F.4.

Data input	Data source	Data processing
Avebe costs [EUR] *Model variables:* `Avebe all costs`	Avebe annual reports	Avebe annual reports between 2001 and 2018 were recovered 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 recovered 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.

Table F.3 The time series data that is used as model input for the `Starch potato farms` module. For more information consult the file Final_data.xlxs in the supplementary material.

Year	Yield			Price			Costs			Profits		
	Starch potato yield	Sugar beet yield	Wheat yield	Starch potato price	Sugar beet price	Wheat price	Costs per ha small farms	Costs per ha medium farms	Costs per ha large farms	Profit per ha other small arable farms	Profit per ha other medium arable farms	Profit per ha other large arable farms
	ton/ha	*ton/ha*	*ton/ha*	*EUR/ton*	*EUR/ton*	*EUR/ton*	*EUR/ha*	*EUR/ha*	*EUR/ha*	*EUR/ha*	*EUR/ha*	*EUR/ha*
2000	44	58	7									
2001	43	53	8									
2002	43	55	7	51	45	106						
2003	38	57	8	26	49	132						
2004	45	62	8	50	49	102	1385	1280	1386	756	2266	1049
2005	44	62	8	65	47	106	1435	1341	1447	1314	2409	1496
2006	38	65	7	85	45	140	1070	1437	1345	1953	2977	2101
2007	42	66	7	50	40	216	1426	1522	1340	1185	2335	1837
2008	46	71	8	47	40	152	1925	1784	1530	1013	1071	1691
2009	45	74	8	67	42	121	1454	1709	1467	3554	1422	1621
2010	40	70	8	77	42	213	2039	1458	1518	1424	2008	2728
2011	44	76	7	77	52	201	1753	1605	1753	362	1120	1435
2012	44	75	8	75	62	238	2370	1618	1793	2954	1711	2861
2013	39	73	8	78	64	191	2412	2123	1969	1734	1326	2170
2014	42	83	9	77	48	169						
2015	43	76	8	82	41	155						
2016	44	74	8	86	43	163						
2017	43	87	8	0	43	163						
2018	34	70	8	0	34	209						
Source	CBS (2019)	CBS (2019)	CBS (2019)	Avebe (2018b)	Agrimatie (2019)	Agrimatie (2019)	FADN (2019)	FADN (2019)	FADN (2019)	FADN (2019)	FADN (2019)	FADN (2019)

Table F.4 The time series data that is required as model input for the `Avebe` module. For more information consult the file Final_data.xlxs in the supplementary material.

Year	Avebe all costs	Price of products
	Million EUR	*EUR/ton*
2001	661	1755
2002	621	1632
2003	601	1565
2004	651	1519
2005	625	1628
2006	583	1581
2007	611	1676
2008	568	1494
2009	511	1340
2010	488	1304
2011	504	1366
2012	530	1355
2013	526	1332
2014	504	1284
2015	536	1352
2016	537	1358
2017	560	1421
Source	Avebe (2018b) processed	Avebe (2018b) processed

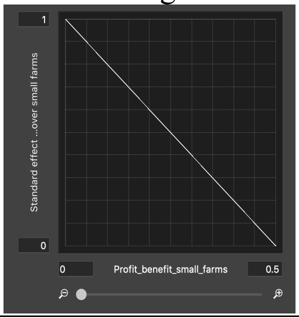
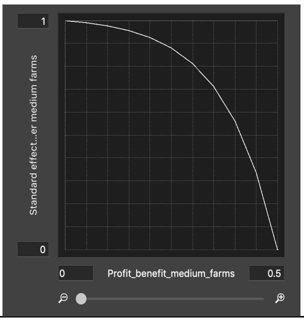
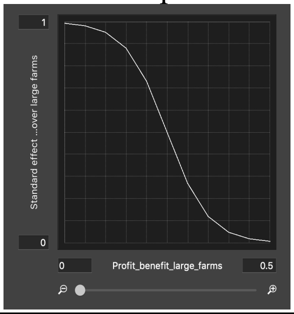
Appendix G: Model testing

A sensitivity analysis was done to by varying all parameter values with +/- 50% from the original value. The change from the base value was calculated for a number of indicators, including total cultivation area, total starch potato production, average farm income, average farm size, starch potato price and Avebe gross profit. No large difference was found between the impacts on different indicators. Below are the results for total cultivation area, for which the largest impact was found for most parameter values.

Table G.1 The relative change in simulated cultivation area in year 2013 when parameter values were varied with +/- 50% the original value.

Parameter name		-0.5	-0.25	0	0.25	0.5
`Size of effect`	Small farms	0.02	0.01	0	-0.01	-0.01
	Medium farms	**0.05**	**0.02**	**0**	**-0.02**	**-0.04**
	Large farms	0.02	0.01	0	-0.01	-0.02
`Time to change farming activities`	Small farms	-0.03	-0.02	0	0.01	0.02
	Medium farms	**-0.07**	**-0.03**	**0**	**0.02**	**0.03**
	Large farms	-0.04	-0.01	0	0.01	0.01
`Area available to medium farms`		0.01	0.01	0	-0.01	-0.01
`Fraction of farms leaving`		-0.01	0.00	0	0.00	0.01
`Average vacancy time of free land`		-0.01	0.00	0	0.00	0.01
`Fraction Veenkolonien`		0.00	0.00	0	-0.78	-0.85
`Payment buffer time`		0.00	0.00	0	0.00	0.00

Table G.2 The relative change of the simulated cultivation area in year 2013 that was caused by changing the shape of the table function in `Standard effect of relative profitability on average turnover small/medium/large farms,` from a straight to a concave to an s-shaped curve.

	Straight  	Concave  	S-shaped 
Small farms	0	-0.053	0.030
Medium farms	**0**	**-0.740**	**0.039**
Large farms	0	-0.116	0.027
Combined	0	-0.858	0.090

Appendix H: Simulation results

Table H.1 Slopes of the first threshold lines for different strategy (S1-S3; x-axis) and challenge (C1, C2, C4, C5; y-axis) combinations.

	S1	S2	S3
C1	1.0	1.3	1.1
C2	0.8	1.0	0.8
C3	0.25	0.16	0.28
C4	3.1	3.1	2.5
C5	2.4	2.4	1.6