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Assessing seed and breeding interventions for organic farming using a multiagent value chain approach

Eva Winter[1,2,3*], Christian Grovermann[2], Monika M. Messmer[2] and Joachim Aurbacher[1]

*Correspondence: eva.winter26@gmx.de

[1] Institute of Farm and Agribusiness Management, Justus-Liebig University of Giessen, Senckenbergstrasse 3, 35390 Giessen, Germany
[2] Research Institute of Organic Agriculture (FiBL), Ackerstrasse 113, 5070 Frick, Switzerland
[3] Economic Modelling and Policy Analysis, Agroscope, Tänikon 1, 8356 Ettenhausen, Switzerland

Abstract

According to the EU's organic regulation, the use of organic seed is generally binding in organic farming. Because of an organic seed shortage, derogations to use nonorganic seed can be obtained. By 2036, the EU plans to phase out these derogations and achieve 100% organic seed use. Previous attempts at achieving this, though, have failed. Ensuring organic seed supply is of particular EU-wide importance to meet EU policy goals, such as the farm-to-fork strategy. To assess the impact of measures to smooth this transition, we developed the VAL-MAS model (*VALue chain Multi-Agent System*). VAL-MAS is a multiagent model based on a heterogeneous agent population and mathematical programming that can provide insights into the performance of different seed system interventions. We selected organic fresh market carrots in Germany for their importance in the national and European organic sector as an example case. Our model suggests that the end of the derogation system poses a challenge to the seed value chain in terms of seed supply and farm incomes. The most effective mitigation solution is an investment in improved pest control during seed multiplication, accompanied by a stepwise phasing out of derogations for the use of nonorganic seed.

Keywords: Simulation, Mathematical programming, Agent-based modelling, Seed and breeding value chain, Organic seed, Ex ante policy evaluation

Introduction

One of the main principles of organic farming is that the agricultural inputs used in organic production systems, such as fertilizers or seed, should comply with the rules of organic agriculture (European Commission 2007). This principle ensures the integrity of organic agriculture along the value chain. However, in the case of seed, this requirement is largely unmet, even though it is at the heart of the farming system. Over the past couple of decades, there has been a lack of sufficient organic seed supply in the EU because of low investments in seed multiplication and breeding for the organic sector. In response to the organic seed shortage, the EU organic regulation allows for derogations at the species or subspecies level to use nonchemically treated (NCT) seed, which is not produced under organic conditions (Döring et al. 2012). By 2036, the EU plans to phase out the derogations and achieve 100% organic seed for the sector (Organic Regulation 848/2018). A strategy is still missing on how to secure a sufficient organic seed supply. This is of particular importance to meeting EU policy goals, as formulated in the farm-to-fork strategy (European Commission 2020). The envisaged increase in organic land share to 25% will create a higher demand for organic seed. Previous attempts to phase out the derogations have failed because the phasing out was not accompanied by a strategy to build up the organic seed sector first, hence leading to seed shortages.

Organic seed production and use vary substantially among countries and crops (Solfanelli et al. 2019). Thus, there is a need to identify crops of high importance for the organic sector for which organic seed is difficult to produce or where organic seed use at the farm level is still very low; this can help in implementing measures towards more organic seed production and use. In the present study, we examine the case of organic carrots for storage and fresh markets in Germany, where little organic seed has been used so far (around 10%). Growers are granted general permission to use NCT seed (Herstatt 2017), and seed producers are confronted with substantial challenges in organic seed production: a lack of effective pest management (Wohleb 2019), limited access to suitable production areas, and a low number of farmers willing to produce this type of seed. The selected case is also of interest because organic carrots are among the most produced and consumed organic vegetables in Germany (Destatis 2018).

Very few measures have been implemented by European countries to encourage organic carrot seed production and use. Only in France are ongoing attempts being made to phase out derogations for organic carrots in a stepwise process (Orsini et al. 2019). Furthermore, in five EU countries, derogations to use NCT carrot seed have to be individually requested. Overall, the NCT seed amount granted through derogations in 2016 has increased on average by 96% compared with the year 2014 in all EU countries and in Switzerland (Orsini et al. 2019).

There is a growing number of studies on the specific aspects of the seed market for organic production. Breeding for organic farming, farmers' attitudes to organic seed, and the current state of the EU organic regulation relating to organic seed have, for example, been subject to investigation (Döring et al. 2012; Lammerts van Bueren et al. 2011; Bocci et al. 2012; Rey et al. 2013; Orsini et al. 2020). However, there is a lack of studies focusing on the obstacles in organic seed use and production and that systematically analyse the effects of interventions to overcome these obstacles along the value chain from breeding to farming. To this end, models are needed that can show the enabling factors, decision-making, and interactions of actors along the seed value chain so that feasible solutions for boosting organic seed use can be identified for the sector. Different actors and their interactions, that is, breeders, seed producers and farmers, as well as the overarching political framework laid down in the EU organic regulation of the organic sector, contribute to the problems in and offer solutions for the organic seed market. As a result, all need to be considered in a policy impact assessment. The mapping of value chains and subsequent benefit–cost or SWOT analyses with or without active stakeholder involvement have been repeatedly conducted to analyse seed and other agricultural value chains (Bellù 2013; Mulugeta et al. 2010; Kumara et al. 2012; Senyolo et al. 2018; Das and Roy 2021; Mallick et al. 2017). These methods can be complemented by more sophisticated assessment approaches, which can provide more in-depth insights into system dynamics. Rich et al. (2011) and Nang'ole et al. (2011) give an overview of existing agricultural value chain analysis frameworks, highlighting that, to a large extent, they are qualitative, which is still true today. Therefore, they recommend system dynamics and agent-based models to conduct quantitative ex ante policy assessments of value chains.

Ex ante policy assessment via simulation models is a useful means of testing policy instruments that could smooth the transition period and deliver long-term solutions to increase organic seed production and use. A large number of studies exist in which agricultural policies and private sector interventions are tested ex ante through simulation modelling. Existing models mostly assess policy implications at the farm or sector levels, while the assessment of entire value chains has so far been neglected (Heckelei and Britz 2001; Janssen and van Ittersum 2007; Grovermann et al. 2017; Häring 2003; Bunte and Galen 2015; Schreinemachers and Berger 2011; Appel et al. 2019). Applications often relate to farm-level input choices under varying conditions (Schreinemachers and Berger 2011; Grovermann et al. 2017; Berger et al. 2017). Numerous value chain models using mathematical programming techniques in the field of operations research exist that strive to optimise the economic and/or environmental behaviour of one or more actors in the value chain under given or predicted conditions (Beamon 1998; Gjerdrum et al. 2010; Banasik et al. 2017). Their aim is to re-allocate resources in order to eliminate inefficiencies. In this field, the importance of value chain analyses has long been established, while policy evaluation in agriculture still heavily relies on analyses of the farm level only, taking only one stage of the value chain into consideration. Nevertheless, the importance of including heterogeneity of farms is increasingly being acknowledged, as policy schemes in Europe have become more tailored to specific farm types over the years. In this context, the farm as the most important instance of decision-making. Consequently, agent-based models have been developed that are able to provide insights into the heterogeneity of farmers' individual decision-making behaviour (El Benni et al. 2023; Reidsma et al. 2018).

However, we argue that there is also an urgent need to capture input supply decisions alongside farmer behaviour in agricultural simulation models, especially in cases where supply is known to be a potential bottleneck. Furthermore, value chains for organic seed are diverse and organic farms are highly dependent on certain external inputs, especially concerning vegetable seed (Orsini et al. 2019).

The present study proposes the VAL-MAS model *(VALue chain Multi-Agent System)*, a mathematical programming and agent-based value chain simulation model for the ex ante assessment of seed system interventions. It represents a novel integrated modelling approach that can generate better insights into the production and use of organic seed, as well as into the effects of organic seed policies in the EU. Based on the VAL-MAS model, our study aims to close the following research gaps:

- Which policy or private sector measures can increase the use and production of organic seed, and what are the economic implications for the actors in the organic seed value chain.

- Quantitative value chain analysis for robust and systematic ex ante evaluation of policy interventions targeting value chains, where the analysis has so far been mainly limited to qualitative assessments.

The materials and methods are explained in the next section, followed by the results. Finally, discussions, policy implications, and conclusions are presented.

Materials and methods

Conceptual background of the modelling approach

Definition of the research question and quantitative outcome variables

The primary quantitative outcome variables that we will assess are the use and production of organic seed. A secondary outcome variable is the gross margin of different value chain entities. A number of factors can influence these variables. The main factors, as well as the nature of their influence, are presented in Table 1. Furthermore, in the last column of this table, the model implementation of the influencing factors in relation to outcome variables is briefly outlined.

The VAL-MAS model

As explained in the introduction, our ex ante impact assessment of seed system interventions relies on the VAL-MAS value chain model, in which a system of agents in the seed and breeding value chain (comprising breeding, seed production, and farming agents) makes decisions based on mathematical programming and heuristics. Agent-based systems are a valuable tool when modelling the behaviour of different actors in a heterogeneous population, where each entity takes individual decisions and reacts to the decisions of other entities (Gjerdrum et al. 2010; Schreinemachers and Berger 2006). In the present study, actors always refer to real-world actors, while agents are their representatives in the modelling context. The term value chain level is used to summarize all actors or agents who are active in the respective value chain level: breeding, seed multiplication, and farming.

Individual decision-making Because the actors along the organic seed value chain and within one level of the seed value chain are highly heterogeneous with respect to their decision-making behaviour (Orsini et al. 2019), a multiagent system is well suited when modelling the vertical and horizontal complexity of the seed value chain. Therefore, we chose an approach representing individual decision-making, not an aggregate modelling approach. In this study, an entire agent population with individual decision-making per agent is considered at the farm level. At multiplication and breeding levels, typical seed supply actors are represented by decision-making agents.

Mathematical optimisation Mathematical optimisation models are often used in agricultural economics to find optimal solutions for economic decisions, such as optimal production plans at the farm level under the given resource constraints. Generally, either production costs are minimized or gross margins are maximized when taking these constraints into account (Hazell and Norton 1987). Based on standard microeconomic theory, optimisation models allow us to model the behaviour of individual agents that

Table 1 Seed system context and model implementation

Outcome variable	Influencing factors	Nature of influence	Model implementation
Production of organic seed	Demand	Currently, demand for organic seed is low. This hampers its production	Expectations on seed demand are endogenously adapted each year by seed producers based on past sales
	Ease of production	For some crops, organic seed production is technically challenging, thus holding it back. For some cultivars, it is not possible to produce organic seed from these crops	Seed production activities are modelled in detail, as well as with an upper limit on production increase
	Cost of production	Organic seed production is in almost all cases more expensive than nonorganic production. This results in a higher price for organic seed and lower demand	Costs and revenues of seed production activities are modelled
	Policy framework	Derogations allowing for the use of NCT seed hampers organic seed production	The current situation is reflected in the baseline while changing regulations are modelled in scenarios
Use of organic seed	The availability of organic seed	There is currently only a limited range and amount of organic seed available	The baseline is calibrated according to the current use of organic seed. This is the starting point in scenarios aiming at a production increase. An upper limit reflecting a realistic growth rate ensures a realistic increase
	Quality of seed	In some cases, organic seed is of lower quality (e.g. regarding the germination rate). This does not make it a farmer's first choice	Crop production activities are modelled at an input and output level disaggregated to seed requirement and price at the hectare level
	Suitability of cultivars	Only a limited number of cultivars are available as organic seed. The cultivars are sometimes not the preferred choice of the organic farmer	Individual cultivars are not modelled but the average characteristics of cultivars available in NCT seed, organic seed, or organic cultivars[a]
	Policy framework	See above	See above
	Attitudes and expectations from downstream value chain actors	Currently, there is limited awareness and emphasis on the use of a specific kind of seed. This does not induce the farmer to use organic seed	The behaviour of downstream value chain agents are not endogenously modelled. Scenarios that include a higher farm gate price are modelled exogenously
	Cost of seed	Organic seed is generally more expensive for farmers than NCT seed. This is a major constraint for farmers to switch to organic seed	Crop production activities are modelled in detail, disaggregated to seed requirement and price at hectare level
	Attitudes and expectations from organic farmers	Attitudes about the importance and need for organic seed varies among organic farmers and can be strong (de) motivators	An individual excess willingness to pay for organic seed per farmer was estimated and included as an exogenous parameter in the model

[a] In the present study, organic cultivars are organically bred cultivars where the entire breeding process is conducted under organic conditions. The seed multiplication process is also conducted under organic conditions

have a vast range of decision options and objectives to choose from. This makes optimisation models particularly suitable for modelling detailed input decisions, such as seed use (Schreinemachers and Berger 2006, 2011). Therefore, optimisation is central in the VAL-MAS model.

Heuristics Clearly, not all decisions by actors are taken "rationally", as described by microeconomic theory, and follow an optimisation logic. Therefore, this has to be complemented with so-called heuristics, where decisions are taken based on a predefined decision tree, which offers far less flexibility in choices than optimisation but can capture behaviours that are not fully rational from an economic perspective. Schreinemachers and Berger (2006) argue that a combination of agent-based systems, optimisation, and heuristics is advisable for realistic modelling of decision-making behaviour at the farm level. Consequently, whereas evidence suggests that other decision rules need to be taken into account, we implemented heuristics in addition to optimisation, adopting a combined approach. The selected heuristics include, for example, an excess willingness to pay (WTP) for organic seed at the individual farm level. This is further explained in "Data collection and parameterization of the VAL-MAS model" section.

Dynamic modelling approach When simulating processes (e.g., breeding and farming) with different time horizons in one model, a dynamic model approach is essential in capturing those developments emerging under different model scenarios. Moreover, once the activities in a particular year are fixed by the agents, a feedback loop is needed between the value chain levels. As a result, the start values of a certain period need to be the end values of the previous period. Thus, we deemed it the most suitable to embed in the model a positive recursive-dynamic decision-making algorithm based on a combination of optimisation and heuristics. The statistical software STATA15 and optimisation software GAMS 24.1 were used to script and parameterize the model. Complete documentation of the VAL-MAS model is available in Additional file 1.

Case study selection and description

Political framework Because derogations for NCT seeds are tied to the country's legislation, and to the specific crop, the boundaries of our case study were accordingly defined. The analysis is limited to one country and to one specific crop at the farm level. The case of wash/storage carrot production for the fresh market (rather than, e.g., processing) was selected for its importance in the organic sector in Germany and the EU as a whole (Orsini et al. 2019). Moreover, it represents the challenges faced across a range of high-value crops in the EU, that is, the great lack of organic seed and cultivars in the value chain. This situation is because of the derogation scheme, as well as prevailing technical difficulties, which require considerable investments to be overcome. This also means that policies and private sector interventions can make a real difference in scaling up the use and availability in such situations.

Data availability at the farm level Another primary criterion for case selection was data availability so that the model could be fully parameterized. The availability of detailed production information was one of the most significant bottlenecks for the present study because economic data on breeding, multiplication, and organic farming is scarce and often confidential. There are approximately 800 organic carrot producers in Germany cultivating around 2100 ha, with a resulting seed demand of approximately 4200 Mio seeds per year (Destatis 2018). Expert estimates indicate that around 50% of organic carrots produced in Germany are for the fresh market segment and belong to the cultivar group "wash/storage".

Data availability at seed production and breeding levels Around 10 relevant seed companies produce the carrot seed used in organic agriculture; these companies are based in the Netherlands and Germany, most of which have a breeding department in addition to seed production. These companies are primarily international players that produce seeds and cultivars for conventional and organic vegetable producers. Furthermore, some organic breeding and seed production initiatives exist. These initiatives produce open-pollinated (OP) cultivars and are mostly active only in Germany and are relatively small (Orsini et al. 2019). For all input data, value added taxes are excluded and deflated with real interest rates, where relevant. All direct payments or subsidies are excluded from calculations unless specifically mentioned so that the effects of scenarios can be observed applying the ceteris paribus assumption.

Data collection and parameterization of the VAL-MAS model

Input data and definition of typical companies and initiatives at seed production and breeding levels

Mapping of value chain actors It was necessary to identify the typical breeding and seed production entities against the background of data scarcity because of the limited willingness of actors to share economic data. We defined a typical entity as a company or initiative with a large market share in organic seed production and/or organic breeding. A value chain mapping of the seed and breeding value chain of German organic carrot production was conducted to obtain an overview of the actor landscape. Data on typical breeding and multiplication processes were then obtained through a series of stakeholder and expert interviews between 2017 and 2020. The mapping revealed that around nine companies were involved in providing seeds for organic carrot producers in Germany and that only very few had a large market share (Herstatt 2017; Orsini et al. 2019). These nine companies and initiatives were contacted, and face-to-face interviews with identified actors willing to participate were conducted (Anonymized information about the companies and initiatives can be found in Additional file 2: Appendix A.1). Two types of actors could be identified.

Types of seed producers and breeders One type of actor was an internationally active commercial seed and breeding company that sold NCT hybrid seed and organic hybrid seed to organic carrot producers in Germany. This type will be referred to as Type I. The second type was a small company or initiative dedicated to breeding and/or locally selling OP vegetable organic seed from organic cultivars. This type will be referred to as Type II. We interviewed three companies corresponding to the first type and three companies or nonprofit initiatives corresponding to the second type. They gave insights into market structures and general figures on breeding and multiplication costs, as well as challenges in carrot seed production and breeding. One company and two organic breeding and seed production initiatives shared detailed information on costs and revenues, inputs, and outputs of carrot breeding and seed multiplication, bottlenecks in seed production, promising breeding goals, and scenarios to boost the organic seed and breeding sector. Family-owned companies constituted the governance model in Type I, with a financing strategy for seed and breeding through commercial seed sales. The size of the companies was large, with a yearly total sales revenue of above 150 Mio €. Their target markets were both national and international. Organic, NCT, and CT vegetable seed was produced. Type II represented companies that specialized in organic vegetable seed and only produced OP (as opposed to hybrid) organic cultivars. They were small-sized (yearly sales revenue below 10 Mio €) shareholder-owned companies and had target markets mostly in Germany and Switzerland. The seed production costs were covered by seed revenues. However, breeding did not need to be refinanced because the cultivars were provided by a breeding initiative, which is described further in the next section.

Technical implementation in the VAL-MAS model Regarding the implementation in the simulation model, two breeding types were also represented in the simulation model. Type I was defined as the breeding department of an internationally active company that also produced seed. No breeding programs specifically or uniquely for organic carrot production were conducted; nevertheless, organic cultivar trials were carried out to choose the best-suited cultivars for organic conditions. Hybrids were developed. Eight to ten new carrot cultivars have been placed on the market each year to stay competitive, and these cultivars were stated as having a life span of around 12 years. To refinance the breeding programs, 13,545 ha of carrot production area needed to be planted with the company's seed. The organic area share was 1,505 ha, 11% of the total area, while the yearly fresh market carrot breeding budget was estimated to be around 30% of the revenue. Type II characterized a company specialized in breeding organic cultivars, which exclusively developed OP cultivars. The governance model consisted of a breeding initiative with fragmented funding. The prefinancing of breeding activities happened through voluntary contributions from seed multipliers, alongside donations and sponsorship. We have assumed that around 10% of the total seed sales from the company's cultivars were voluntarily returned to it for refinancing purposes. A complete list of the input and output parameters of the VAL-MAS model can be found in Additional file 2: Appendix A.2.

Scaling factors to make value chain levels compatible To model the entire wash/storage carrot seed production enterprise of both agents, scaling factors were implemented in the model. These ensured compatibility between the actual seed sales market and available German organic carrot production area.

If this were omitted, economies of scale would not be realized. The cultivated area in the case study would not be interesting enough as a seed market for the larger of the two typical seed producers. Because the present agent-based value chain model was the first to simulate the seed value chain fully, there was no precedent for this procedure.

Nevertheless, scaling factors have been commonly used to ensure compatibility between agents or activities in multiagent and integrated farm system modelling (Troost and Berger 2015b; Gibbons and Ramsden 2008). In the present study, the scaling factors were used to connect the three value chain levels to match supply and demand. For example, one of the interviewed carrot seed producers had a market size of 1505 hectare organic carrot production, while, according to German statistical data, the organic carrot producers in Germany covered 2100 ha (Destatis 2018), of which around 1200 to 1400 ha were covered by carrots for main production and storage (German organic carrot expert estimation). Consequently, the scaling factors from seed multiplier (Type I) to farmers varied from 0.8 to 0.93, depending on the random seed value for the generation of the agent population, and from farmers to multiplier, it ranged between 1.1 and 1.25.

Input data and creation of an agent population at the farming level

Input data at the farm level To generate the agent population of organic carrot producers in Germany, we relied on the farm accountancy data ("Agrarstrukturerhebung") from 2016, provided by the national statistical office in Germany (RDC 2016). For the analysis and agent generation, STATA15 was used. The organic wash/storage carrot farm agent population for carrots was generated and verified with 100 agents. However, in reality, there were around 325 farmers (Destatis 2018). The results did not differ significantly, while the more parsimonious specification of the agent population allowed for speeding up the modelling runs substantially. To ensure compatibility, we used a scaling factor of 3.25, which scaled up the farming level to reality.

Agent generation using a copula approach A copula approach was used to estimate a joint distribution between selected key farm characteristics, here by following the procedure proposed by Troost and Berger (2015a). The aim was to obtain combinations of the characteristics of individual observations and their frequencies. For the joint distribution, farm characteristic variables were divided into quintiles (a higher resolution was not possible because of privacy restrictions). Subsequently, matrices were created from the combinations of quintiles along the farm characteristics of each observation in the dataset. This is illustrated in Fig. 1. The observed frequencies within the multidimensional space

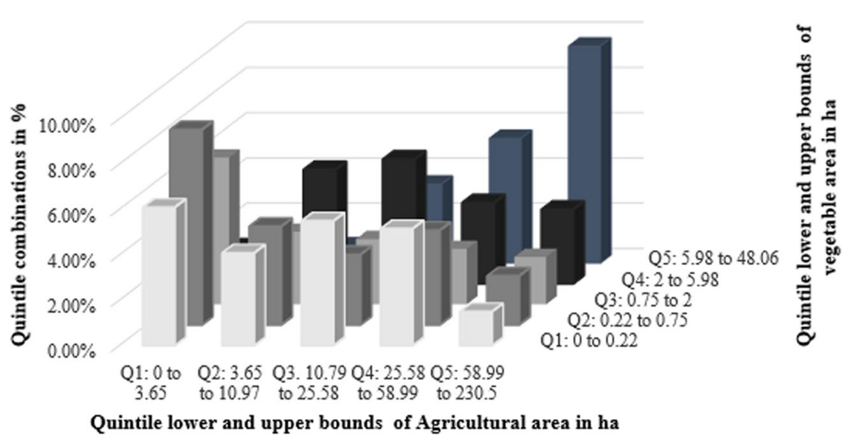

Fig. 1 Copula of arable area and vegetable area based on own calculations using the data from the RDC (2016)

served as an empirical copula from which the agents for the agent population were drawn. An approach with several copulae, including total agricultural area as the main matching variable and other important farm characteristics, was adopted to avoid the barring of values in the copulae because of privacy restrictions.

Farming types One copula included the total agricultural area, farm area, organic vegetable area in rotation with other vegetables and with arable crops, and available labour per farm. Other copulae included the total agricultural area and one other relevant crop area (winter wheat, winter rye, legume mixture, beans, potatoes) or the farm manager's education.

Here, 85% of farm agents depicted in the simulation model belonged to the farm type "carrot production in crop rotation with arable crops." The farm type "carrots in rotation with other vegetables" comprised 15% of all farm agents. The average agricultural area of the two types at the relevant farm enterprise level was 25 ha, and the vegetable area 3.79 ha on average. These parameters were based on own calculations using the data within the scope of this research from the Research Data Centres of the Federal Statistical Office and Statistical Offices of the Federal States (RDC 2016).

Figure 1 depicts an example of the copula between the agricultural and vegetable areas. The copula approach captured linear and nonlinear relationships between farm characteristics.

Diffusion of innovations To model the diffusion of organic seed and innovations revolving around organic seed and breeding in the farm agent population according to the differences in the aptness of farmers to adopt organic seed, the model included a feature representing the diffusion of an innovation according to the network threshold theory of Rogers (2003) and procedure proposed by (Troost and Berger 2015b). Following this theory, farm agents were categorized into five segments: innovators (2.5% of the population), early adopters (13.5%), early majority (34%), late majority (34%), and laggards (16%). This reflects learning in a social network and incomplete information, as can often be observed in reality. In this case, only if the first group has adopted the innovation will the second group be able to adopt it and so on. The agents in the model were assigned to the network segments based on the statistical estimation of propensity scores. To establish the innovativeness scores in the agent population, influential characteristics were regressed on organic seed use with recent survey data on organic farmers (Orsini et al. 2020). More information can be found in Additional file 2: Appendix A.3.

Price data at the farm level Further farm population data were obtained from diverse sources. Whole-sale price data for washed carrots for the fresh market were available as a time series for 10 years from Agrarmarkt Information GmbH (AMI 2020) and detrended to correct for trend-related changes, such as a general increase in prices (Baum 2006). The ranges of the prices were implemented in the model as triangular distributions for sensitivity analysis. From the German national statistics on vegetable yields (time-series data comprising 5 years), the yield ranges of crops in crop rotation were calculated and, as with prices, were implemented in the model as triangular distributions for sensitivity analysis (see "Sensitivity analyses" section for further information). The interactions between seed prices and farm gate product prices were captured in a range of scenarios, where higher farm gate prices could, for instance, compensate for the price gap between organic seed and NCT seeds.

Crop rotations The first farm type, "carrot production in crop rotation with arable crops", was assigned a typical mixed crop rotation, including carrots, onion, winter wheat, winter rye, beans, and green manure. Similarly, the second farm type, "carrots in rotation with other vegetables", was assigned a typical vegetable crop rotation comprising carrot, salad, leek, cabbage, and green manure. Both crop rotations were selected based on a survey among German organic carrot producers and expert verification.

Further input data at the farm level Because no complete data set with all the necessary parameters was available, the technical coefficients and variable costs for the crops in the crop rotation were taken from Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL 2016), the German national database on agricultural figures, and were matched with the agent population. The main matching variable was vegetable area. With the help of a small survey among German organic carrot producers (more information in Additional file 2: Appendix A.4), we narrowed down the relevant farming systems from KTBL out of all available farming systems relating to the range of plot sizes, degrees of mechanization, typical crop rotations, distance between farm and field, and type of production system (bed or bank cropping).

Specification of agent decision-making

Decision-making of agents via individual objective functions

Objective functions At the farming level, the gross margin per farm enterprise agent was maximized. The farm enterprise agent in this model application was defined by the crops in the organic carrot crop rotation. At the seed production level, the gross margin of organic and NCT carrot seed production was optimised for each seed multiplication agent. The processing, packaging, and marketing costs were largely the same for conventional untreated and organic seeds; thus, these costs were disregarded at the multiplication level. Finally, at the breeding level, we implemented a revenue maximization of the wash/storage carrot section of the breeding agent, including nonorganic seed (chemically and nonchemically treated). The breeding revenue was represented by 10–30% of the seed sales revenue, depending on the actor. A revenue maximization for the breeding agents was chosen because the breeding costs were treated as constant over time; thus, the revenue maximization can be seen as a proxy of profit maximization. Both of the typical breeding actors we identified did not consider the gross margin at the breeding level as a key performance indicator, but they required a constant breeding budget as part of research and development (Kuin 2018; Syngenta 2015). Simplified decision-making matrices based on the optimisation of each value chain level can be found in Additional file 2: Appendix of the ODD-Protocol of the VAL-MAS model.

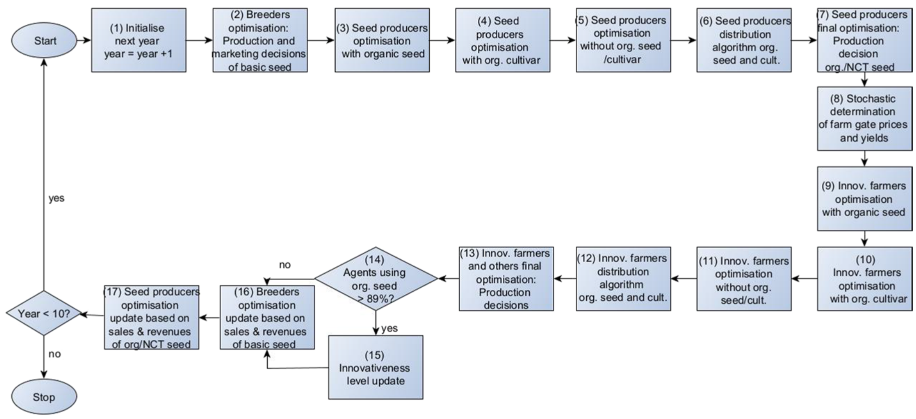

Fig. 2 Flow chart of the VAL-MAS value chain model

Model structure and interactions The interactions between the value chain levels are based on information, the financial and material exchange between the value chain actors regarding seed sales, and the amounts and prices, including a feedback loop on demand and supply of seed types (organic seed from typically used cultivars, NCT seed from typically used cultivars, seed from organic cultivars, etc.). Figure 2 shows the simplified interactions in the model, illustrating the decision-making sequence of the agents in the form of a flowchart. The agent groups are indicated in Fig. 2 by naming the respective group (e.g., breeders), followed by the activity that all breeders conduct (e.g., optimisation). This schematic flowchart follows the standard syntax according to DIN 66001. The food industry and policy framework are not included in the flow chart because they are exogenous factors with no endogenous decision-making implemented in the model. Its influence can be seen if scenarios change, such as higher end product prices for organic seed use and policy schemes, such as the phasing out of derogations. Under these scenarios, the behaviour of the endogenously modelled actors can change; for example, more organic seed might be produced and/or used. For more information, please see the technical documentation in Additional file 1.

Adaptive expectations of the seed producing and breeding agents

Because it is likely that seed producers will not immediately react to changes in demand for organic seed, we implemented an adaptive expectations mechanism at the multiplication level to smooth out the increase in the quantity of organic seed supply. The theory of adaptive expectations is based on the assumption that a behaviour, such as organic seed production, is determined by past sales (Galbács 2015). We defined the upper limit R of the amount that can be produced in a year as the average of the sold amount s of the last 2 years multiplied by a growth expectation factor G. This factor indicates the trend in demand and is computed as the %—difference between the sum of the current and last year and the sum of the last year and year before times the production reserve factor p. The production reserve factor specifies how much more than the estimated amount is produced for reserves in the case of unexpected higher demand. The lower and upper bounds of G were defined as 0.5 and 2. Given the technical difficulties in organic hybrid carrot seed production, we assumed that any increase above the doubling of seed production from 1 year to another would be improbable. R_{lo} ensures that a small amount of seed is produced, even though there is currently no demand so that resowing is possible.

Furthermore, to account for uncertainties because of technical difficulties, p under a growth scenario where an increasing organic seed demand is expected is always bounded by 1.2 and 1.5, respectively. This range reflects the uncertainty based on difficulties in finding organic carrot seed producers, suitable areas, and technical difficulties in production. These difficulties are substantial in the chosen case. The bounds for G and p are based on expert opinions as part of the present study's data collection because empirical data were unavailable. Thus, the values needed to be interpreted with caution. The formulas for calculating G and R are as follows:

$$G = \min\left(\max\left(((s_t + s_{t-1})/(s_{t-1} + s_{t-2}))p, G_{\mathrm{lo}}\right), G_{\mathrm{up}}\right) \tag{1}$$

$$R = \max\left(((s_t + s_{t-1})/2)G, R_{\mathrm{lo}}\right) \tag{2}$$

R_{up} = Maximum possible production amount of organic seed; G = Growth expectation factor of organic seed production; p = Production reserve factor of organic seed; s = Sold amount of organic seed.

At the farm agent level, adaptive expectations were not modelled for parsimony's sake. However, each modelling year, farming agents receive a forecast of possible farm gate prices and yields for the current year and the years after by solving the dynamic linear programming algorithm. This forecast is then updated in each modelling period to reflect uncertainty in farming.

Verification, calibration, and validation

To ensure that the model generates results corresponding to real-world observations, verification, calibration, and validation procedures were conducted.

Verification

During verification, the generated agent population should be examined to determine how well it represents the characteristics of the observed data on the actor population. The agent population in our case was *verified* by cross-checking the summary statistics of generated variables and correlations between generated variables with the original farm accountancy data set. The data can be found in Additional file 2: Appendix A.5.

Calibration

The calibration of a model is the process of adjusting certain parameters so that the model produces results in the baseline that are as similar as possible to real-world conditions (Howitt 1995; Troost and Berger 2015b). Calibration of the simulation model was conducted by calibrating the amount of organic seed used in the model to the real-world observation of 10% seed use for German organic storage carrot and 1% seed used of organic cultivars of the overall seed used (Herstatt 2017). First, this was achieved by first assuming that the organic hybrid seed producer was willing to accept an income reduction for organic seed production amounting to 50 € per 1 Mio marketed seed compared with NCT seed in the current conditions. This number was revealed when comparing the gross margins of NCT and organic seed production as part of our data collection. We can assume that this willingness to forego some income for the sake of producing organic seed was a strategic marketing decision to gain an advantage once derogations had been phased out. Second, an excess WTP for organic seed at the farming level was assumed, depending on the innovativeness segment of each farm agent. This excess WTP seemed plausible, as currently there is no subsidy for organic seed use and no evidence for a higher farm gate price rewarding organic seed use (Herstatt 2017; AMI 2020). Yet in reality, we observed a 10% share of organic seed use among carrot growers. The overall distribution of the excess WTP for organic seed compared with the NCT price was derived from a small survey among organic carrot producers in Germany, as mentioned in "Input data and creation of an agent population at the farming level" section. In Additional file 2: Appendix A.6, further details can be found.

Table 2 Overview of validation indicators, real-world observations, and model results

Validation indicator	Observation	Model baseline result (Av. of ten agent populations*)
Farm level		
Total organic carrot production in tons and hectares	Overall organic carrot production: 2102.5 ha, 102,418.3 tons (Destatis 2018) Wash/storage carrots: 1260 ha (On approx. 60% of this area, carrots for the fresh market and storage are produced (own data collection) 51,209 tons (approx.. 50% of total production)	Carrots for the fresh market and storage: 1300 ha, 51,023.3 tons
Organic carrot seed use in Mio seed	10% organic seed use and less than 1% organic seed use from organic cultivars (Herstatt 2017)	9% organic seed use, 0.3% seed use from organic cultivars
Farm enterprise gross margins in €/farm enterprise	Estimated gross margin at farm enterprise level is 7503.8 € for a crop rotation comprising mostly arable crops and 14,954.79 € for a crop rotation comprising mostly vegetable crops (KTBL 2016; AMI 2020; Destatis 2018)	The average yearly gross margin at farm enterprise level over all farm agents is 6457.82 € with a crop rotation comprising mostly arable crops and 11,589.45 € with a crop rotation comprising mostly vegetable crops
Seed multiplication and breeding level		
Gross margin at organic carrot multiplication level in € (excluding costs for processing and packaging)	Type I: 848,025 € Type II: 5975.2 € (own data collection)	Type I: 717,065 € Type II: 1365 €
Breeding budget for carrots in €	Type I: 5,180,480 € Type II: 300–1500 €, as only less than 5% acquired through refinancing and 30,000 € of yearly carrot breeding budget mostly acquired through donations (own data collection)	Type I: 5,121,817 € Type II: 314 € if 10% of sales revenue goes back into breeding. However, the breeding budget is mostly financed through alternative sources. This assumption of 10% seed sales going back into organic breeding results in coverage of around 1% of the current yearly breeding budget in the baseline scenario

* This is part of the sensitivity analysis. See further information in "Verification, calibration, and validation" section

Validation

Validation is the process of cross-checking whether the model gives realistic results in its baseline run (Troost and Berger 2020). This was carried out by comparing the model outcomes with general statistics about areas, yields, and gross margins at the farm level, as well as aggregate model results, such as overall area, production amounts, and number of agents. As illustrated in Table 2, in most cases, the model baseline results and observations were closely matched. Only in the case of seed multiplication Type II was the difference in gross margins rather large. However, because all other values seemed valid, this deviation was acceptable, and the impact estimates were considered valid evidence.

Furthermore, to validate aspects of the model where a lack of real-world observations exists for comparison purposes, structural validation can be useful. During structural validation, the stakeholders involved in the investigated problem are consulted to validate these assumptions and model results (Qudrat-Ullah 2005). The assumption that the excess WTP stays constant across scenarios and occurrence of an organic seed shortage in a derogation scenario without other measures underwent structural validation and confirmation through seed sector expert interviews.

Scenario definition

The interventions were codesigned during interviews with project stakeholders and value chain actors in 2018 and 2019 and during an expert workshop in 2019 (Orsini et al. 2019). The interventions of greatest interest to the stakeholders were selected and are as follows:

- Stepwise phasing out of derogations at farm level to use organic seed and/or organic cultivars [Derog]
- Condition "Higher germination rate": lygus bug control in organic carrot seed production realized (Weijland 2020)[1] [HgermR]
- Condition "Sufficient seed": Constraint on organic seed production ($G_{up} <= 2$) is relaxed so that the supply can catch up with the organic seed need in a stepwise phasing out of derogations, for example, through close communication between seed producers and organic seed expert groups [SuffS]
- Subsidy for organic seed use related to cultivation area [Subs]
- Organic carrot farm gate price premium per ton of organic seed use [Prce]

Standalone or combined interventions were implemented as the model scenarios. Scenario development involved a number of specifications. Table 3 provides a detailed overview of all the scenarios and corresponding model specifications.

[1] The lygus bug causes considerable damage in carrot seed production if it is not controlled. Experts have confirmed that this is currently the main challenge in organic carrot seed production for wash/storage carrots. In conventional production, there is a multitude of pesticides available for control (Wohleb 2019). In organic production, solutions have yet to be found. Investments in finding solutions could lead to a germination rate equal to conventional seed and the possibility to increase the production amount at a faster rate.

Table 3 Overview of scenarios and specifications

(1) Baseline [Bsl]	Adaptive expectations mechanism: Growth expectation factor's upper bound equals 2 Production reserve factor ranges between 1.2 and 1.5
(2) Stepwise phasing out of derogations at the farm level to use organic seed and organic cultivars [Derog]	Same specifications as in Scenario 1 Stepwise phasing out of derogations for NCT seed Two-year steps: Year 2: 80% NCT seed allowed per farm, year 4: 50%, year 6: 30%, year 8: 0%
(3) Condition "Higher germination rate" [HgermR]	Adaptive expectation mechanism: Upper bound of growth expectation factor equals 3 Production reserve factor equals 1.5 as uncertainty is reduced Multiplication level: Organic hybrid seed price 1 Mio organic seed increases by 20% Farm level: Germination rate increases by 20%, thus reducing the sown density from 2.4 Mio seed/ha to 2 Mio seed/ha
(4) Scenario 2 [Derog] + and 3 [HgermR]	No new specifications
(5) Scenario 4 [Derog, HgermR] + Condition "Sufficient organic seed" [SuffS]	The adaptive expectations mechanism of seed producers is relaxed to the extent that organic seed supply can meet organic seed demand: Growth expectation factor is calibrated to 3. At this value, there is no organic seed shortage for the 2-year stepwise phasing out of derogations, as proposed in Scenario 2
(6) Subsidy for organic seed and organic cultivars use related to cultivation area [Subs]	Same specifications as in Scenario 1 Different levels of subsidies at the farm level are tested. The goal of this process was to identify subsidy levels that induce farm agents to adopt organic seed and organic cultivars up to certain thresholds (e.g., up to the last adopter group)
(7) Organic carrot farm gate price premium per ton for organic seed and organic cultivar use at farm level [Prce]	Same specifications as in Scenario 1 Different levels of price premiums at the farm level are tested. The goal of this process was to identify price premium levels that induce farm agents to adopt organic seed and organic cultivars up to certain thresholds (e.g., up to the last adopter group)
(8) Scenarios 3 [HgermR] + 6 [Subs]	No new specifications
(9) Scenarios 3 [HgermR] + 7 [Prce]	No new specifications
(10) Scenario 8 [HgermR, Subs] + Condition "Sufficient organic seed" [SuffS]	No new specifications
(11) Scenario 10 [HgermR, Subs, SuffS] + 7 [Prce]	No new specifications

Sensitivity analyses

Sensitivity analyses helped obtain greater insights into the variations of the outcomes caused by specific model parameters, for example, input prices or expected yields. We created ten different farm agent populations in STATA based on the input data described in "Definition of the research question and quantitative outcome variables" section, using 10 different seed values. This generated farm agent populations with slightly changing resource endowments. As a next step, we included one agent population at the time in the GAMS model and simulated the different scenarios with a random seed value per agent population in GAMS. Here, the excess WTP, yields, and prices at the farm level were implemented as random triangular distributions, these values changed with each model run if the seed value was adjusted. Furthermore, yields and farm gate prices changed every model period as a proxy for farming uncertainty. Farm gate prices were the same for all farming agents in one modelling year because the prevalent marketing channel was supermarkets, where the prices tended to be very similar for all farmers (AMI 2020). Furthermore, the price differences between agents were much lower than fluctuations between years (these differences have been included in the model) because they depended on world market trends. Negotiating the skills of farmers could be the only other reason for price differences, and these were difficult to measure and find evidence for.

The yields were farm agent specific because, here, a larger variability due to, for example, local weather patterns and soils, was to be expected. Seed prices were held constant over time because they were not subject to a large variation according to expert opinions. The triangular distributions of excess WTP, prices, and yields comprised minimum, maximum and mode of the distributions. For example, yields for carrots in tons per hectare were captured in the following standard formula (min = 13.9; mode = 17.9; max = 22):

$$f(x) = \begin{cases} \frac{2(x-13.9)}{(22-13.9)(17.9-13.9)}, & \text{if } 13.9 < x < 17.9 \\ \frac{2}{22-13.9}, & \text{if } x = 17.9 \\ \frac{2(22-x)}{(22-13.9)(22-17.9)}, & \text{if } 17.9 < x < 22 \end{cases}.$$

All complete triangular distributions are listed in Additional file 2: Appendix, i.e. Tables A.6 (triangular distributions of excess WTP) and A.7 (triangular distributions of yields and prices). The means of the sensitivity results are shown in Table 4. As result, we generated possible outcomes for 10 different agent populations with different price and yield assumptions.

Results

The area under organic cropping was held constant over the eight model periods so that the effects of interventions could be compared with the baseline without having to account for crop area changes. The results on gross margins and breeding budgets presented in this section were calculated from the last three model periods (years six to eight). Organic seed amounts were also averaged over these 3 years. Different levels of subsidies and price premiums were tested, and the most interesting regarding organic seed use and production are presented in this section.

Three public policy or private sector interventions were tested under two different conditions, as shown in Table 3. The results of the most relevant intervention scenarios were compared with the baseline results, as shown in the following two subsections and in Table 4.

Command and control phasing out of derogations with and without improved lygus bug control (Scenarios 2 to 5)

Regarding scenarios with derogations, an interval of 2-year steps (Year 2: 80% NCT seed allowed per farm; Year 4: 50%, year 6: 30%, year 8: 0%) was tested. In Scenario 2 [Derog], representing phasing out of derogations under current conditions, not enough organic seed can be produced according to the model results because of technical limitations in seed multiplication. In all scenarios that involve derogations, the farm agents must bear the burden of insufficient organic seed supply; they incur additional seed costs and must switch to other, less profitable crops because of seed shortage for carrots. In Scenario

Table 4 Summary of the results using key outcome variables

(1) Scenarios	(2) % Δ GM/Farm Enterp	(3) % Δ GM/ seed multipl. org. + NCT seed	(4) % Δ GM/ seed multipl. org. cultivars	(5) % Δ breeding budget (org., NCT, CT seed)	(6) % Δ breeding budget org. cultivars	(7) Costs of intervention in model period in €	(8) Predicted total costs of intervention in €	(9) % marketed organic seed of the total market	(10) % marketed seed of org. cultivars of total market	(11) Diffusion of organic seed to adopter group	(12) Cost-effectiveness (Ha planted with organic seed per €)
(2) [Derog] (Scen. 2)	−11	−3.6	515	0.60	401	n/a	n/a	23.70	1.88	n/a	n/a
(3) [HgermR] (Scen. 3)	0	0	0	0	0	n/a	n/a	0	0	n/a	n/a
(4) [Derog, HgermR] (Scen. 4)	−9	8	582	0.58	501	n/a	n/a	37.86	2.38	n/a	n/a
(5) [Derog, HgermR, SuffS] (Scen. 5)	−3	36	373	4.3	937	n/a	n/a	81.25	1.51	n/a	n/a
(6) [Subs] (500 €/ha) (Scen. 6)	0.08	−0.4	1246	0.36	1293	164,792	690,000	20.62	3.13	Laggards	0.0020
(7) [Subs] (150 €/ha) (Scen. 6)	0.00	−0.3	950	0.35	1095	23,015	103,500	19.58	2.54	Early Majority	0.0067
(8) [Prce] (10 €/ton org. carrots) (Scen. 7)	0.03	−0.1	1078	0.58	1160	162,009	690,000	20.35	2.99	Laggards	0.0020
(9) [Prce] (5 €/ ton org. carrots) (Scen. 7)	0.00	0.0	941	0.36	1098	22,692	103,500	19.22	2.59	Early Majority	0.0067
(10) [HgermR, Subs (500 €/ ha)] (Scen. 8)	0.11	8	1538	0.54	1795	273,980	690,000	34.36	6.4	Laggards	0.0020
(11) [HgermR, Prce (10 €/ton org. carrots),] (Scen. 9)	0.02	8	1507	0.55	1794	270,537	690,000	34.09	5.09	Laggards	n/a

Table 4 (continued)

(1) Scenarios	(2) % Δ GM/Farm Enterp	(3) % Δ GM/seed multipl. org. + NCT seed	(4) % Δ GM/seed multipl. org. cultivars	(5) % Δ breeding budget (org., NCT, CT seed)	(6) % Δ breeding budget org. cultivars	(7) Costs of intervention in model period in €	(8) Predicted total costs of intervention in €	(9) % marketed organic seed of the total market	(10) % marketed seed of org. cultivars of total market	(11) Diffusion of organic seed to adopter group	(12) Cost-effectiveness (Ha planted with organic seed per €)
(12) [HgermR, Subs (500 €/ha), SuffS] (Scen. 10)	0.11	36	1338	4.3	2093	700,000	690,000	73.03	5.99	Laggards	0.0020
(13) [HgermR, Subs (150 €/ha), Prce (7 €/ton), SuffS] (Scen. 11)	0.01	35.5	1339	4.3	2102	700,000	690,000	78.54	7.89	Laggards	0.0020

GM Gross margin, *NCT* Not chemically treated, *org.* Organic, *CT* Chemically treated, for abbreviations of scenarios, see Table 3

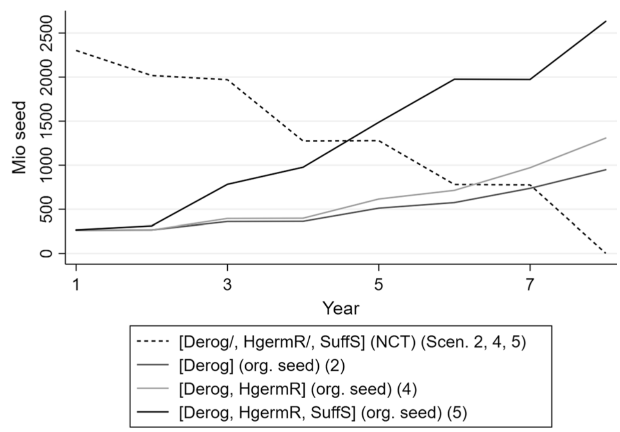

Fig. 3 Development of the mean of aggregated organic and NCT seed use over 8 years under stepwise phasing out of derogations

2 [Derog], this amounts to an average 11% loss in farm enterprise gross margin (see Table 4, row 3, column 2).

In Scenario 3 [HgermR], technical difficulties regarding lygus bug control are overcome. However, because organic seed is still substantially more expensive than NCT seed, there is no demand from farming agents. Only in Scenario 4 [Derog, HgermR], where the derogation scheme is applied, do farming agents start to use organic seed. Yet organic seed production still cannot match demand because, according to the model implementation, seed producers are conservative with their production increase and form their expectations based on previous experiences (see Sect. "Adaptive expectations of the seed producing and breeding agents"). However, because of the higher germination rate, organic seed production becomes more profitable than NCT seed (see Table 4, row 4, column 3). Consequently, the gross margin of seed multiplication for Type II (Table 4, row 4, column 4) and the overall organic seed production (organic seed and organic seed from organic cultivars) increase substantially (see Table 4, row 4, columns 9 and 10). This scenario translates into a slightly lower gross margin reduction at the farm level, in the magnitude of 9%. If the seed producer agents increase their production according to expected future demand, accepting a higher risk of losses in case they cannot sell all seed as expected, farm agents incur only a gross margin loss of 3%, here according to Scenario 5 [Derog, HgermR, SuffS] in our simulations. The organic seed use and NCT seed use trajectories in this scenario are illustrated in Fig. 3 as the black and dotted lines, respectively. The compensation for income trade-offs incurred in scenarios 2 and 4 is depicted in Fig. 5, which, for various scenarios, displays the distribution of the average yearly gross margins per farm enterprise across the farm agent population. When looking at columns 5 and 6 in Table 4, the change in the breeding budgets of both breeding company types is positive. This shows that, in scenarios 2, 4, and 5, the necessary breeding budgets can be sustained or increased.

Voluntary measures to incentivize farmers to use organic seed (Scenarios 6 to 11)

A number of measures were identified to support farmers in covering the additional costs of organic seed use, including compensation payments (subsidies) or increased

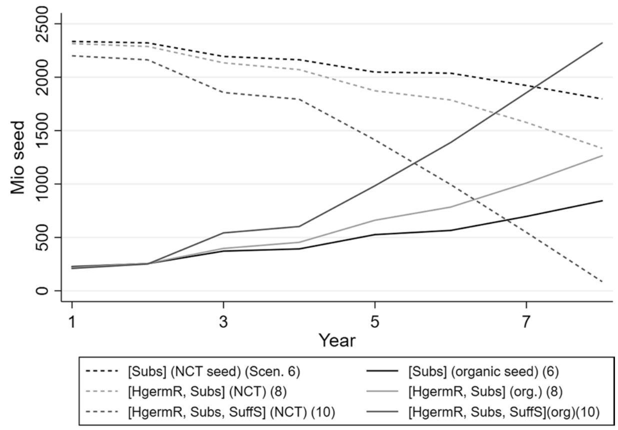

Fig. 4 Development of the mean of aggregated organic seed use over 8 years under different incentive schemes

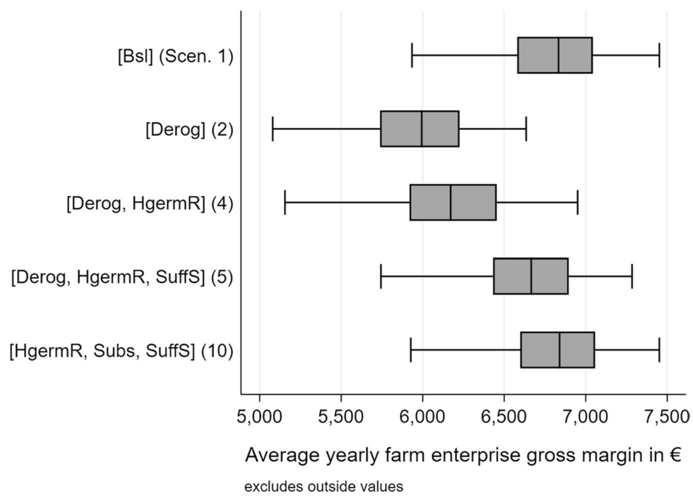

Fig. 5 Distribution of yearly gross margins per hectare at the farm enterprise level under selected scenarios [excluding values that do not lie within 1.5 times the interquartile range (outside values)]

product prices at the production level. In Table 4, Scenario 6 [Subs], an area subsidy for using organic carrot seed of 500 € per ha, provides an incentive for all farm agents (down to the last adopter group, the "laggards") (see Table 4, row 6, column 11) to use organic seed when available. Over the entire modelling phase of 8 years and all agents, this amounts to a total subsidy cost of 164,792 € (Table 4, row 6, column 7). This goes up to around 690,000 € (see Table 4, row 6, column 8) once organic seed production capacities have been increased to match demand [HgermR, Subs, SuffS]. For scenarios 6, 8, and 10, the modelled subsidy impacts on seed use trajectories can be seen in Fig. 4, under current conditions [Subs], under improved lygus bug control [Subs, HgermR], and in a combined scenario [HgermR, Subs, SuffS] (Scenario 10). The gross margin impact of Scenario 10 [HgermR, Subs, SuffS] is shown in Fig. 5. This implies that farm agents are compensated by the 500 €/ha subsidy and that no gross margin losses occur on the whole, while policy costs are estimated at approximately 690,000 €.

The model results in Scenario 7 [Prce] also demonstrate that, as an alternative to subsidies, a price increase of 10 € per ton of organic carrots provides an incentive to all farm agents (down to the last adopter group, the "laggards") to use organic seed when available. Over the entire modelling phase (8 years), this amounts to a total cost of the price premium of 162,009 € with around 24% organic seed use across the agent population and around 690,000 € when organic seed production capacities have increased to match demand so that 100% organic seed is used. Once the price premium is reduced from 10 to 5 € per ton of organic carrots produced with organic seed, organic seed diffuses only to the early majority of the farm agent population, while the intervention would only cost around 22,692 €, with overall organic seed use reaching approximately 50% (see Table 4, row 9, column 12). As such, this intervention would be more cost-effective but cannot induce the entire agent population to adopt organic seed. Lastly, a combination of a subsidy amounting to 150 €/ha and a price premium of 7 €/t would also lead to an adoption of the entire farm population, if measures to ensure sufficient seed supply are taken.

Discussion

Policy implications

Organic carrot producers in Germany have been shown to have a rather high excess WTP for organic seed and cultivars, estimated at 45% on average when compared with NCT seed. Other studies have confirmed that the higher price of organic seed is not always the main obstacle for farmers to use organic seed (Hubbard and Zystro 2016; Levert 2014). However, organic carrot seed use from hybrids or OP cultivars in carrots of the market segment wash/storage is very pricy (around 60% more expensive than NCT seed). Thus, the excess WTP across the farm population is not high enough to induce the whole farm agent population to use organic seed. To encourage farmers and stimulate investments in organic seed and breeding in this segment, a subsidy at the country level or a premium price at, for example, the processor level, could be a potential first step. In Estonia, Slovenia, and the Czech Republic, a payment for organic seed use is already integrated into the Common Agricultural Policy (CAP) area payments. For example, in Latvia, the CAP area payment is 20% increased if organic seeds are used as a second pillar measure (Fuss et al. 2020). However, because this payment has only recently been integrated, there is no available evidence about its effectiveness. Based on simulation runs, we have estimated that a hectare-based subsidy of around 500 €/ha or a higher product price of around 10 €/ton would be necessary to induce the entire organic carrot producer agent population to adopt organic seed. However, a subsidy of 500 €/ha seems to be rather high, on top of 390 to 590 €/ha already received by organic vegetable producers in Germany as part of the second pillar rural development payments for organic production (BLE 2021). Conversely, a 10 € increase of the farm gate price per ton of organic carrots would only result in an increase of around 1% of the current average end consumer price (AMI 2020). This higher price does not seem prohibitive and, thus, could be a way forward towards more organic seed use. Approximately half of the modelled organic carrot producer population gains access to organic seed with a hectare-based subsidy of around 150 €/ha or a higher product price of around 5 €/ton. A recent study has shown that social norms are a major factor for organic farmers to use organic seed. Thus, it is possible that, once organic seed use has diffused to the early majority, further uptake will be accelerated (Orsini et al. 2020). Another option could be a combined subsidy and higher product price. In this case, for example, a subsidy (150 €/ha) could be supplemented with a price premium of 7 €/ton to achieve an adoption of the entire farm agent population. However, a mixture of public and private sector measures might be challenging to implement in real life.

High uncertainty in seed production occurs with respect to organic carrots in the market segment wash/storage because there are several technical problems in organic seed production. This is also true for other crops, to varying extents, especially for other biennial seed crops, for example, cauliflower. Furthermore, the results of the present study imply that, under current conditions, organic seed production is not yet profitable. If technical problems are not addressed first, there may be a seed shortage under scenarios like phasing out derogations for the use of NCT seed.

It has been argued that phasing out of derogations could serve as a sufficient market stimulant. However, earlier attempts at phasing out derogations of NCT seed for all crops often resulted in a severe shortage of organic propagation material and the subsequent need to reintroduce the derogation regime. In recent years, the number of derogations in many countries for numerous crops has increased (Solfanelli et al. 2019). Thus, it seems advisable to prioritize investment in research on the stability of organic carrot seed production for the investigated segment. Furthermore, under the condition "higher germination rate," organic hybrid carrot seed production becomes more profitable than NCT, possibly inducing more actors to join the market. This investment could be financed through public means, or the currently needed WTP of the seed producer to produce organic seed could be paid as a subsidy to seed producers to incentivize them to produce organic seed. However, an investment in pest control seems a better long-term solution and, thus, is preferable. This may be true for other biennial seed crops, such as cauliflower. According to our modelling results, the investigated organic and NCT carrot seed multiplier can increase their gross margin by 36% if they produce organic seed as opposed to NCT seed if the germination rate is higher. This is in line with statements from seed producers that, so far, organic carrot seed production is not yet as profitable as NCT seed and that advances in pest management would be essential to changing this. For example, lygus bug management in carrot seed production is frequently mentioned as the main challenge (Wohleb 2019; High Mowing Seeds 2021).

It seems advisable to conduct similar studies for important organic crops throughout Europe to establish sound scientific knowledge about the necessary steps to increase organic seed use and production. This is of particular importance in light of the farm-to-fork strategy recently put into action by the EU. With this strategy, the EU commits to increasing the organic farmland share by 25% until 2030 (European Commission 2020). The realization of this goal will need to be accompanied by a substantial increase in organic seed production and breeding for the organic sector.

Limitations and novelties of this study and outlook

Some limitations of the present study need to be mentioned. We used a case study approach by selecting one country-crop combination but also by selecting specific companies and initiatives for data collection. Thus, conclusions are not necessarily representative of the organic sector as a whole, and they also need to be interpreted with caution at the value chain level. Furthermore, some parameters that influence the simulation outcome are based on expert assumptions, such as the growth expectation factor (see "Adaptive expectations of the seed producing and breeding agents" section). Uncertainties in these parameters were addressed through sensitivity analyses, wherever possible. Furthermore, this study does not consider an increase in organic carrot farm land that the farm-to-fork strategy foresees. To keep the model parsimonious and concentrate the analysis on seed system transitions, we excluded this aspect, as well as the possibility of nonorganic farms converting to organic agriculture in order to meet the goal of 25% organic land area. We assume that an increase in organic area would be conducted by similar farms as already included in the model, which would thus likely show a similar decision behaviour.

Although there are some limitations inherent to the VAL-MAS *modelling* approach, this is the first study, to the best of our knowledge, that models the behaviour of an entire value chain using a mathematical programming and agent-based approach. This goes beyond previous approaches in value chain analysis, which have mainly focused on qualitative analyses of seed systems (Bellù 2013; Mulugeta et al. 2010; Kumara et al. 2012). Taking the heterogeneity of value chain agents across the seed and breeding value chain into account, the agent-based approach is more refined than a sector model. In the latter, important aspects, such as the diffusion of an innovation or individual behaviour of seed multipliers, cannot be addressed (Möhring et al. 2016; Crooks and Heppenstall 2012). In VAL-MAS, on the contrary, dynamics in the seed and breeding value chain, as well as in the entire farm population, could be represented over time. Another novelty is the simulation of future policy scenarios for the organic seed and breeding sector while taking the economic situation of the entire chain into account and investigating an important country-crop case in Europe. For future research, this model could be adapted to other crop-country cases to move forward the discussion on a road map to 100% organic seed use in Europe. Potential extensions of the model could be the incorporation of risk or external effects because innovations that reduce risk or provide positive externalities (e.g., pesticide reduction or diversification of crop rotations) gain importance when trying to achieve more sustainable food systems, which is in line with the farm-to-fork strategy of the European Commission (2020).

Conclusion

The VAL-MAS model application confirms that the end of the derogation system poses a challenge for the organic carrot seed value chain. Addressing this issue is of particular EU-wide importance to meet EU policy goals, such as the farm-to-fork strategy. Countervailing measures are needed to smooth the transition from the current system to the end of derogations. Our scenarios suggest that investment in agricultural innovation at seed multiplication, together with economic incentives for farmers, represent viable mitigating measures. Improved germination for pest control during seed production, accompanied by a stepwise phasing out of derogations for the use of nonorganic seed, is a potential way forward. Furthermore, to avoid income trade-offs at the farm level, our model results imply that either a subsidy or price premium for organic seed use would be required. The simulation results show that a subsidy of 500 €/ha organic carrot production or price premium of 10 €/t organic carrots for the use of organic carrot seed at the farm level would be necessary to counter trade-offs.

Supplementary Information

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Additional file 1: VAL-MAS Model Documentation.

Additional file 2: Additional VAL-MAS model data.

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Author contributions
In this study, EW was involved in the conceptualisation, methodology, validation, formal analysis, data curation, and writing of the original draft preparation. CG and JA were involved in the conceptualisation, methodology, validation, formal analysis, data curation, and editing of the manuscript. MMM was involved in the conceptualisation, data curation, and editing of the manuscript.

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Availability of data and materials
All data that can be disclosed is found in the Additional files 1 and 2 of this manuscript.

Declarations

Competing interests
The authors declare that they have no competing interests.

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