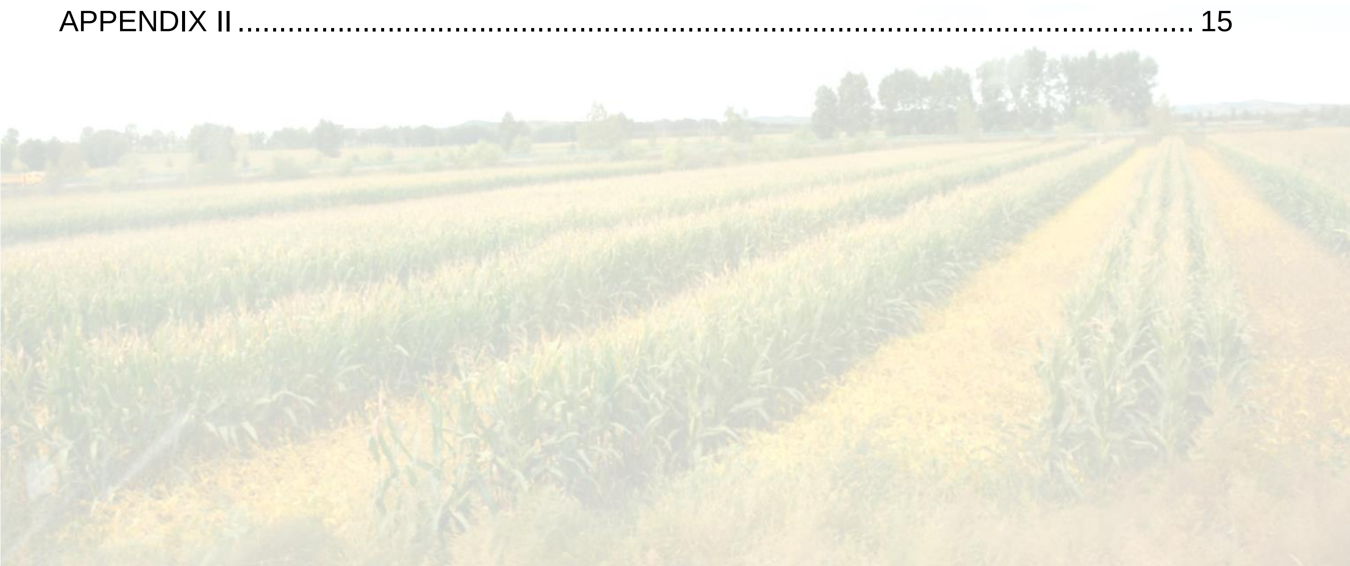
FINAL REPORT ON CHALLENGE #8: Fundamentally different case studies of nature-based solutions - how can they be integrated into a common agent-based modelling approach?

Name of mentor(s): Anke Möhring (FiBL), Yuquan Chen (CAU)
Number of participants: 13 (see Appendix I)

Content



INTRODUCTION

Background to the challenge

Models can help to understand the transition process to implementation of innovations in general, and of nature-based solutions (NBS) in particular. While the adoption of innovations through diffusion theory has long been known and widely used in models (Kiesling et al. 2012), there are still few cases for modelling the adoption of NBS (Giordano et al. 2021; López-Maciel et al. 2023). Challenge #8 therefore provides a unique opportunity to establish a joint Sino-European modelling framework to provide ex-ante impact assessments of the implementation of NBS aimed at achieving more sustainable nutrient management strategies in intensive agricultural systems.

Explanation of the challenge defining the scope of effort

The ambition is to develop a flexible, scalable and transferable agent-based model that can evaluate the adoption and impact of Nature Based Solutions in different regions. By integrating various case studies from China and Europe, the model will provide a comprehensive framework for assessing the net effects of NBS on agricultural innovation, policy impacts, and diffusion pathways. This will enable policymakers and stakeholders to make more informed decisions regarding NBS implementation and scalability. The participants have developed a **joint Sino-European ABM specification plan** that can assess the social and technological impacts of NBS adoption. The challenge #8 focuses on two case studies (Figure 1):

1. The Danish NBS-site Northern Jutland of the Limfjord catchment.
2. The Chinese NBS-site in northeastern China's Inner Mongolia autonomous region – Xing'an League, Hulunbuir city, and Tongliao city.

Each case study region defines its own NBS adapted to its specific conditions. It was therefore necessary to first identify the lowest common denominator over all case study regions, which summarises the changes in the NBS compared to the traditional intensive farming practices across all sites. These are crop rotation and bio-based fertilization.

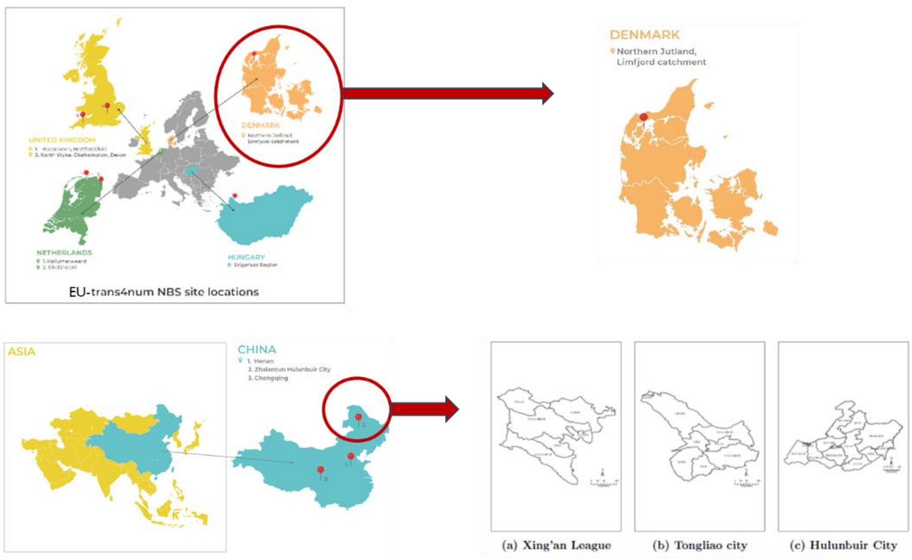


Figure 1: Case study site locations in the trans4num project (© trans4num, WP5 & CAU).

METHODOLOGY

Team description

The Challenge Team #8 consists mainly of scientists from the European and Chinese project partners. A list of the persons involved can be found in Appendix 1. The most important cornerstones of the joint concept were developed in several individual meetings. The meetings took place both in person and online. A collection of pictures is provided in appendix II.

Technical Background

The model code will be implemented in NetLogo 6.4.0 (Wilenski 2024). The model concept published by Crooks (Crooks 2022a; 2022b) for valuating an incentive for soil organic carbon sequestration from carinata production in the Southeast United States was used as a starting point (Ullah and Dwivedi 2022; Ullah and Crooks 2023; Ullah, Oladosu, and Crooks 2023).

Furthermore, it is planned to use the statistical software Rstudio for the following purposes:

- processing the database of input data,
- processing the spatial database,
- data preparation for sensitivity and scenario analysis,
- visualisation of output data.

The model itself is still under construction. It is not yet published.

Description of the process of solution

Participants have been collaborating to define the model specification, ensuring the model addresses the complexities of working with limited data, modular structures, and varied agent types. The model will incorporate key elements such as innovative crop rotations, diffusion pathways, and policy impacts. The first step was to visualize the model in Figure 2. At the same time, all the necessary parts and requirements were formulated.

The model will have a two-dimensional modular structure, where the first dimension is covered by the core model, which is developed in six different parts:

- **Part 1** focuses on the agent population. Depending on data availability, we will use different strategies to build the agent population, that represents all relevant agents in the region. Either we will have a sample of all existing farms and processors in the case study region, including the corresponding database, or we will use a representative sample of farms in the case study region for cloning or upscaling to the entire population. For the pilot model we will start with a small agent population size while we will extend the number of agents at a later stage of the modelling process.
- **Part 2** addresses decision-making behaviour which refers to profitability, farmer's attitudes regarding adoption and farmer's trust in the new technology, risk and uncertainty, social networking and social learning.
- **Part 3** captures the influence of farmer's neighbourhood on decision-making.
- **Part 4** relates to an extensive scenario analysis that provides baseline- & intervention scenario results, as well as sensitivity analysis on case study specific outcome parameters.

- **Part 5** validates the model to show the uncertainty level of our model results, e.g. through stakeholder workshops and behaviour space sensitivity analysis.
- **Part 6** transfers code and model documentation to our partners in a suitable and publishable format to provide reusable model code for case-study specific requirements and sub-modules.

The second dimension of the modular structure is granularity:

- The model will be developed in a coarse-grained manner initially, including a small pilot dataset, and
- then optionally extended with fine-grained submodule extensions that can be activated or deactivated according to the specific requirements of the case study sites, as well as the case study site-specific dataset of the entire agent population.

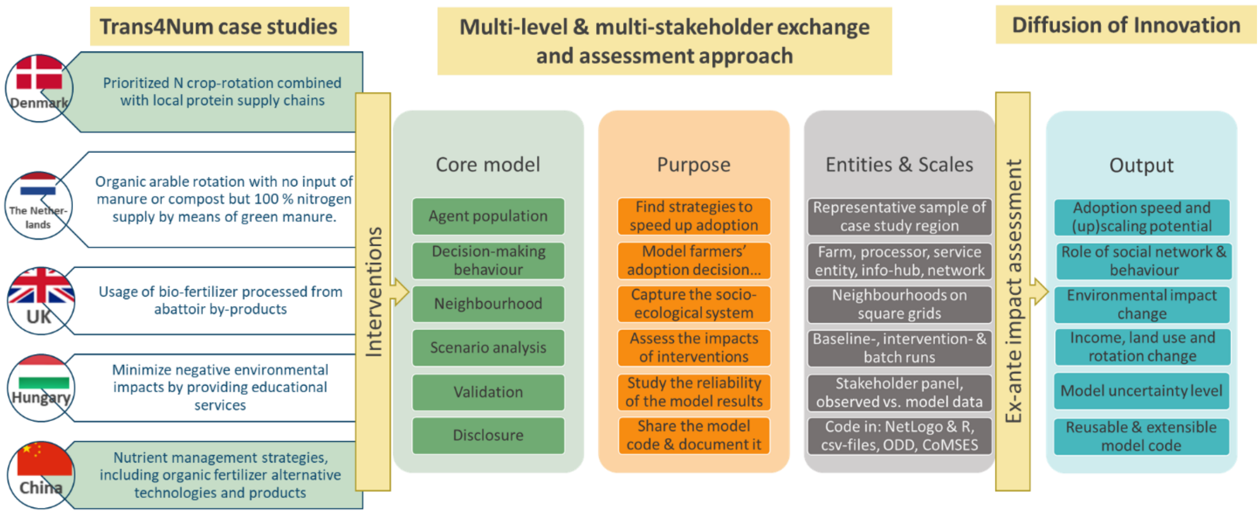


Figure 2: Overview of the modular structure of the agent-based model approach.

In addition, the specific purposes of the two case study regions were identified and described.

PURPOSE OF THE DANISH PILOT MODEL

The core model for the Danish case study focuses on the green inner cycle in Figure 3 where the integration of "green" manure into the crop rotation is mainly processed from clover grass on both arable and grassland, but also from intercrops and legumes. Not only the application of green manure is taking place, simultaneously, the clover grass has been processed in a biorefinery plant where also co-products such as protein fodder for monogastric animals and press cake for ruminants are produced[1]. The purpose of the pilot model of the Danish case study is the evaluation of intervention strategies to accelerate the

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[1] The inclusion of the full food production cycle, including livestock and biogas production, will be the subject of future model extensions and is not considered in the first pilot draft of the model that is presented here.

adoption and diffusion of biomass crops, e.g. through the replacement of cereals with grass-clover mixtures in the rotation, to reduce nitrogen leach in Northern Jutland of the Limfjord catchment in Denmark.

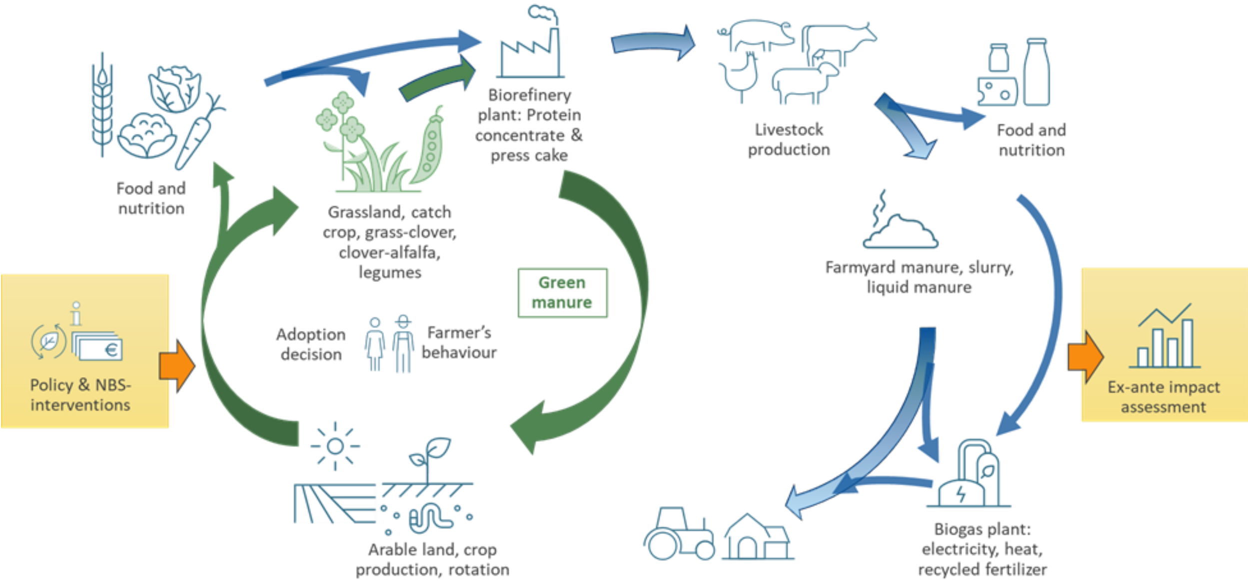

Figure 3: The food production cycle as a system boundary for nature-based solutions.

Particular emphasis will be placed on incorporating a social network between the farmers themselves and between the farmers and the processing biorefinery into the model. The aim is to explore solutions and barriers in the exchange of the required biomass, which needs to be provided in sufficient quantity and quality, and to ensure a smooth substitution of farmyard manure with green manure.

Purpose of the Chinese Pilot model

The main objective of the Chinese ABM is to understand the effects of soybean-corn and maize-corn rotations by integrating grassland cultivation into the rotation, with the aim of using the biomass as fodder in livestock production and, according to the positive attributes of grass in terms of protecting soil health, to benefit yield stability and economic profitability in north-eastern China.

Data & Equipment list

As described earlier, there are large differences in data availability between the case study regions. Based on a test dataset, we define the minimum dataset that should be available to parameterise the agent population of the model (Table 1). There are significant differences between the European and Chinese case study regions. While the Chinese case study has to cover a much larger area and a much larger number of agents, for some of which neither individual farm data nor spatial data are available, the Danish case study can provide data this is available for all farms and biorefineries in the region and these data are even spatially explicit.

Table 1: Agents' attributes represented by state variables and parameters.

	Used in sub-module[2]:	state variable / parameters	Values for simulation	Unit	Reference DK	Data available in CN?
Farm						
	all	Farm identifier		ID	AU & ICOEL	Yes
	Profit	Type1	Animal / mixed / plant / …		AU & ICOEL	Yes
	Profit	Land use type	organic / conventional		AU & ICOEL	Yes
	Profit	Size of the farm in total		ha	AU & ICOEL	Scale of the farm
	Land allocation	Size of the farm in the site		ha	AU & ICOEL	Yes
	Land allocation	Proportion of farm area in the site		%	AU & ICOEL	Yes
Field						
	Profit	3-year crop rotation (2019-2021) (7-year crop rotation (2015-2021 is also available)	Reference gross margin	€/ha	AU & ICOEL (standard values)	Yes
	Profit	Yield	Reference crop yield	t/ha	AU & ICOEL	Yes
	Profit; Land allocation	Soil quality	Sand = 10 clay = 20		AU & ICOEL	No
	Social network	Distance to nearest biorefinery	bird distance	meters	AU & ICOEL	No
	Social network	Distance to nearest biogass plant	bird distance	meters	AU & ICOEL	No
	Land allocation	Size per field		ha	AU & ICOEL	Yes
	Land allocation	Number of fields per farm		Number	AU & ICOEL	Yes
	Land allocation	High nature value (HNV)	Calculated as the mean of the field	10x10 m cells	AU & ICOEL	Yes
	Land allocation	HNV minimun value on the field of the		10x10 m cells	AU & ICOEL	Yes
	Land allocation	HNV maximum value on the field		10x10 m cells	AU & ICOEL	Yes
Farmer's behavioural and neighbourhood influence parameters						
	Diffusion	Neighbourhood polygon	adjacency matrix		Yes	Yes

[2] Sub-module refers to section nnn and figure xxx below….

	Used in sub-module[2]:	state variable / parameters	Values for simulation	Unit	Reference DK	Data available in CN?
	Diffusion	farmer's cognitive understanding of the innovative / traditional technology	farmer's learning ability, depending on average cognitive understanding of its neighbours		No	Yes
	Diffusion	Initial adoption rate			Derived from survey data (AU & ICOEL)	No
	Diffusion	Adoption threshold/initial willingness to adopt			Derived from survey data (AU & ICOEL)	No
	Land allocation	Risk preferences (based on cumulative prospect theory)	risk averse, risk neutral, risk loving		Derived from survey data (AU & ICOEL)	Yes
Biogas / Biorefinery plant						
	Social network	Capacity / Demand		t/a	Survey data (AU & ICOEL)	No
Economics						
	Profit	Value of grass in the rotation	Fodder value	t/ha €/ha	AU & ICOEL	Yes
	Profit	NBS-rotation specification	What NBS-rotation fits best from an agronomical point of view, depending on the traditional rotation		AU & ICOEL	Yes
	Profit	Perception of intervention	Farmer's perception of costs and benefits of NBS technologies		Stakeholder agreement	Yes
	Profit	a) Yield development		%	Stakeholder agreement	Yes
	Profit	b) Price development		%	Stakeholder agreement	Yes
	Profit	c) Cost development		%	Stakeholder agreement	Yes
	Profit	Annual discount rate			assumption	Yes
Outcome variables						
		N-leach		kg/ha	Model endogenious	No
		Carbon sequestration potential			Model endogenious	Yes
		Regional income	Gross margin per simulation run	€	Model endogenious	Yes
		Area under NBS			Model endogenious	Yes

	Used in sub-module[2]:	state variable / parameters	Values for simulation	Unit	Reference DK	Data available in CN?
		Number of adopters	Total adopters, total non-adopters		Model endogenious	Yes
		…				

Detailed implementation plan

The steps for specifying the modular agent-based model were defined as follows: 1.) Identification of parts and properties = Identification of agents and their attributes. 2.) Description of the agent's environment, where the agents are located and in relation to each other. Interactions between agents are based on neighbourhood criteria and their relationships within a social network. 3.) Specification of agent interactions covering the rules of a) which agents interact, b) when agents interact and c) how they interact during the simulation. Additionally, the network topology of information hubs influencing farmers is included. 4.) Definition of the model dynamics for the specification of the methods by which agent attributes are updated, and for the scheduling of the order of computations performed during each discrete time step. 5.) Definition of model outputs and developing sustainable future food system scenarios with improved nutrient management and reduced pollution levels in relation to the specific requirements of each NBS case study. 6.) Conducting an extended model open library search to find similar modelling approaches or model sequences that could be used as a source of learning material. 7.) Implementation of the ABM in the computational software NetLogo by using an existing, already coded model approach as a starting point (Ullah, Oladosu, and Crooks 2023).

The main agent category in the core model is the farmer. For the Danish case study, we consider another type of agent, the processor. Relationships are built on social network patterns (Table 2).

Table 2: Entities in the Pilot-ABM.

	Entity	that is…	that supplies…	that demands…
A	Farmer	- Adopter of the NBS technology	- Rotation & Biomass (e.g. clover grass)	- Bio-fertilizer
B	Processor (only available for the Danish version of the ABM)	- Biorefinery or/and Biogas producer	- Bio-fertilizer (green manure) & protein fodder	- Biomass (e.g. grass)
C	Social network	- Farmer's interaction with other agents	- Know-how & information	- Know-how & information
D	Grid space (spatial units)	- Farmer's interaction with the environment	- Neighbourhood polygon	- Biophysical characteristics (e.g. soil quality, nitrogen retention, high nature value) - Crop data layers (e.g. yield level, 3 to 5-year-rotation)

Analysis of needs of stakeholder groups

One of the key success factors for the agent-based model approach lies in its transferability between regions, contexts, and stakeholder groups. Current research highlights the importance of both local case studies and the wider diffusion of these solutions (Quintero-Angel, Cerón-Hernández, and Ospina-Salazar 2023). In this context, agent-based modelling offers a unique opportunity to simulate the socio-economic impacts of NBS adoption, understanding the diffusion pathways and policy impacts in different environments. The approach is useful not only for strengthening communication between researchers and the farming and processing community at the NBS site, by sharing knowledge about important socio-economic and environmental impacts and about barriers to the adoption of innovative NBS. It enables also policy makers to identify the most effective policy measures to accelerate the transition to sustainable nutrient management.

Experimental results

The result of our challenge is a process diagram that describes the essential model elements, their dependencies and the sequence of their execution (Figure 4). The individual elements must be worked out in more detail in a second step. However, this is beyond the scope of our hackathon challenge.

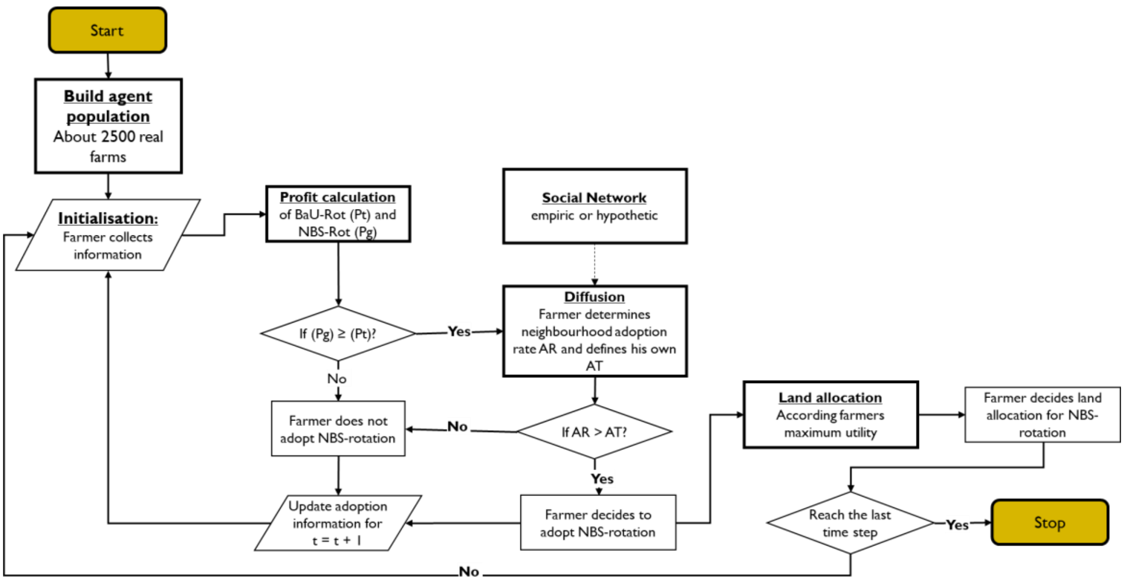

Figure 4: Process chart of the Danish Case study of Trans4Num EU-Horizon-Project.

Source: Derived from Ullah, Oladosu, and Crooks (2023), adapted. Adoption rate (AR) is calculated from the net proportion of positive minus negative profit experiences from NBS-rotation among the farmers in the neighborhood from the previous time step, Adoption Threshold (AT) is the value that defines farmers degree of 'resistance' to change.

Farmer agents' adoption decisions of NBS-rotation are reflected in four sub-models: i) profit modelling; ii) diffusion modelling; iii) social network modelling, and iv) land allocation modelling. The profit modeling evaluates farmers' profits of row crop rotations with and without grass cultivation in their rotation. The diffusion modeling determines farmers' attitudes towards adopting NBS-rotation under neighbourhood influences. The profitability of the NBS rotation is strongly connected to transportation costs and relationships that are emerging by collaborating with a processing biorefinery plant. Here, we could at the same time take into account the ability to learn, which is influenced by the interactions with the social network in which the farmer is involved. Farmers decide to adopt clover grass for the current period only when they find their profit with NBS rotation is greater than the traditional or Business as usual (BaU) rotation in the previous period, and the neighbourhood influences from the same previous period build a positive outlook for adoption (AR > AT). Land allocation decisions determine farmers' expected utilities, depending on farmer's individual risk aversion parameters and, of course, on specific local and environmental requirements. Finally, for each farmer, the adoption behaviour of the current period is updated and feeds into the next time step. Thus, the model works in a recursive manner until the end of the simulation period.

For the Chinese model, there are distinctions in the diffusion framework. In addition to considering neighborhood effects, we also account for the role of local government in organizing relevant technical training and subsidy programs, which significantly influence farmers' adoption of NBS technologies.

FINDINGS & CONCLUSION

Discussion of the results and findings

The goal of developing a common modelling approach for fundamentally different case studies in different geographical regions and different political systems is a huge challenge. However, it also creates excellent opportunities and synergies arising from the collaboration itself, but also from the exchange of knowledge between researchers and stakeholders across continents.

A model that uses commonly accepted and proven patterns and theories can be applied anywhere. Of course, individual adaptations are necessary depending on the context. Therefore, we prefer a two-dimensional granularity in our model approach (Figure 2). Accordingly, the main differences are in model parameterisation and spatial resolution. While a high resolution of individual farm data is available for Denmark, this is currently limited to some survey data in China, which has an important impact on the procedure for building the agent population. Furthermore, the agricultural production systems are very different. While currently only two crop rotation systems dominate in the Chinese case study region (corn-corn continious, corn-soybean alternating), we find much greater heterogeneity in this respect in the Danish case study region (Figure 5 &).

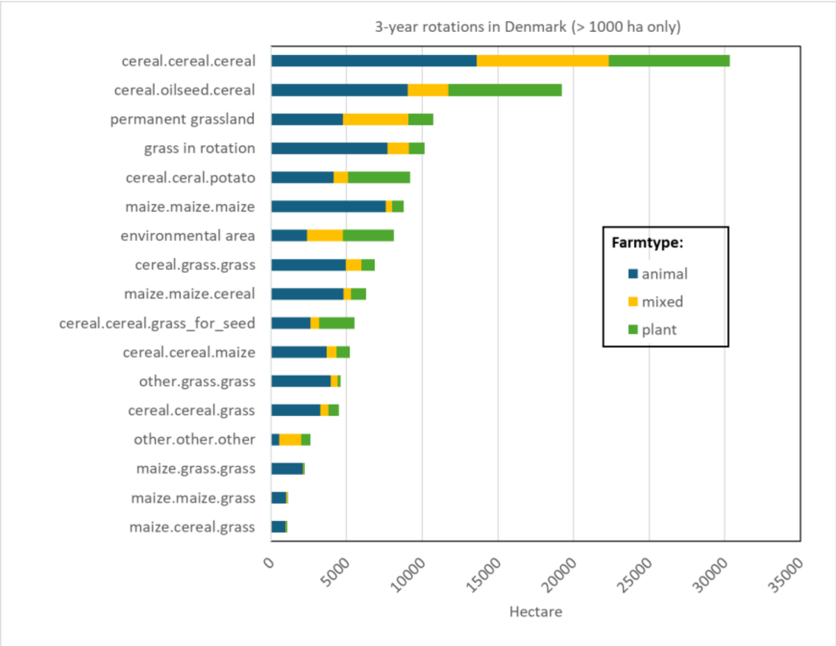

Figure 5: Three-year crop rotations in Denmark with a total area of > 1000 ha (2019-2021).

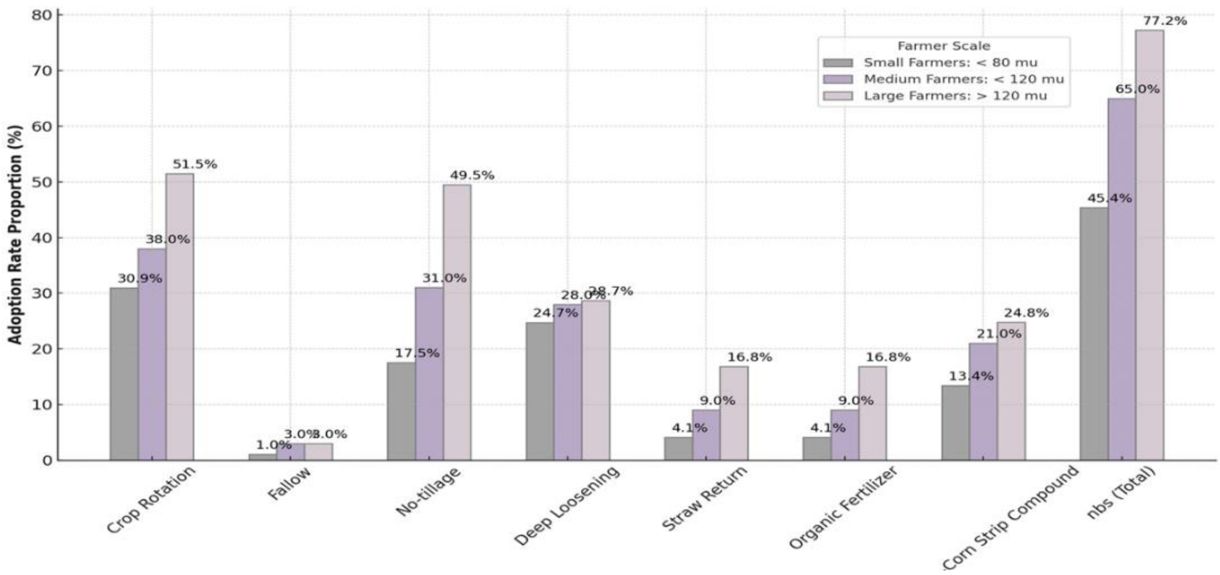

Figure 6: NBS practices in Northeast China by farm scale

There are also major differences in the way the diffusion of innovation is modelled. The behaviour of farmers must be modelled differently and is influenced by a variety of exogenous and endogenous parameters. Furthermore, country-specific policy frameworks require different policy-specific interventions.

Table 3: Key differences in a joint Sino-European agent-based modelling approach.

Aspect	Danish NBS site	Chinese NBS site
Farm agent population	≈ 2500 farms	≈ 1 Mio. Farms
Spatial data	Vector data (polygons)	Raster data (pixel)
Traditional crop rotation	More than 400 different crop rotations	Basically two crop rotations • corn-corn continious • corn-soybean
Biomass exchange	Exchange with a processor (Biorefinery)	Exchange with a livestock farm
Site-specific factors that influence farmer‘s behaviour	• Relationship to the processor and transport distances • Policy intervention design	• Trust in agricultural technicians • Land lease system • Policy intervention design • Knowlege on NBS technology • Attitute on green production technology • Cost of labor input

Source: Stakeholder exchange

Next steps

There are several prerequisites that need to be carried out or developed in order to be able to implement, validate and improve the current model specification, e.g:

- Provide data and conduct surveys to derive adoption behaviour
- Gain a better understanding of how to integrate geospatial data for both the Danish and the Chinese NBS case study sites.
- Work out the methodological design for building the agent population in China
- Select agronomically feasible crop rotations to be modelled & explore relevant crop-rotation and pre-crop effects
- Define site-specific and agent population specific assumptions as a basis for model simulations
- Discuss possible scenarios (baseline, intervention & sensitivity)
- Validate the model with stakeholders

Conclusion

The success of NBS adoption depends on its acceptance by society. The development of innovation must be a collaborative effort, and the impact of innovation must be widely understood. However, innovation also occurs through scalability and transferability. NBS are developed at the local level, but provide solutions for global systems and must be transferable - to other societies, to other places, to other framework conditions. The innovation in the field of modelling lies in the achievement of this flexibility, and at the same time, in the mastery of the complexity. It is challenging to work this out, but - at least from a scientific point of view - it is very promising.

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APPENDIX I

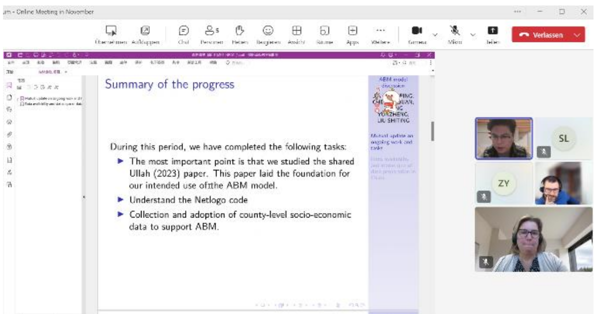
Table 4: Information about team members and their skills and expertise.

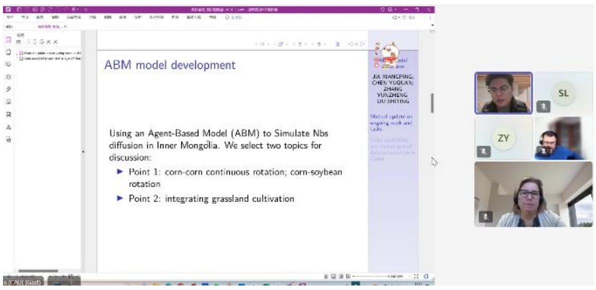
Institution	Team member	Skills and expertise
Research Institute of Organic Agriculture (FiBL)	Anke Möhring	Agricultural economist, Modelling, Production Economy
	Christian Grovermann	Agricultural economist, Impact Evaluation, Modelling
	Claudia Meier	Environmental economist, Consumer and Social Research, Modelling
	Fatma Fevzi	Environmental scientist,
Aarhus University (AU)	Morten Graversgaard	Department of Agroecology, Tenure Track Assistant Professor
	Mette Vestergaard Odgaard	Department of Agroecology, Research associate
Innovation Centre for Organic farming (ICOEL)	Morten Winter Vestenaa	Plant nutrition, Senior Advisor
	Anton Rasmussen	Conservation agriculture, organic fertilizers, plant production, Chief Advisor
Chinese Academy of Agricultural Sciences (CAAS), Agricultural Information Institute (AII),	Xiangping Jia	Chief Scientist of International Agricultural Research Group at Agricultural Information Institute
	Yunzheng Zhang	Research associate
	Minglong Zhang	Research associate
China Agricultural University (CAU), College of Economics and Management	Yuquan Chen	Agricultural economist, Agri-food Supply Chain, Household Risk Management; Digital Agriculture
	Shiting Liu	Research associate

APPENDIX II

Pictures 1: Treffen zwischen Modellentwicklern aus der Schweiz und China in Frick, Switzerland. (© Anke Möhring)

Pictures 2: Presentation und Diskussion der Zwischenresultate mit FiBL-Experten (© Anke Möhring)





Pictures 3: Online Meeting during the Hackathon process to exchange information between project partners from China (CAAS, CAU) and Switzerland (FiBL) (© Anke Möhring)