Supplementary Material

Reflections on linking economic equilibrium models with agent-based models in the context of agricultural land use

Supplementary Material A: Questionnaire

- In your opinion, which are the greatest challenges when combining ABM & PE/CGE for land- use modelling?
- Do you have any ideas on how to overcome them?

ABM modelers

- Name of your model (including reference)
- Which is the key research question addressed in your model?
- What are the behavioral rules that agents follow?
- Which are the temporal and spatial scales of your model (resolution and extent)?
- How is heterogeneity represented?
- Which type of land- use change represented and how is it modelled?
- Which agricultural policies are represented and how is it simulated?

CGE/PE modelers

- Name of your model (including reference)
- Which is the key research question addressed in your model?
- Which are the scales of your model (resolution and extent)?
- Which type of land-use change represented and how is it modelled?
- Which agricultural policies are represented and how is it simulated?

- Do you have suggestions for specific topics to discuss in thematic sessions?
- Apart from these questions, do you have any suggestions or hints we should consider for organizing the workshop (with respect to content and organization)?

Supplementary Material B: Existing applications of ABM - CGE/PE model linking

Linking CGE/PE models with ABMs is rare. To our knowledge, only one study exists that combines an ABM with a CGE model, and two examples combine an ABM with a PE model. These examples are described below.

Supplementary Material B.1: ABM-CGE linking

Niamir et al. (2020) link an ABM simulating diffusion of households' uptake of low-carbon investment choices calibrated using survey data with a CGE model covering all European NUTS2 regions. The main challenge in the study is aligning the key assumptions (e.g., heterogeneous vs. representative agent, perfect vs. bounded rationality, static vs. adaptive behavior). Furthermore, several technical issues required resolution, such as aligning the number of ABM agents with the demographic and sectoral composition of the equilibrium model, scaling up or disaggregation of data flows between the models, and establishing a soft link between the two models. To address these challenges, Niamir et al. (2020) scale up based on age and education to model behavioral patterns derived from surveys and simulated with ABMs to the representative household groups in the CGE model. The upscaling of agent behavior was linked to the CGE model via complementary Eurostat regional socio-demographic data, which allowed to meaningfully scale-up of behavioral patterns elicited from household surveys in two NUTS2 regions. A soft link between the two models was implemented via gross domestic product growth (GDP). In conclusion, the authors highlight additional conceptual challenges that arise when linking two distinct modelling concepts such as data availability and sensitivity analysis. Niamir et al. (2020) suggest using more case studies and improving validation for real policy analysis.

Supplementary Material B.2: ABM-PE linking

Möhring et al. (2016) developed a model linking the ABM sector model SWISSland with a PE model to explore interactions between farm-level production decisions and national market outcomes (see Figure B.2). In this approach, the SWISSland model simulated the production behavior of approximately 3,000 individual Swiss farmers based on data from the FADN. These micro-level outputs—specifically, the supply volumes—were upscaled and aggregated to represent the national agricultural sector, consisting of roughly 50,000 farms. The PE model, in turn, determined consumer responses and national market prices based on economic behavior, trade policy, and macroeconomic trends, such as GDP and population growth.

The two models were linked in an iterative framework: market prices from a prior simulation round served as price expectations for the following year's decisions by farmers in SWISSland. To reduce volatility between iterations, average prices across two iterations were used, thereby smoothing annual fluctuations in prices and supply. The link between models enabled endogenous feedback between farmer behavior and national market dynamics. However, it also significantly increased the demand for computational and modelling resources, particularly for testing, validation, and sensitivity analysis, compared to versions of SWISSland that used exogenous price forecasts.

Over time, this linked modelling framework was applied in multiple studies. Möhring et al. (2015) projected long-term supply, demand, and prices of major agricultural commodities in Switzerland. Mack and Kohler (2019) assessed the effects of direct payments for grassland-based meat and milk production on national milk supply and prices. Schmidt et al. (2021) examined the impacts of a food tax on both production and consumption.

Currently, the hard link between the two modules is no longer maintained due to the high resource requirements for testing and validation, as well as the loss of PE modeling expertise in the team. In addition, communicating the potential and limitations of the model to the stakeholders was often challenging due to the complexity of the model design.

A second example of ABM-PE linking is from Morgan & Daigneault (2015) and Morgan et al. (2015). They did a "loose coupling" (Morgan & Daigneault, 2015) of the PE model NZFARM and the ABM ARULUNZ. The PE runs at regional, catchment or even farm level. The model uses a positive mathematical programming approach and optimizes the net revenue over the catchment (Daigneault et al., 2014). The ABM represents the Hurunui-Waiau catchment in North Canterbury. It incorporates 25275 cells of 25 ha. The farmer agents are boundedly-rational and are specified based on a large-scale survey in New Zealand from 2013 and cadastral data. The ABM provides information on farmers' responses to changing conditions and resulting economic and environmental indicators (Morgan et al., 2015).

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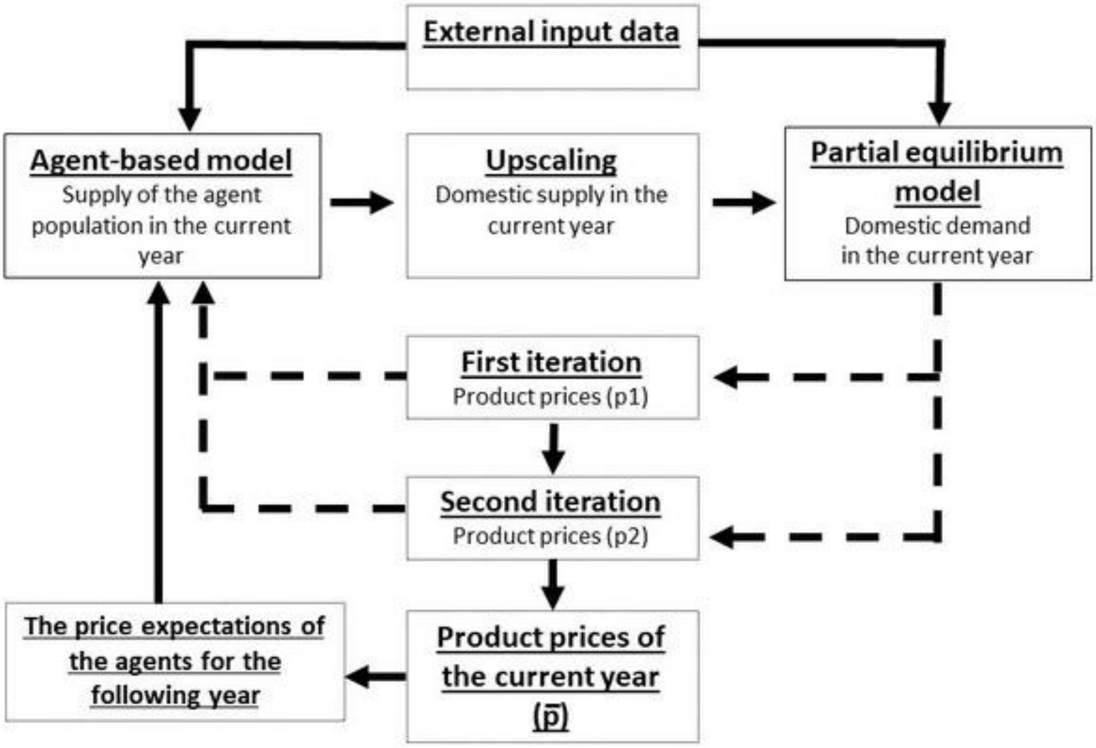

Figure B.2: Representation of the linking between the agent-based model and the partial equilibrium model in SWISSlandExperiences of ABM-CGE/PE model linking from the AGRICLUSTER models.

The ABM uses information from the PE about commodity prices, environmental policies, and the profitability for all enterprises (Morgan et al., 2015). The model run time was long and the model link behaved temperamental (M. Fraser, personal communication, 03rd of June 2025).

Supplementary Material C: Experiences of ABM-CGE/PE model linking from the AGRIMODL cluster

The AGRIMODELS cluster is the response to the European Commission call "Analytical tools and models to support policies related to agriculture and food - RIA Research and Innovation action" (RUR-04-2018) aims at combining different models from ABM and PE/CGE models to better evaluate agricultural policies. They may benefit from linked models, which are explained for each project below.

Supplementary Material C.1: BESTMAP

Purpose: The BESTMAP project aims to improve predictions of how European agricultural policies impact land use. While standard economic models provide depictions of market-based instruments such as direct payments, voluntary schemes are not as well-represented. As an example of these schemes BESTMAP focuses on agri-environmental schemes (AES) (Ziv et al., 2020).

The project involves the development of an ABM for five different EU regions. Additionally, there was a discussion about linking it with DART-BIO, a global multi-sectoral, multi-regional recursive-dynamic CGE model that provides a more detailed representation of the agricultural sector, land use, and biofuels (Delzeit et al., 2016). During the project, the linking of the two models was discussed, but not yet achieved.
The ABM assesses the impact of farmers' decision-making on the adoption of flower strips and cover crops, or the preservation or restoration of permanent grassland, while considering current opportunity costs (Popova et al., 2024).

Main challenges: The BESTMAP ABM only could profit from model linking from any CGE model analysis if different opportunity costs for adopting AES were implemented. The opportunity costs are currently considered to be constant. In the beginning of the project, the strengths and weaknesses of the different models were not well understood by the different teams. Therefore, the models were not optimally developed to be linked.

How challenges could be addressed: To link the model, both modelling teams need to develop a sufficient understanding of the other model. A person who has expertise in both model types needs to be part of the team. Based on this, a clear research question is needed to assess whether linking is useful. Based on the research question, the model should be adapted to be linked.

Supplementary Material C.2: MINDSTEP

Purpose: The MIND STEP project explored the potential integration of AgriPoliS (Happe et al. 2006), an ABM, with the GLOBIOM PE model (Havlík et al. 2014). AgriPoliS simulates farm-level decision-making and structural change in agriculture, typically at regional scales (NUTS 2 or 3), assuming exogenous and stable prices. In contrast, GLOBIOM operates on a global scale, modelling land-use competition and market feedback across agriculture, forestry, and bioenergy sectors. The objective of the linking was to enhance the realism and policy relevance of both models: AgriPoliS would benefit from price feedback generated by GLOBIOM, while GLOBIOM would be enriched with bottom-up structural changes captured by AgriPo-liS. This coupling aims to improve the assessment of long-term agricultural policies and their potential unintended consequences on market dynamics and land use.

Main challenges: The main challenge encountered during the exploration of this model integration was the lack of sustained funding and limited project timeframes meant that only conceptual work on the linking could be conducted within MIND STEP. The technical effort required for data harmonization, interface development, and validation of cross-model consistency exceeded what was feasible under existing resource constraints.

How the Challenges Were Addressed: While full technical implementation was not possible within MIND STEP, foundational work was completed to prepare for integration in a follow-up project. This included joint workshops to align model assumptions and data requirements of the already existing models, initial exploration of interface specifications, and clarification of each model's role in the coupling.

Supplementary Material C.3: Agricore

Purpose: The AGRICORE project, funded under the EU Horizon 2020 program (Grant Agreement No. 816078), aimed to enhance the assessment of agricultural policies by developing an advanced ABM tool. This tool simulates individual farm behaviors and their interactions within various contexts—such as environmental conditions, rural integration, ecosystem services, land use, and markets—across different geographic scales.

The project's primary objective was to develop a modular and customizable ABM suite, released as an open-source project, to enable institutions to transparently update and improve the tool as needed. The model represents each farm as an autonomous decision-making entity, allowing for the simulation of interactions between farms and their broader context. A short-period module (an ABM based on Positive Mathematical Programming) and a long-period financial module (Model Predictive Control) were developed to simulate individual behaviors and farm interactions, in order to assess the effects of regional and EU-level policies.

The analysis of the AGRICORE use cases demonstrated that ABMs are well suited for detailed simulations of individual farm behavior and interactions within agricultural systems. However, the realism and applicability of ABM simulations could be further enhanced through integration with CGE models, particularly where regionally calibrated economic information is needed.

In the Emilia-Romagna case study (Baldi et al., 2023), the ABM simulation showed that dairy farms would significantly reduce herd sizes in response to progressive CO_2 taxation, resulting in marked declines in dairy cow numbers and corresponding reductions in nitrogen and carbon emissions.

Main challenges: The absence of a CGE model to capture broader market dynamics and regional economic feedback implies that these outcomes may oversimplify the systemic effects of such policy measures. An attempt was made to develop a "market" module representing the demand side, but it was ultimately unsuccessful, primarily due to the complexity involved and limited project resources.

How the challenge could be addressed: More project resources would be needed to achieve a linking.

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