Li, Sen; Juhász-Horváth, Linda; Pintér, László; Rounsevell, Mark D.A.; Harrison, Paula A. 2018. **Modelling regional cropping patterns under scenarios of climate and socio-economic change in Hungary**.

Title

Modelling regional cropping patterns under scenarios of climate and socio-economic change in Hungary

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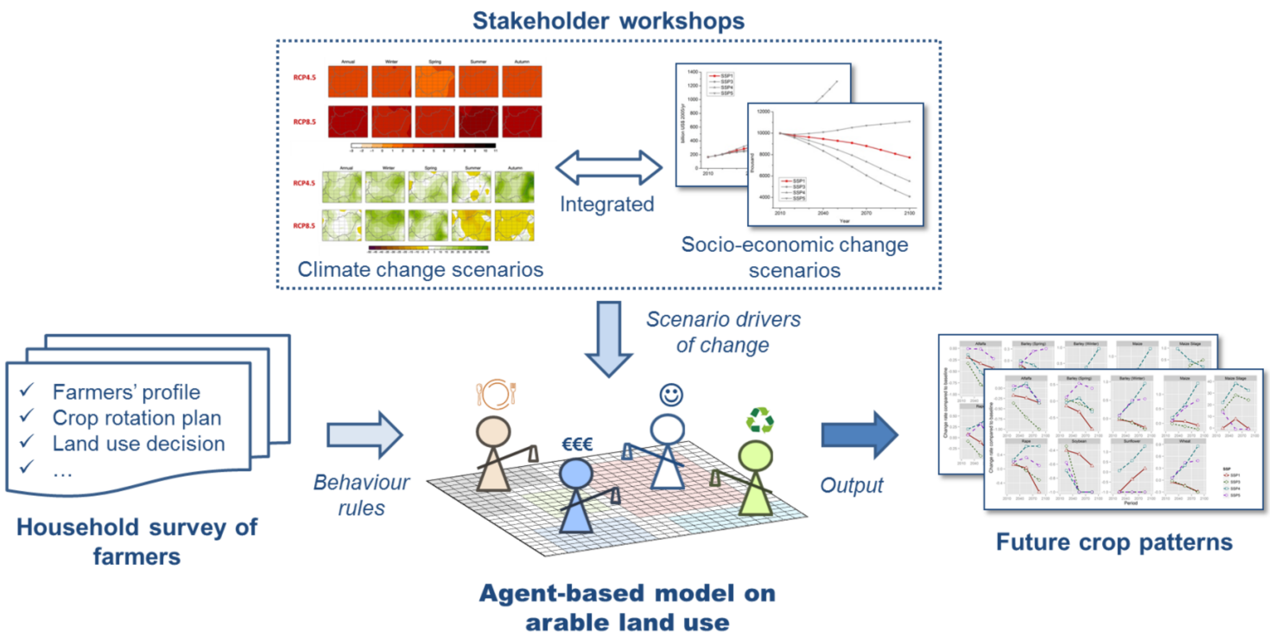
Highlights

- We emphasise the critical role of regional level actors in developing effective responses to arable land use changes.
- We describe the development of an empirically-grounded agent-based model for projecting future cropping patterns.
- We apply the model to stakeholder-driven scenarios of plausible future socio-economic and climate change.
- The model projects strong differences in future land use change between two Hungarian regions.
- The results support the need to implement focused adaptation policy at the regional level.

Graphical abstract



Abstract

Impacts of socio-economic, political and climatic change on agricultural land systems are inherently uncertain. The role of regional and local-level actors is critical in developing effective policy responses that accommodate such uncertainty in a flexible and informed way across governance levels. This study identified potential regional challenges in arable land use systems, which may arise from climate and socio-economic change for two counties in western Hungary: Veszprém and Tolna. An empirically-grounded, agent-based model was developed from an extensive farmer household survey about local land use practices. The model was used to project future patterns of arable land use under four localised, stakeholder-driven scenarios of plausible future socio-economic and climate change. The results show strong differences in farmers' behaviour and current agricultural land use patterns between the two regions, highlighting the need to implement focused policy at the regional level. For instance, policy that encourages local food security may need to support improvements in the capacity of farmers to adapt to physical constraints in Veszprém and farmer access to social capital and environmental awareness in Tolna. It is further suggested that the two regions will experience different challenges to adaptation under possible future conditions (up to 2100). For example, Veszprém was projected to have increased fallow land under a scenario with high inequality, ineffective institutions and higher-end climate change, implying risks of land abandonment. By contrast, Tolna was projected to have a considerable decline in major cereals under a scenario assuming a de-globalising future with moderate climate change, inferring challenges to local food self-sufficiency. The study provides insight into how socio-economic and physical factors influence the selection of crop rotation plans by farmers in western Hungary and how farmer behaviour may affect future risks to agricultural land systems under environmental change.

Keywords

Agricultural land use, crop rotation, empirically-grounded agent-based model, environmental change impact assessment, farmer household survey, stakeholder-driven scenarios

1. Introduction

Socio-economic and political changes are critical drivers of agricultural land use in Europe (Ewert et al., 2005; Holman et al., 2016; Lambin and Meyfroidt, 2011; Rounsevell and Reay, 2009). Development of new farming technologies and crops, increasing population density, mobility and changing consumption patterns, and diversified international trading patterns have all affected the profitability of domestic agricultural production to varying extents and influenced farmer decision-making. Climate change also plays an important role through shifts in weather patterns (e.g. precipitation and temperature) and extreme weather events (e.g. floods, droughts and storms) affecting crop suitability and yield variability in agricultural systems (Olesen and Bindi, 2002; Olesen et al., 2011). Such socio-economic, political and climatic changes are expected to continue, and may even accelerate in the future resulting in potentially severe, but highly uncertain, impacts on agricultural land systems (Holman et al., 2017).

Land use/cover change (LUCC) modelling techniques have advanced rapidly (c.f. reviews by Lambin et al. (2000), Matthews et al. (2007) and Verburg et al. (2004)). This has led to model-based projections of future LUCC being more often used for decision support in urban/rural planning policy (Harrison et al., 2016; Prestele et al., 2016). Several authors have suggested that for modelling studies of future LUCC to be useful and relevant for land use decision-makers, they should: (i) represent real-world processes and sectoral interactions of importance within the context of a specific socio-ecological system; (ii) develop participatory scenarios with stakeholders to gain qualitative insight into possible future changes; and (iii) recognise uncertainty and error propagation in model outputs explicitly rather than focusing on precise predictions (Audsley et al., 2006; Harrison et al., 2015; Millar et al., 2007). Moreover, effective policy responses to environmental change need to coordinate across governance levels and across sectors (Adger et al., 2005; Ciscar et al., 2011; Hurlimann and March, 2012). In particular, the role of lower level (regional and local) actors in determining responses to LUCC are essential in understanding the effectiveness of management interventions under uncertain future scenarios (Antonson et al., 2016; Eikelboom and Janssen, 2013; Kumar and Geneletti, 2015). To date, most scenario-based LUCC studies have focused on the continental- and global-scale (Ewert et al., 2005; Holman et al., 2017; Hurtt et al., 2011; Rounsevell et al., 2005). Regional- and local-level LUCC studies have been rare, with a few recent exceptions (Guillem et al., 2015; Houet et al., 2016; Li et al., 2017b; Murray-Rust et al., 2013).

Farmers make agricultural land use decisions. Whilst farmers may be operating within similar socio-economic contexts at the regional scale, land use decisions can be highly diverse, owing to differences in individual objectives, preferences and experiences, as well as farm-level physical constrains such as soil type and accessibility. This suggests that models of agricultural LUCC need to incorporate explicitly representation of the mechanisms of how individual and/or farm-level attributes affect farmer management strategies (Rounsevell et al., 2003). From this perspective, agent-based modelling (ABM) is an approach that offers a flexible, bottom-up way of representing the processes of individual land use decision-making and cross-scale interactions (Murray-Rust et al., 2014; Valbuena et al., 2010). ABMs have been shown to provide greater explanatory power than many top-down approaches (e.g. linear programming modelling) (Filatova et al., 2013; Kelly et al., 2013) and thus offer the potential for interpreting the reasons behind projected patterns of land use change.

This study builds on recent research on applying an empirically-grounded ABM for scenario-based future LUCC projections, e.g. Castella et al. (2007), Guillem et al. (2015), and Murray-Rust et al. (2013). The objectives were (i) to project possible future patterns of arable land use at the regional level for two counties, Veszprém and Tolna, in western

Hungary, and (ii) to identify potential county-specific challenges for crop production, which may arise from environmental change. To achieve these objectives, an extensive farmer household survey was designed and implemented to investigate the current patterns of arable land use in western Hungary. This was used to explore the environmental factors influencing farmer decisions in selecting crop rotation plans. The model's structure was designed within the *Aporia* framework, an ABM of agricultural LUCC (Murray-Rust et al., 2014), and functions were calibrated based on the survey data as well as census data from various sources. A scenario analysis was performed using four integrated climate and socio-economic scenarios co-created with stakeholders from the two counties. The modelling experiments sought to identify potential changes in future arable land use patterns due to environmental and related socio-economic change and challenges for adapting to these changes within the two counties.

2 Materials and methods

2.1 Study sites

Farmers' land use decisions and how they affect arable land use dynamics were explored for two predominantly rural counties in western Hungary, Veszprém and Tolna (Figure 1). These counties were chosen because of the interest of key stakeholders in the communities in an assessment of the impacts of environmental change, and particularly extreme or high-end climate change, on vulnerability in their regions and the degree to which adaptation options may reduce their vulnerability. The two counties have a similar cultural profile, and the geographical distance between their centres is approximately 100 km. Hydro-climatic conditions in the two counties are particularly important for regional agriculture, with Veszprém located at the northeast shore of the Lake Balaton, the largest lake in Central Europe, and Tolna located on the west bank of the river Danube, Europe's second-longest river. Individual farmers from Veszprém and Tolna manage 75,782 and 119,485 ha agricultural land, respectively, representing below-average and average levels in the country (KSH, 2011). Even though the extent of total arable land at the national level has only slightly increased by 0.5 % between 2000 and 2010, the proportion of major crops has changed considerably: by -9.4% for cereals, -33.8% for pulses, -54.8% for potatoes, -70.6% for sugar beet, -18.9% for fresh vegetables, melons, strawberries and +87.1% for industrial crops (EUFSS, 2012). Based on these census data, the study focused on the dynamics of land use proportions rather than their extents.

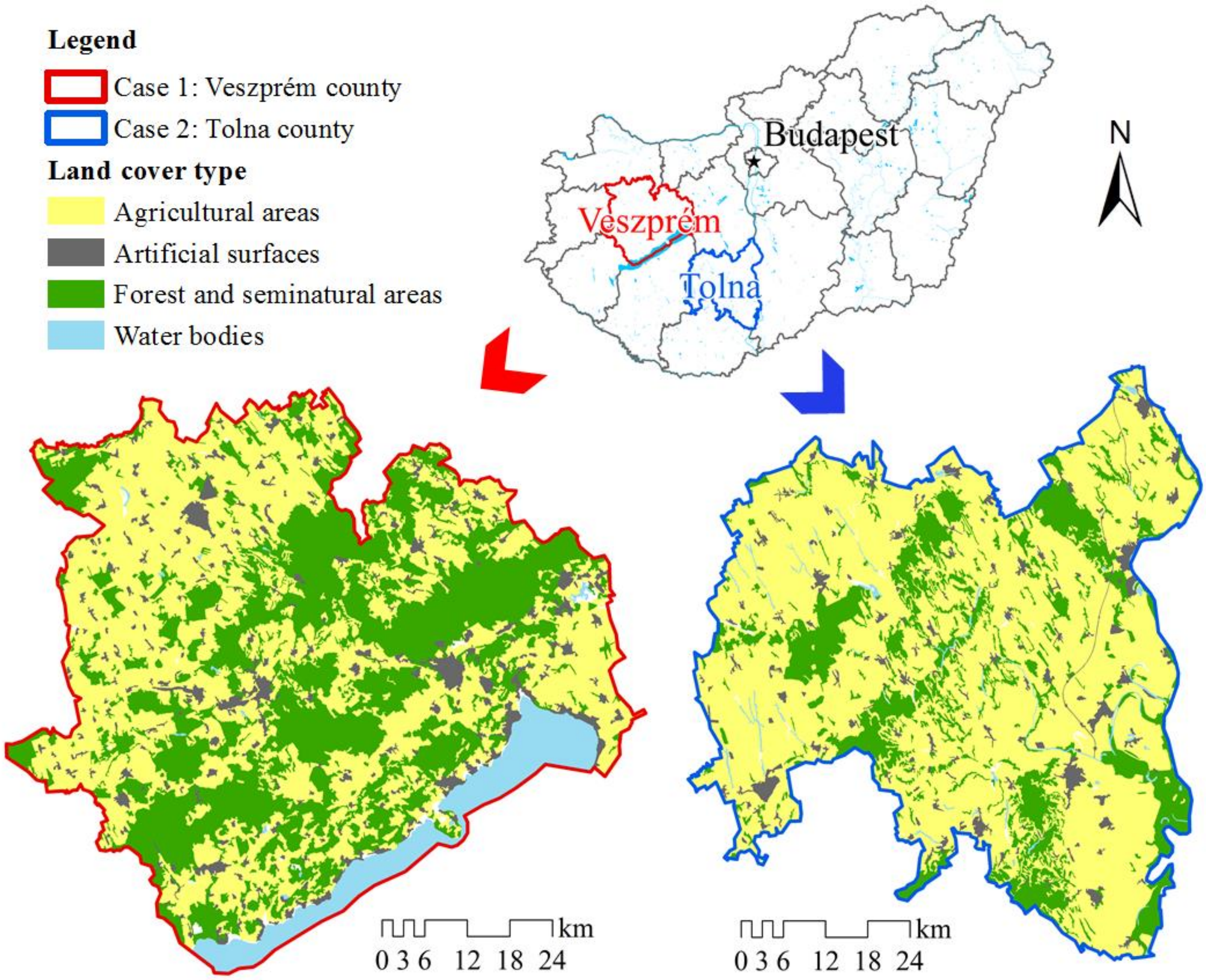


Figure 1 The two study sites in Hungary: Veszprém and Tolna counties.

2.2 Model development

An empirically-grounded model was developed for the case studies, using the *Aporia* framework for agent-based modelling of agricultural land use change (Guillem et al., 2015; Murray-Rust et al., 2014). The model developed in this study, termed *Aporia-Lite*, adopted the *Aporia* concepts and was programmed in a reduced form to only include the important components for the case study (see Figure 2). As an empirically-grounded model, the database and key functions of *Aporia-Lite* model are highly specialised for the case study. Readers interested in the technical details in developing agent-based models using the *Aporia* framework are referred to Murray-Rust et al. (2014). The free software and guidance for the full version of the *Aporia* model are available at http://www.wiki.ed.ac.uk/display/Aporia.

The *Aporia-Lite* model consists of two types of agents (*farmer* and *parcel*) and a *regime* database: A *farmer* agent represents an individual agricultural land manager of specific socio-economic and attitudinal attributes. Their farms are represented as *parcel* agents depicted by a set of physical attributes. A farmer agent manages a parcel agent through a *regime*, or a crop rotation plan, which has specific attributes describing its social, economic and environmental values. Thus, the *regime* database serves as a local knowledge base of crop rotation plans for farmer selection. The regime selection process is assumed to be driven by a joint consideration of all the *farmer* and *parcel* attributes and the available knowledge on adoptable *regimes*. A farmer typology is embedded in the model to better understand and categorise the differences in regime selection. The model generates patterns of farmer types and arable land use on an annual basis.

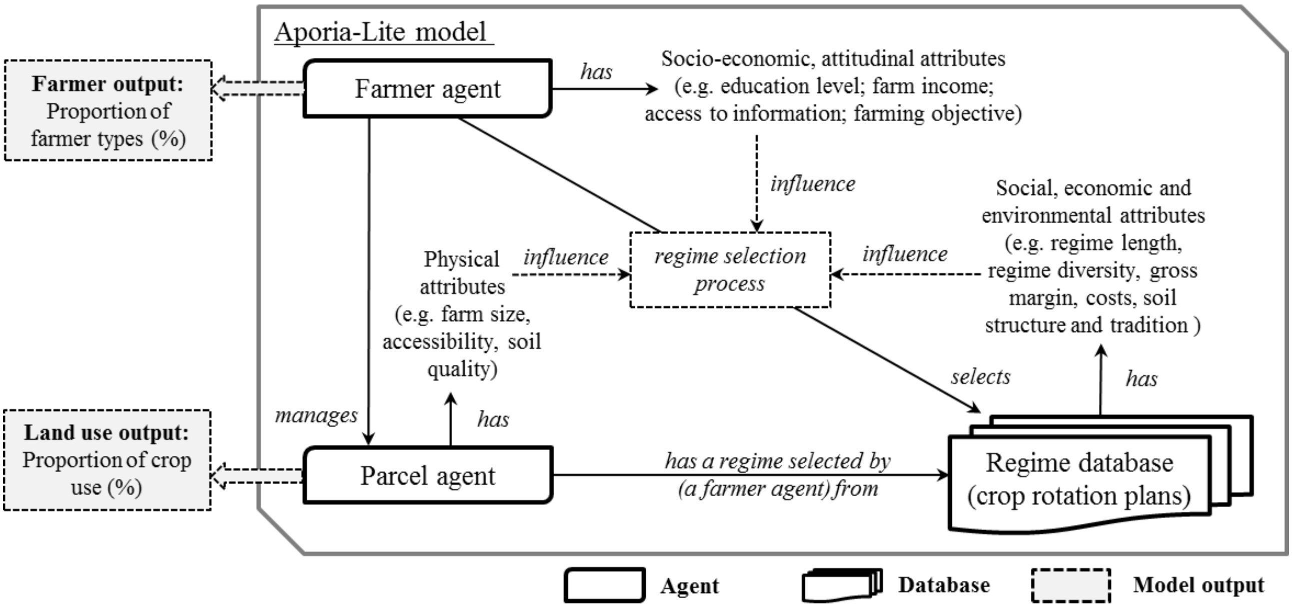


Figure 2 The theoretical framework of the *Aporia-Lite* model.

2.2.1 Local farmer household survey

An extensive, multi-purpose farmer household survey was conducted between June and August 2015 for the two study areas. The survey was designed to serve two key purposes. Firstly, to investigate current agricultural land use patterns and collect information on major local crops and sample crop rotation plans. Secondly, to collect attitudinal, socio-economic attributes and physical attributes that may influence farmers' land use decision-making. The survey study was designed with assistance from the Hungarian Central Statistical Office (KSH), and was conducted jointly with the KSH's regular agricultural survey in 2015 by trained and experienced KSH surveyors. For each county, the KSH determined 110 survey participants by randomly selecting farmers who manage private holdings from its annual sampling pools which contain 687 farmers (out of 13,529) in Veszprém and 1253 farmers (out of 18,092) in Tolna. These sampling pools were determined by the KSH's internal experts to adequately reflect the local distribution of farm size and farming objective. For the 220 survey participants selected from the two counties and visited, all helped to complete the questionnaire. Finally, 172 farmers who provided information on their regimes were included in this study. Further details about the survey study can be found in Li et al. (2017a). The attributes of farmers and regimes collected for this study are summarised in Table S1, the Electronic Supplementary Materials 1.

2.2.2 Regime database

In the farmer household survey, participants were asked to provide detailed information on (i) the length of current crop rotation plan (in years), (ii) the rotation scheme listing the crops planted for each year, and (iii) which year of this crop rotation scheme they are currently in. The survey collected 172 regime records in total, 164 of which were different, suggesting a high diversity in farmers' regime selection process. To reflect this diversity, a regime database was developed from the survey results to cover as many adoptable regimes as possible. The database was constructed to include regimes of 2-8 year duration, which is the common range found in the survey. A variable describing the general adoptability of the regime was generated to reflect the ease with which a crop rotation plan could be adopted based on existing local knowledge. This was estimated from the likelihood of different crop-to-crop chains as found in the local survey and termed the 'crop match possibility' (Figure 3). For example, the total crop match possibility of a three-year regime 'Maize->Sunflower->Wheat' was estimated as the 'Maize->Sunflower' match possibility' * the 'Sunflower->Wheat' match possibility. All possible crop rotations of length 2-8 years were generated. In order to reduce the computational burden, no more than 1000 crop rotations were retained for each length, by selecting the 1000 with the greatest crop-match possibility. Finally, 4855 and 5526 potentially adoptable crop rotation plans were included in the regime databases for Veszprém and Tolna, respectively.

The databases were then completed by compiling further economic, social and environmental attributes for each regime. The attributes used in this study followed previous Aporia modelling studies (Guillem et al., 2015; Murray-Rust et al., 2014), including regime length, regime diversity, gross margin (average yield * price + subsidies – costs), costs (seed, labour, machinery, fertiliser, pesticide and other costs), soil structure, nitrogen demand, cropland coverage, and scores for tradition, scenery and recreation. The 2013 agro-economic statistics provided by the Hungarian Research Institute of

Agricultural Economics (AKI) were used to calculate gross margin and costs. The qualitative scores of soil structure, nitrogen demand and crop cover were calculated following the method in the DEFRA guidebook of 'Arable Cropping & the Environment' (DEFRA, 2002). The tradition score was based on the crops' contribution to sown area in 1990, based on the FAO country profiles for Hungary. The rankings of scenery and recreation were generated with the help of local experts during stakeholder meetings (section 2.5).

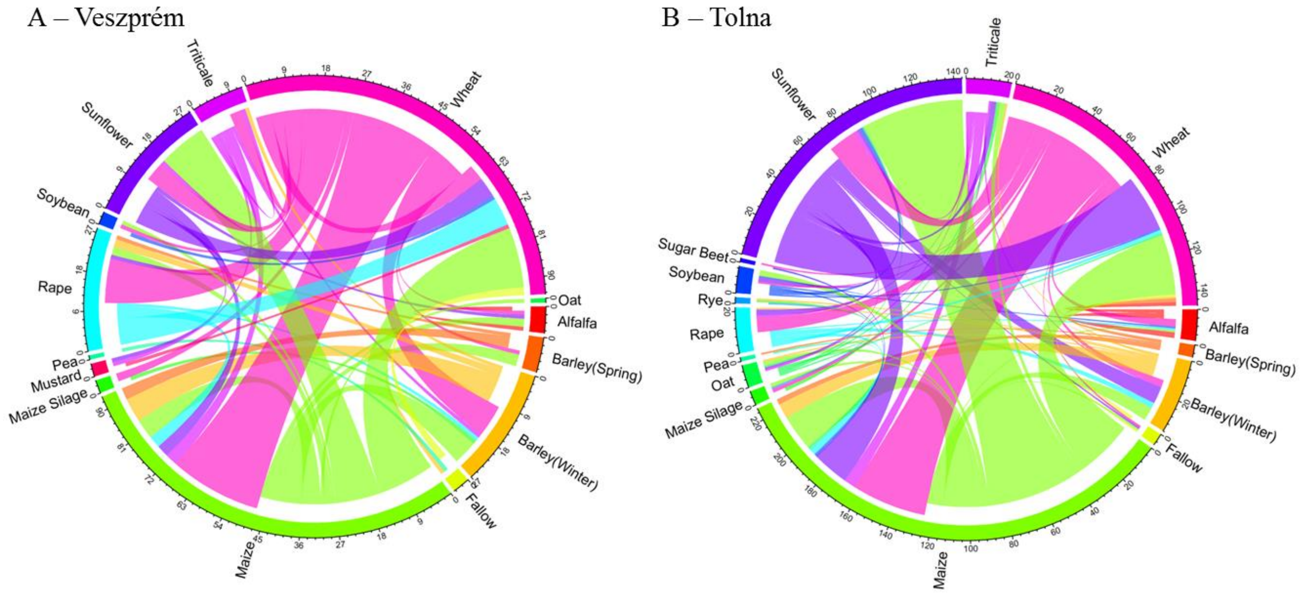


Figure 3 Match possibility of major crops in the two case study areas: (A) Veszprém and (B) Tolna. Scales of the colour segments indicate the total number of times the crop in question was mentioned in a regime by a respondent, either as a 'from' (greater gap to the circumference) or as a 'to' (smaller gap) in a 'from->to' crop match possibility.

2.2.3 Farmer's executive typology

Typologies are often used to simplify the diversity of farmers and their land use strategies, by defining different groups statistically based on specific criteria (McKinney, 1950). These criteria reflect not only the research objective, but also define how the diversity of land use decisions is simplified and included in the ABM of LUCC (Valbuena et al., 2008). In this study, the "executive typology" is defined as a categorisation of the farmers based on the differences in the styles of crop rotation plan actually applied. A classification analysis was performed following the approach used in previous typology studies (Guillem et al., 2012; Karali et al., 2013). First, a principal components analysis was conducted to extract the principal components describing the variation of regime attributes. Attributes with anti-image correlation < 0.3 were excluded, leading to six attributes being kept, including length of regime adoption, diversity of regime, gross margin, costs, soil structure and tradition. Second, all the regime records were classified based on the principal components using a K-means cluster analysis (with Ward's method). Four groups of regimes, or the executive types of farmers, were determined:

- (i) *Business-oriented* famers who adopt regimes with high margin/costs, which contain non-traditional crops, but result in degraded soil structure;
- (ii) *Traditional/non-diversified* famers who adopt long-term, low-diversity regimes with traditional crops;
- (iii) *Traditional/diversified* famers who adopt short-term, high-diversity regimes with traditional crops and relatively high margin/costs, and;
- (iv) *Supplementary* famers who adopt short-term regimes of low margin/costs, and create good soil structure.

The selected regime attributes were compared between the executive types of the farmers and the summary statistics are provided in Table S2, the Electronic Supplementary Materials 1. Multinomial logistic regressions were performed for the two sites separately, to identify which farmer and parcel attributes affect the categorisation of farmers' executive types. Attributes were entered into the regression model and selected based on their statistical significance ($P<0.1$), correlations with other attributes ($-0.5<$ Spearman correlation coefficient < 0.5) and contribution to the functions predictive power (using the likelihood-ratio statistics). Using these empirical functions, it was possible to project how socio-economic and environmental changes could shift farmer type and, consequently, their regime selection. The two final county-specific functions had satisfactory predictive power with the Nagelkerke's Pseudo R-Square greater than 0.6 and an overall rate of correct classification higher than 67%. The following four attributes were included in both functions: size of the parcel, multiple parcel management (binary), attitude towards the importance of the environment, and accessibility to information via social groups (binary) of the farmer. In addition, the function for Veszprém included farmers' income and commercial objective (binary), while that for Tolna also included farmers' education, attitudes toward the importance of revenue and effort, soil quality and arable type of the parcel. Detailed parameter estimates are presented in Tables S3 and S4, the Electronic Supplementary Materials 1, for Veszprém and Tolna, respectively.

2.2.4 Regime selection

In the model, the decision strategy of a farmer agent follows a utility maximisation procedure. The attributes of the farmer agent and its parcel agent depict the limits of socio-economic and physical resources. Considering these limitations, an executive type was assigned to a farmer agent by applying the multinomial logistic regressive functions (section 2.2.3). A pool of candidate regimes was then selected using three steps. First, a random number was generated for each regime attribute following a normal distribution with the surveyed mean and variance values (Table S2, the Electronic Supplementary Materials 1). These randomly generated attributes were assumed to be the target attribute that reflects the maximum utility the farmer would seek. Secondly, the regimes which met all of the following requirements from the database were selected into the candidate pool: (i) candidate's length = target length; (ii) candidate's gross margin ≥ target gross margin; (iii) candidate's costs ≤ target costs, and; (iv) candidate' diversity, soil structure and tradition ϵ [0.8 * target values, 1.2 * target values]. Thirdly, if the pool remained empty after looping through the database, then the randomisation of target regime attributes and regime selection were repeated. Finally, the regime's adoptability (or the 'crop match possibility', section 2.2.3) was considered to represent the potential to acquire local knowledge and support for implementing the regime. A random selection scheme was applied to allow regimes with a higher adoptability to have greater chance of being selected from the candidate pool.

2.3 Model implementation, workflow and evaluation

The *Aporia-Lite* model was scripted in the Java-based Repast toolkit version 2.1 for agent-based modelling (North et al., 2013). All the data analysis and empirical functions mentioned previously were performed and developed using the IBM SPSS statistics version 22 (Field, 2013), before being integrated into the model.

When initialising the model, farmer agents and their parcel agents were co-created. Each farmer-parcel pair was assigned randomly generated attributes according to the summary statistics (mean and variance) from the agricultural census data or the household survey data. The agricultural census from the Hungarian Central Statistical Office (KSH) (retrieved for the year of 2013) was used to generate: farming objective (commercial, semi-subsistence, or subsistence) and farm type (arable, mixed, or livestock) for farmer agents; and farm sizes (distribution of sizes available in the census) for parcel agents. As this stage, 1000 farmer agents were generated for both study sites, and because of the research focus only those who manage 'arable' or 'mixed' farm types were kept in the model. This resulted in approximately 590 and 570 farmer agents being retained for Veszprém and Tolna, respectively. Then, the summary statistics based on the household survey on farmers' land use (Table S2, the Electronic Supplementary Materials 1) were used to generate the remaining attributes found to be important in classifying the agent executive types (section 2.2.3). After the agents were created, the regime selection procedure (section 2.2.4) was applied. All the farmer agents were assigned an initial regime and a random number to indicate the year of the regime the famer agent was in. Then, for each year, farmer agents managed their farms and made land use decisions simultaneously. They would first check if a regime was finished: if no, the land use planned for the next year would be applied; if yes, the regime selection procedure (section 2.2.4) was executed and new regimes applied.

The model was evaluated through (i) stakeholders' qualitative assessment and acceptance of the model structure and usefulness of model projections, and (ii) a quantitative comparison between the projected arable land use patterns and the observed patterns recorded in the local agricultural census. For each county, the model was run for 100 years with baseline settings (for 2010) and the proportion of land uses for major crops was summarised and compared with census data (retrieved from the KSH for 2013).

2.4 Modelling experiments: projecting future arable land use pattern

2.4.1 Integrated scenarios for local environmental changes

Understanding how environmental conditions are likely to change in the future is an important first step in scenario analysis, as it provides the conditions for which the model's parameters need to be modified. Through working closely with local stakeholders from the two study sites, a set of integrated scenarios were developed to describe plausible alternative future climate and socio-economic trajectories. The socio-economic scenarios were based on downscaling four of the global Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2015) for Hungary. PKD (Pink dream – SSP1) describes a sustainable future with a healthy economy and improved environment. RRV (Regional Rivalry – SSP3) represents an internationally fragmented future with highly degraded environmental conditions. IEQ (Inequality – SSP4) is characterised by a political and business elite with increased disparities between the elite and masses in social, economic and political dimensions, and a degraded environment. PPU (Pató Pál Úr – SSP5) portrays a fossil-fuel-based and highly industrialised future with rapid economic growth and highly overexploited environment. The PKD and IEQ scenarios were coupled with intermediate climate change based on the RCP4.5 emissions scenario, while the RRV and PPU were linked with high-end climate change based on the RCP8.5 emissions scenario. Details of the participatory methodology for developing the scenarios through a series of stakeholder workshops is given in Li et al. (2017b). A full description of the development of the four local scenarios can be found in Kok and Pedde (2016). The rationale behind the selection and integration of the local scenarios are discussed in Kok et al. (2015) and Madsen et al. (2016).

2.4.2 Scenario driver selection and quantification

For each scenario, future patterns of arable land use were projected by (i) tuning the agents' attributes based on a quantification excise and (ii) adjusting the yields of major local crops according to projections from crop models. The *Aporia-Lite* model was run for 100 time steps with scenario-specific settings, through which results at the annual level were summarised and compared.

The four attributes found to be important in the classification of farmers' executive types in both case study areas (section 2.2.3) were selected for the quantification excise. 'Farm size' was assumed to be associated with the total agricultural land use change, i.e., farm size in general decreased as total agricultural land use decreases. Whether a farmer manages 'multiple parcels' was assumed to correspond to the size of the rural population (i.e., a smaller rural population leads to more people managing multiple parcels) and technology (i.e., greater development of technology means less labour is needed and, thus, more multiple parcels). 'Access to social network' was assumed to be dependent on changes in social capital, i.e., increased social capital creates more chances for farmers to access knowledge. 'Attitude towards (the importance of) the environment' was assumed to be influenced by a general awareness of environmental protection and sustainable development, i.e., enhanced awareness leads farmers to have a stronger feeling of the importance of environment. The potential changes in these attributes were interpreted qualitatively for each scenario, based on the rationale and storylines underpinning the localised scenarios (Table 1). The 'low' and 'medium to high' change extents were assumed to be 15% and 35% for all attributes for experimental purposes. These values were selected as they are not too extreme to be impossible in the future but still able to cause considerable changes in projected future cropping systems.

Potential changes in crop yields were derived from the Integrated Assessment Platform (IAP) at the pan-European level (Harrison et al., 2016; Holman et al., 2015). In the IAP, crop yield projections are influenced by climate, CO_2 levels and SSP-specific assumptions about yield improvements due to improved agronomy and/or crop breeding. Projections for several major crops were extracted for Hungary (see Figure S1, the Electronic Supplementary Materials 1). In general, crop yields were projected to improve dramatically under PPU (SSP5) and IEQ (SSP4), but decrease slightly under PKD (SSP1) and RRV (SSP3). Since minor cereals and legumes were not modelled by the IAP, their crop yields were assumed to remain unchanged under the different scenarios in the modelling experiments.

Table 1 Settings of selected agents' attributes for future land use projection.

Scenario	Time slice	Farm size	Multiple parcels	Access to social network	Attitude towards (the importance of) environment
PKD	2010-2040	–	–	↗	↗
	2040-2070	↘	↘	↗	↗
	2070-2100	↘	↘	↗↗	↗
RRV	2010-2040	↗	↘	↘	↘
	2040-2070	↗↗	↘↘	↘	↘
	2070-2100	↗↗	↘↘	↘↘	↘↘
IEQ	2010-2040	↗	–	↘↘	–
	2040-2070	↘↘	↘	↗	↗
	2070-2100	↘	↘	–	–
PPU	2010-2040	↘↘	↗↗	↘	↘↘
	2040-2070	↘↘	↗↗	–	–
	2070-2100	↘	↗	↗	↗

† Changes between the start and end of the time slice: '–' indicates a marginal change; '↗' and '↘' mean low increase and decrease; '↗↗' and '↘↘' mean medium to high increase and decrease.

3 Results

3.1 Model performance

Qualitative evaluations by the stakeholders (through discussions) suggest general acceptance of the model structure. In a post-workshop survey with stakeholders, 20 out of the 23 respondents found model projections useful or very useful for discussing possible policy responses. The comparison between the baseline model projections (2010) with the census results suggests a satisfactory model performance (Figure 4): the projected rank of the proportion for major crops in total arable land use was in line with the rank found in census data; for the major crops (9 out of 11 in Veszprém and 7 out of 11 in Tolna), the recorded proportion of the crop in total arable land use in the census data fell within the projected min-max range.

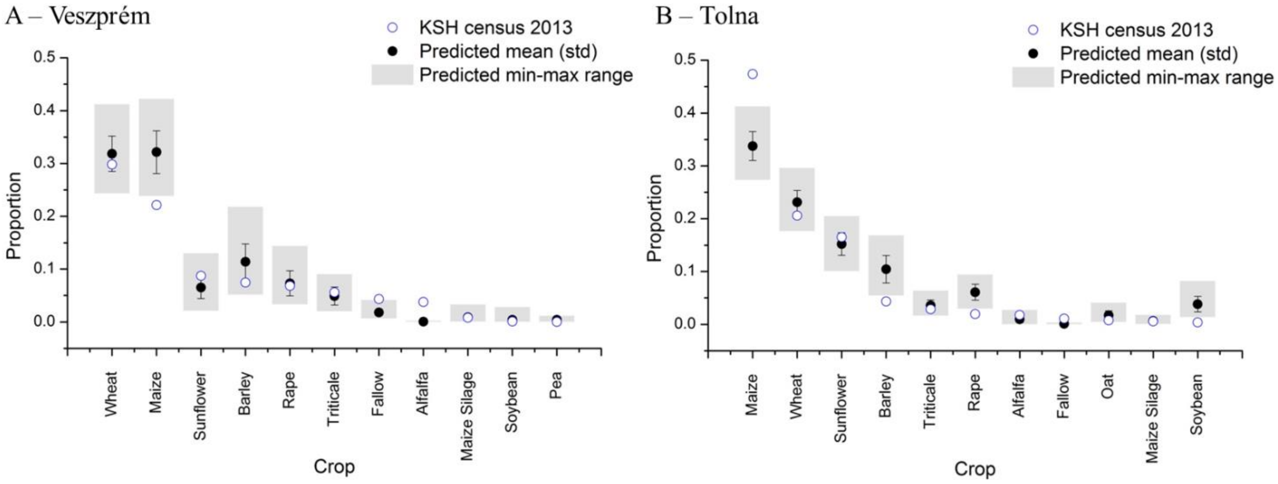


Figure 4 Comparison between the predicted proportion of arable land use (2010) and census data (KSH 2013) in Veszprém (A) and Tolna (B).

3.2 Projected changes in farmer's executive types

Projected patterns of change in farmer types are similar in both case study areas for some scenarios, but different for others (see Figure 5A, for the extents of changes by 2100; see Figure S2, the Electronic Supplementary Materials 1, for trends over time). In general, projected changes in farmer types were driven by the differences in the baseline farmer type proportions and assumptions made about the scenario drivers (Table 1). The most dramatic changes were projected under RRV and PPU in Veszprém but under PKD in Tolna. The IEQ scenario was projected to lead to a relatively lower level of change in both areas.

Under PKD, farmers were expected to be more environmentally friendly and self-sustained for both case study areas by 2100: an increase in the supplementary (+10.6% in Veszprém and +14.8% in Tolna) and traditional/non-diversified (+25.5% in Veszprém and +17.8% in Tolna) farmer types were projected, as well as a decrease in business-oriented (-3.0% in Veszprém and -11.4% in Tolna) and traditional/diversified (-33.1% Veszprém and -21.1% in Tolna) farmers.

Under RRV, farmers were more inclined to adopt higher gross margin regimes and to be less responsible in protecting soil structure: decreases were projected for the supplementary (-9.8% Veszprém and -7.2% in Tolna) and traditional/non-diversified (-11.0% Veszprém and -39.5% in Tolna) farmers. Owing to a strong increase in the business-oriented farmers in Tolna (+39.5% by 2100), traditional/diversified farmers were projected to decrease in 2070-2100. In contrast, in Veszprém, the business-oriented farmers were projected to be stable (+1.4% by 2100) and the traditional/diversified farmers were projected to increase continually (+7.2% by 2100).

Under IEG, the proportions of farmer types were projected to be relatively stable by 2100: Veszprém had a moderate increase in supplementary farmers (+17.7%) and decreases (absolute changes < 10%) in all of the other farmer types; Tolna, however, had an increase in the traditional/diversified farmers (+11.3%) and slight decreases in the other types.

Under PPU, farmers were expected to adopt more flexible land use strategies (with a shorter regime length) and look for an optimal trade-off between environment sustainability and profit, i.e., a shift to the traditional/diversified type was projected by 2100 (+21.6% in Veszprém and +33.0% in Tolna) for all other farmer types.

3.3 Projected changes in arable land use

In the model, apart from the type of farmer, crop yield also influenced the patterns of arable LUCC by affecting the potential gross margin of a crop rotation plan, the key economic driver of farmer land use decision making. This further amplified the difference in the projected regional patterns of arable land use between case studies (see Figure 5B, for the extents of changes by 2100; see Figure S3, the Electronic Supplementary Materials 1, for trends over time).

Under PKD, the two areas were projected to have a similar arable LUCC pattern by 2100, both with a slight decrease in cereal croplands (-5.8% in Veszprém and -1.7% in Tolna) and an increase in major energy crops (+8.2% in Veszprém and 2.6% in Tolna). For cereals, both areas were projected to experience a shift from wheat to maize: in Veszprém wheat decreased by 18.2% and maize increased by 7.5%, and in Tolna wheat decreased by 11.1% and maize increased by 9.2%. Such a shift was associated with a decreased gross margin of wheat (as a result of decreased crop yield). For energy crops, sunflower was projected to increase moderately in both Veszprém (+11.7%) and Tolna (8.4%).

Under RRV, a small change in arable land use was projected in Veszprém, with a 3.9% increase in major cereals and a 1.3% decrease in energy crops. However, arable LUCC in Tolna was projected to change rapidly, with a 13.1% decrease in major cereals (-8.9% for maize) and a 12.9% increase in energy crops (+13.4% for soybean, +3.6% for sunflower and -4.1% for rape). This difference was mainly due to the projected increase in business-oriented farmers in Tolna, making more profitable crops (e.g. soybean and sunflower) more frequently selected.

Under IEQ, projected arable LUCC was at a low level for both areas, as less significant changes in farmer types were projected than for the other scenarios. In Veszprém, where supplementary farmers increased, regimes with lower gross margin, but which create better soil structure, were more frequently selected. As a result, land use for maize was projected to reduce by 7.5%. In Tolna, the increase in traditional/diversified farmers and improvements in crop yields led to increases in wheat (by 6.6%) and sunflower (+4.8%), and decreases in maize (-8.6%) and rape (-3.8%).

Under PPU, similar patterns of change were projected for the two areas: increases in the major cereals (+3.4% in Veszprém and +1.8% in Tolna) and decreases in energy plants (-7.9% in Veszprém and -4.2% in Tolna). Wheat was projected to be the most popular crop because for both areas under IEQ and PPU, owing to an increase in its potential gross margin resulting from a large yield increase. Compared to maize, wheat also had lower baseline costs, and the regimes which included wheat were more accessible by traditional and supplementary farmers who dominated regional farmer populations in both areas.

A – Changes in farmer types

Farmer types	Pink dream (PKD)		Regional Rivalry (RRV)		Inequality (IEQ)		Pató Pál Úr (PPU)	
	Veszprém	Tolna	Veszprém	Tolna	Veszprém	Tolna	Veszprém	Tolna
Business-oriented	-3.04%	-11.42%	1.35%	39.54%	-1.52%	-3.34%	-2.03%	-5.80%
Traditional/non-diversified	25.51%	17.75%	-10.98%	-39.54%	-7.09%	-7.38%	-11.66%	-27.42%
Traditional/diversified	-33.11%	-21.09%	19.43%	7.21%	-9.12%	11.25%	21.62%	33.04%
Supplementary	10.64%	14.76%	-9.80%	-7.21%	17.74%	-0.53%	-7.94%	0.18%

B – Changes in arable land uses

Major arable land uses	Pink dream (PKD)		Regional Rivalry (RRV)		Inequality (IEQ)		Pató Pál Úr (PPU)	
	Veszprém	Tolna	Veszprém	Tolna	Veszprém	Tolna	Veszprém	Tolna
[Cereal] Maize	7.46%	9.22%	4.67%	-8.68%	-7.53%	-8.57%	-3.18%	-7.72%
[Cereal] Oat	ns	1.53%	ns	-0.35%	ns	0.98%	ns	0.41%
[Cereal] Spring Barley	-1.19%	-2.34%	-1.48%	0.17%	0.19%	2.63%	0.86%	4.09%
[Cereal] Triticale	6.69%	3.37%	-0.11%	0.54%	3.33%	-0.10%	3.75%	-0.08%
[Cereal] Wheat	-18.23%	-11.19%	4.92%	-2.03%	0.05%	6.62%	3.40%	8.56%
[Cereal] Winter Barley	-0.71%	-2.26%	-4.06%	-2.71%	-0.72%	-2.44%	-1.47%	-3.38%
[Energy] Mustard	1.67%	ns	-0.30%	ns	-0.04%	ns	-0.36%	ns
[Energy] Rape	-4.86%	-5.45%	-0.55%	-4.14%	-3.81%	-4.94%	-5.54%	-5.29%
[Energy] Soybean	-0.28%	-0.32%	1.70%	13.40%	-0.28%	-1.93%	-0.28%	-2.10%
[Energy] Sunflower	11.72%	8.38%	-2.10%	3.61%	0.62%	4.80%	-1.74%	3.17%
[Forage] Alfalfa	0.04%	0.23%	-0.19%	-0.18%	0.03%	2.10%	-0.12%	1.90%
[Forage] Maize Silage	-1.57%	-0.60%	-1.49%	0.01%	1.08%	-0.21%	1.10%	-0.15%
[Other] Fallow	0.50%	0.09%	0.35%	1.04%	5.82%	1.73%	3.14%	1.28%
[Other] Pea	-0.07%	ns	-0.21%	ns	2.43%	ns	1.60%	ns

Figure 5 Projected changes by 2100 in the executive types of farmer (A) and arable land use pattern (B) in Veszprém and Tolna, under the four integrated scenario. ns: not selected by the farmer agents.

4 Discussion

The *Aporia-Lite* ABM was developed as an explanatory tool to better understand the range of arable land use patterns under different plausible futures, rather than to make precise predictions. The validity of the model projections are supported in several ways. Firstly, the scenarios describing the possible future climate and socio-economic conditions were developed by working closely with stakeholders to ensure the scenarios were credible within the local context and relevant for policy decisions (see Li et al. (2017b) for the timeline of scenario development). Secondly, the conceptual framework of the model followed an existing approach whose flexibility, extensibility, verification, and transparency has been extensively tested against real-world issues (Guillem et al., 2015; Murray-Rust et al., 2014). Thirdly, the accuracy of the baseline arable land use projections was found to be satisfactory for the two case study areas (section 3.1). Finally, local stakeholders found the future projections appropriate in the context of the model and scenarios, and useful in terms of supporting discussions on policy responses to environmental changes.

The model is empirically-grounded and calibrated on data collected from a household survey of farmers. Empirical data have various uses in the development of ABMs (Smajgl and Barreteau, 2017) and in this study the survey data contributed in two ways. Firstly, the survey adds important empirical evidence to support understanding of the characteristics of local crop rotation plans and factors affecting farmers' decision-making. In Hungary, the data (i) improves understanding of what motivates individual-level decision-making which previously was very limited, and (ii) encapsulates existing evidence about landscape-level determinants of arable land use change (Munteanu et al., 2014; Verhulst et al., 2004), thus providing a richer picture of the processes underpinning Hungary's land use system dynamics. Secondly, the observed patterns played an important role in guiding the design of the *Aporia-Lite* model structure. From the theory of the pattern-oriented approach (Grimm et al., 2005), we sought to build rigorous models based on relevant patterns observed in the real system, rather than develop an overly-complex model to approximate the system in as much detail as possible. As such, several differences can be noted when comparing this study with two previous studies for Lunna in Scotland and Aarau in Switzerland which applied the same *Aporia* modelling framework (Murray-Rust et al., 2014). The empirical analysis presented here suggests that crop rotation plans used in western Hungary are highly diverse. Hence, a comprehensive regime database was constructed for farmers' crop selection, instead of using a characteristic regime database with only a few key crop rotation plans. The survey data also enabled an exploration of actual land use, through which an executive typology of farmer types was developed. By contrast, the typologies developed in previous studies only categorised farmers' attitudes and objectives (Guillem et al., 2012; Karali et al., 2013). Previous studies also included both crop and meat production, whereas this study focused solely on crops, owing to different research objectives, data availability and local characteristics.

In this study, different drivers of arable land use change determining current and projected future cropping patterns were found in the two counties, suggesting that policy options for dealing with, or adapting to, these drivers are needed that are county-specific and implemented by lower level actors. The farmer typology shows a clearly distinct baseline pattern of farmers' actual selection of land use practices between the two areas. This may seem counterintuitive, as one might not expect such large differences between the two counties from a cultural and technological perspective. In particular, the model estimated the proportion of 'supplementary' farmers, to be 50.5% in Veszprém and 7.4% in Tolna, while the 2013 census data from KSH shows a nearly identical proportion of such farmers, with Veszprém having 54.6 % and Tolna, 54.4%. It should be noted that the 'supplementary' farmers in this study were assumed to represent farmers who not only produce food for their own consumption, but also adopt sustainable land use practices to avoid soil overexploitation. A projected reduction in sustainable use practices would pose future challenges for Tolna in achieving its local food self-sufficiency and security goals. The results presented here suggest that future policies to address this challenge may need to increase farmer access to social capital (e.g. creating agricultural organisations and societies) and enhance their awareness of the importance to farming of the environment and maintaining natural capital. Conversely, it is likely that physical constraints (as indicated in the survey) have contributed to a higher proportion of 'supplementary' farmers in Veszprém. For example, poorer soil quality, a topography less favourable for large-scale farming and thus smaller farm sizes may indicate that some farmers have no choice but to utilise less-exploitative practices. This is supported by a related study that found that the overall rate of climate change adaptation was lower among farmers from Veszprém than those from Tolna (Li et al., 2017a). Thus, future policies in Veszprém targeting sustainable local food production may need to support improvements in farmers' ability to adapt to various physical constraints.

The future projections for the farmer typology and arable land use also showed clear differences between the two counties, under the same integrated climate and socio-economic scenarios. For the PKD (Pink dream) and PPU (Pató Pál Úr) scenarios, the extent of change differed somewhat in spite of the projected trends being similar in both areas. However, under the RRV (Regional Rivalry) and IEQ (Inequality) scenarios, both the trends and extents of change were projected to be distinctly different. These differences at the regional level are consistent with the national level socio-economic storylines underpinning each scenario, which implies different magnitudes of challenges for adaptation policies. PKD (SSP1; environmental sustainability oriented scenario) and PPU (SSP5; highly industrialised infrastructure scenario) are both associated with rapid economic development, reduced inequality and low challenges to adaptation. By contrast, RRV (SSP3; fragmented with ineffective institutions scenario) and IEQ (SSP4; highly divided society scenario) both have slow economic development, increased inequality and high challenges to adaptation with future environmental change (O'Neill et al., 2015). Such challenges may be further amplified for Tolna under RRV and Veszprém under IEQ. For example, a huge decline (-13.1%) in major cereals was projected for Tolna, which may threaten the region's capacity to be self-sufficient. Moreover, securing food from other regions may be difficult as RRV (SSP3) is characterised by various barriers to trade, especially for agricultural products (O'Neill et al., 2015). Veszprém was projected to have declines in land for both major cereals (-4.7%) and energy crops (-3.5%), but increases in fallow land (+5.8%), which was the highest in all simulations. This implies that some individual farmers, especially smallholders, may face severe difficulties in sustaining regular food production and thus decide not to use their land. This situation is likely to be even worse in IEQ (SSP4), as resources are controlled by an elite part of society, leaving small-scale farmers struggling with low productivity (O'Neill et al., 2015). Fallow lands are, therefore, at risk of abandonment.

The findings of this study are of substantial regional importance within Veszprém and Tolna and have potential relevance to other regions. In the next step, the projected impacts on agriculture will be used to test the ability of existing development/sector strategies and adaptation plans for the two counties to reduce vulnerability by lowering exposure and increasing resilience. As agricultural land use in the two counties is broadly similar to other parts of the country, our findings are generally relevant to other areas of Hungary, as well as areas of Eastern Europe that have similar farm ownership structures and historic land use changes. In particular, our impact assessments are relevant to the areas around the Lake Balaton and within the Danube river basin that have similar hydro-climatic conditions. Moreover, the modelling method has much wider relevance as it can be implemented in different cropping environments provided a survey is undertaken to parameterise the *Aporia* model. When applying the method for other regions, researchers need to reflect on whether simplifying or extending the model components/functions using different approaches (e.g. the pattern-oriented theory used in this study) is necessary in order to better meet the case-specific research objectives and data availability. Good practices related for evaluating model complexity for a case study purpose are described in Sun et al. (2016).

From a methodological perspective several future improvements and directions in this research are possible. Firstly, to better represent individual-level decision-making processes, the regime database could be replaced by an algorithm to allow farmer agents to build their own crop rotation plans automatically, such as approaches reviewed in Dury et al. (2012). In this study, due to data constraints, only the within-regime crop match possibilities were considered. Future investigations are needed to evaluate the connectivity between regimes, especially on the factors influencing the crop matches that connect the end of one regime to the beginning of another. Secondly, the impact of regional/local climate change could be explored further. This includes modelling the consequences of climatic variability and extreme weather events on crop yields, water availability and pests and diseases (Bachinger and Zander, 2007; Delpla and Rodriguez, 2014; Steffens et al., 2015; White et al., 2011). Thirdly, it would be useful to better integrate spatial heterogeneity within the model. Here, we were unable to explore the spatial pattern of land use change, due to data constraints, i.e., a lack of observed agricultural parcels for case study areas and insufficient evidence for the spatial effects of farmer decision-making. Empirical studies are needed to address these shortcomings and further understand how land use may be promoted or constrained by the exchange of knowledge between adjacent farmers (Alexander et al., 2013; dos Santos et al., 2011). Finally, while this study focused on projecting future scenarios, the model could also be used to test the effectiveness of different policies. For example, the model could be used to explore how different subsidy strategies change land use patterns, or when novel crops are taken-up.

5 Conclusions

We demonstrate the development and application of an empirically-grounded ABM to explore differences in arable land use under future scenarios for two case study areas in western Hungary, Veszprém and Tolna counties. Despite the fact that the two areas share a similar cultural and technological background and largely comparable agroclimatic conditions, our model projected a distinctly different pattern in the types of farmers from the two areas, in particular for the 'supplementary' farmers who are self-sustained and adopt sustainable land use practices, and, hence, different patterns of arable land use. Policy that encourages local food self-sufficiency and security may need to target improving the capacity of farmers to adapt to physical constraints in Veszprém and enhancing farmer access to social capital and environmental awareness in Tolna. The projected differences in land use between the two counties were further exacerbated in the future even under the same climate and socio-economic scenario, suggesting different foci for local policies to adapt to long-term environmental changes. For example, under an unequal future with increased social disparities and higher-end climate change, Veszprém was projected to have a growth in fallow land, which implies difficulties for smallholder farmers in sustaining regular food production and, therefore, risks of land abandonment. Alternatively, under a de-globalising future with ineffective institutions and moderate climate change, Tolna was projected to have a considerable decline in land for major cereals, which may influence local food self-sufficiency. The future projections provide fundamental information to support a risk assessment for environmental change. The agent-based model developed can be used in future studies to test the effectiveness of policy responses in adapting farmer's behaviours to various socio-economic and climate changes.

Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement number 603416 (The IMPRESSIONS Project - Impacts and Risks from High-End Scenarios: Strategies for Innovative Solutions; www.impressions-project.eu).

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