SUMMARY

In the coming decades, agricultural land systems are expected to face a multitude of complex sustainability challenges. Firstly, the expected growth in global population will lead to an extraordinary increase in the global demand for food. Therefore, there will be a need to increase food production; yet, this will have to be achieved while simultaneously coping with a growing set of climate change-related risks (for instance, increased frequency of droughts and floods) and attempting to reduce the overall environmental impacts of intensive agricultural activities (for example, water contamination by fertilizers and pesticides). In addition, the need to expand food production will take place in a context of increasing land competition for other uses, such as urbanization, biofuel production and nature conservation.

While most of the drivers of these challenges operate at regional and global scales, the extent to which agricultural land systems will be able to balance trade-offs and manage risks will largely depend on the local land-use decisions made by farmers and on the eventual land-use and -cover change processes resulting from their decisions. Therefore, there is a need to better understand the determinants of agricultural land-use patterns in order to provide integrated analyses of local production systems that are contextualised within their regional and global contexts. This is not only required to assess possible developments of agricultural land systems and their impacts in the environment, economy and society, but also to support the development of robust strategies that are able to cope with the impending challenges.

Since experiments in real land systems are hardly possible, spatial analysis and land-use modelling can be used as learning tools to test hypothesis and formalise knowledge on understanding land systems and provide information on their possible future states. A large diversity of approaches for land-use spatial analysis and modelling has evolved over the past decades, with considerable differences in terms of theoretical background and range of applications. A broad distinction can be made between empirical and theory-based approaches. Empirical (or inductive) approaches aim at constructing hypotheses about the relationship between proximate factors and land-use patterns, through fitting of empirical data using statistical methods. Theory-based (or deductive) approaches apply a structured theory to real case studies, using logic deduction to guide the characterisation of land-use change processes and explain the casual relationships between decisions on land use and their outcomes.

Both empirical and theory-based approaches have their merits and limitations in explaining and forecasting (agricultural) land-use patterns. However, the preference for using either one type of approach or the other usually seems to be more related to the disciplinary background of the researchers involved, rather than based on its appropriateness to the case studies at hand. For instance, geographers tend to focus on spatial patterns and typically rely on empirical approaches to describe and explain them, whereas economists usually rely on deduction from theoretical principles that emphasise processes. Hence, there is still a poor understanding on

the comparative ability of empirical and theory-based approaches to explain, simulate and explore the spatial patterns of agricultural land systems.

The goal of this dissertation was to examine how different spatial analysis and land-use modelling approaches can contribute to help understanding the spatio-temporal patterns of agricultural land systems. In particular, the ability of empirical and theory-based approaches on explaining past and current agricultural land-use patterns was investigated, as well as their aptitude for simulating and exploring future developments in agricultural land systems. To this end, the following research questions were addressed:

Q1. To what extent are empirical and theory-based approaches of spatial analysis and land-use modelling able to explain observed spatial patterns in agricultural land systems?

Q2. To what extent are empirical and theory-based approaches of spatial analysis and land-use modelling able to simulate and explore future spatial patterns in agricultural land systems?

Several case studies were presented, covering prominent topics addressing different challenges and opportunities in agricultural land systems, particularly: agricultural expansion, intensification, extensification and abandonment, among other land-use change processes; competition for land of agricultural land systems with other types of land uses; competition for land among different agricultural production systems, including the introduction of bioenergy crop production and resulting direct and indirect land-use change processes; multifunctionality and the provision of ecosystem services from second generation biofuel crops; adaptation of agricultural land systems to climate change and more frequent extreme weather events; and land availability resulting from increased productivity in agricultural systems.

Regarding the ability to explain observed spatial patterns in agricultural land systems (first research question), empirical approaches were found to be especially suitable for exploratory data analysis, in order to reveal patterns and test hypothesis on the relationships between proximate factors and observed agricultural patterns. They appeared to be able of incorporating a large number of different types of drivers and land-use change processes and allow to construct relatively simple models with standard statistical techniques that are easily reproducible. The simulation models constructed with this kind of approach were able to reproduce the observed patterns and processes in agricultural land systems reasonably well, particularly if neighbourhood factors were included. However, the ad-hoc characteristics of each case study and the difficulty to distinguish causality from correlation seem to hamper the formulation of more general, sound causal relationships. This type of approach also showed to perform poorly when explaining/simulating the patterns of land-use types that are dispersed across the study area, that occur less frequently and/or that are highly heterogeneous. Although empirical relationships between drivers and land-use change processes appeared to be relatively stable over time, the ability to reproduce patterns tends to decrease over time when the same relationships are used to simulate future land use. Most importantly, this type of approach fails to represent competitive advantages among different types of land use and how they influence the decisions of farmers on the management of land.

In contrast, theory-based approaches allow to explore the contribution of different budget components in the economic performance of agricultural activities and their role on land-use decisions. They are able to explain the economic rationale in decisions on agricultural land systems and ensuing competition among different users, both within the agricultural sector and among non-agricultural sectors. The simulation models constructed with this kind of approach are able to reproduce the observed spatial patterns in agricultural land systems well, particularly if production systems are specified with detailed data at the crop level. Land suitability can be defined in a relatively objective and flexible way, that allows the incorporation of information from different research frameworks describing the utility of land for different types of uses and sectors. However, the ability to reproduce observed patterns greatly depends on the availability of large amounts of detailed data, which may not always be available. Furthermore, basic assumptions on economic rationale might not always apply, depending on specific characteristics of actors, thus failing to capture motivations and preferences other than profit maximisation (e.g. altruism, concern for next generations, survival) that may be relevant in particular types of agricultural systems (e.g. organic farming, subsistence agriculture). It is also difficult to fully incorporate socio-cultural characteristics (e.g. entrepreneurship profile) or political and institutional factors that are not easily captured by a quantitative approach (e.g. war, market freedom, land rights, information and/or power asymmetries), which might undermine its aptitude to entirely explain complex processes in agricultural land systems such as structural/technological change, agricultural abandonment and land grabbing.

Regarding the ability to simulate and explore future spatial patterns in agricultural land systems (second research question), empirical approaches showed to be able of extrapolating and replicating currently observed land-use trends into the future, allowing for, for example, the establishment of a reference scenario. They are also suitable to explore future developments on the land uptake for agricultural production and resulting spatial distribution of agricultural land uses arising from, e.g. changes in the demand for agricultural commodities, increased productivity and/or reforms on trade policies. Furthermore they allow for conducting uncertainty analysis on the main factors affecting land uptake and suitability to explore future developments resulting from explicit changes in the spatial factors influencing the local suitability of agricultural land uses, such as gradual changes in crop suitability due to climate change, and/or the deployment of infrastructure for transportation and processing of agricultural commodities. Empirical approaches are, however, unable to explicitly incorporate and simulate the effects of disruptive events or other discontinuities in the land system such as the emergence of new land uses, the effects of non-spatial policies affecting the local economic performance of agricultural production systems, and/or the economic decisions leading to the adoption of innovative agricultural practices. Furthermore, predictive power of long-term simulations may be limited, due to exclusive reliance on observed short-term trends and limited link to understanding the drivers and/or behaviour causing the changes.

Conversely, theory-based approaches proved to be useful for exploring the potential emergence of future agricultural land-use patterns as a result of economic decisions in agricultural land systems. This type of approach allows to explicitly insert a large number of discontinuities and policy alternatives in the definition of scenario-based changes, such as the emergence of new types of land-use (e.g. novel crop systems), changes in subsidies and taxes schemes, and adoption of new technologies and infrastructure. They also enable to monetise and explicitly internalise externalities related to non-productive services from agricultural land use (e.g. recreation) in the definition of utility. Hence, these features allow these approaches to evaluate a wider range of scenarios. They also offer the option to couple local cost-benefit analysis and utility-based land-use modelling within a single framework, allowing for straightforward assessment of the extent to which the obtained patterns are sensitive to variations in the underlying factors. Finally, theory-based approaches have the advantage that they can be combined with empirical approaches, whereas the opposite is not possible. This is useful in case available data on economic or technological factors is not sufficient to fully specify utility. However, a number of drawbacks could also be identified. Firstly, the construction of these models depended on the availability of a large amount of detailed data, with the ability to reproduce observed patterns greatly depending on the level of detail of the available data. Secondly, it is difficult to operationalise a complete description of all endogenous economic processes taking place in agricultural land systems into the model, such as economies of scale, spatial externalities, trade and price formation processes in the global economy, and, in particular, interactions between short-term fluctuations in supply (e.g. due to occurrence of extreme events) and resulting crop price volatility. Finally, current approaches to simulate economic decision-making in agricultural land systems is too deterministic in its current form; in particular, the role that risk perception and uncertain developments can have in farmers' decisions still needs to be addressed.

The approaches presented in this dissertation proved valuable for testing hypothesis, assessing possible developments of agricultural land systems and evaluating the resulting impacts on environment, economy and society. Furthermore, they also proved suitable for application in the development of spatial tools supporting policy-makers in developing robust strategies to cope with imminent challenges in the agricultural sector. Despite these promising achievements, various methodological issues and limitations that deserve further attention were identified throughout the chapters, in particular:

- the need for developing and implementing more advanced data and methods in empirical analysis of agricultural land use change;

- the need for developing methods that can quantify the role of spatial interaction and neighbourhood effects;

- the need to incorporate more explicitly the role of uncertainty, risk perception and timing in economic decision-making of agricultural land systems;

- the need to better understand and address the role of socio-cultural, political and institutional factors in shaping agricultural land-use patterns;

- the need to improve the way in which feedbacks between demand, supply and prices of agricultural commodities can be captured in simulation models.

The case studies presented here demonstrated that the appropriateness of the approach in use depends, to a large extent, on the research questions at hand, characteristics of the case study area and availability of data. The findings of this thesis are thus meant to help researchers and policy-makers in selecting the most suitable approaches to be applied in forthcoming studies assessing possible developments in agricultural land systems. Many of the topics and integrated approaches presented in this thesis are inherently interdisciplinary, with different epistemic values stemming from the various disciplinary perspectives. Therefore, they call for the collaboration of researchers from different disciplines that may need time to learn each other's language. The case studies also emphasised the importance involving relevant stakeholders and policy-makers that can contribute important insights and perceptions to the problems at hand. This dissertation thus firmly advocates that the further development of methods for exploring, explaining, and simulating the spatial patterns of agricultural land systems should take place within such collaborative, multidisciplinary teams, bringing together the knowledge and views from scientists, policy-makers, and stakeholders alike.