PART I.
INTRODUCTION
Chapter 1

INTRODUCTION

Abstract: In the coming decades, agricultural land systems are expected to face a multitude of complex challenges. 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 local land-use decisions made by farmers, and on the eventual land-use change processes resulting from their decisions. Spatial analysis and land-use modelling can be used as learning tools to test hypothesis, formalise knowledge on understanding land systems and provide information on their possible future states. A broad distinction can be made between empirical and theory-based approaches for land-use spatial analysis and modelling. Both types of approaches have their merits and limitations in explaining and forecasting (agricultural) land-use patterns. This chapter introduces the research topic; discusses the most commonly applied methods for spatial analysis and modelling of agricultural land-use patterns; and presents the outline of the dissertation.

Keywords: Agricultural land systems; Spatial analysis; Land-use modelling; Empirical approaches; Theory-based approaches
1. Land systems: from local interactions to global impacts

“If everything occurred at the same time there would be no development. If everything existed in the same place, there could be no particularity. Only space makes possible the particular, which then unfolds in time.”

August Lösch (1940) – *Die Räumliche Ordnung der Wirtschaft*

The Earth’s land surface and its properties—topography, geology and climate—are heterogeneous across space, as manifested in the existing spatial gradients of environmental conditions and clustered distribution of landscapes. Such heterogeneity endows every location with a unique combination of geophysical and ecological attributes that determines, to a large extent, its ability to provide vital resources such as food, fuel and raw materials, and many other services that support production functions and regulate natural hazards. As a result, land properties set the opportunities and constraints for the establishment of human settlements and related activities, thus playing a major role in the geographical distribution of human societies across the globe.

The spatial patterns of land properties, human activities and resulting landscapes are not static over time though. For instance, gradual geophysical processes (e.g. climate change, sedimentation, soil erosion) as well as extreme short-term events (e.g. floods, droughts, wildfires) can substantially alter land properties and its ability to deliver specific functions. Human interventions, by means of land management practices and technological innovations, can also dramatically transform landscapes and its natural endowments. Notable examples are the introduction of mechanised agricultural production practices or the deployment of buildings, industrial facilities and infrastructure networks in urban areas. Societal developments such as population growth, migration flows and lifestyle changes can also have far-reaching implications on the uptake of land and transformation of its properties for the fulfilment of the demand for land-based resources and services (DeFries et al., 2010; Seto et al., 2012), particularly in an increasingly teleconnected and globalised world (Liu et al., 2013; Meyfroidt et al., 2013).

Land systems can thus be conceptualised as the result of human interactions with the natural terrestrial environment. These interactions include the processes and activities related to the human use of land, their socioeconomic, technological and organisational arrangements, as well as their (expected) benefits and (unintended) ecological and social outcomes (Verburg et al., 2013a). Hence, land systems represent a critical intersection between socioeconomic
and ecological systems, with complex spatio-temporal dynamic interactions being established among them.

The effects of human interventions on land systems are usually described by means of changes in the spatial patterns of land cover (i.e. the physical surface attributes such as the type of vegetation or the presence of artificial structures) and land use (i.e. the human activity taking place at or near the surface). Land-use change processes can be understood as aggregated flows representing groups of transitions sharing common features (Feranec et al., 2010), for example: urbanisation as the conversion of natural and agricultural land to built-up areas, or agricultural expansion as the conversion of natural areas for the creation of cultivated fields and livestock-grazing areas. Land-use change has occurred since the advent of civilisation and is intrinsically associated with continuing increases in food and fiber production, in resource-use efficiency, and in wealth and well-being (Lambin et al., 2001; Klein Goldewijk et al., 2011). However, the increase in pace and magnitude of land-use change processes experienced in the last decades is unprecedented (Foley et al., 2005; Ramankutty et al., 2006). In fact, between 50% and 83% of the global terrestrial surface is estimated to have been disturbed in some way by human activities (Hannah et al., 1994; Vitousek et al., 1997; Sanderson et al., 2002). Even though land-use change processes take place at the local level, their cumulative impact has widespread consequences affecting the functioning of the carbon, hydrological and nutrient cycles (Postel et al., 1996; Vitousek et al., 1997; Kaplan et al., 2012), contributing to regional climate change and global warming (Eltahir and Bras, 1996; Kalnay and Cai, 2003; Houghton et al., 2012), and causing habitat fragmentation and loss of biodiversity worldwide (Sala et al., 2000; Schröter et al., 2005; Nagendra et al., 2013). Therefore, land-use change is regarded as one of the main drivers of global environmental change (Foley et al., 2005; Turner et al., 2007).

Concurrently, these global changes feedback on the local environmental conditions and human well-being, possibly affecting the resilience of ecosystems and communities to climatic and socioeconomic perturbations, and consequently influencing human decision-making (Kasperson et al., 2005; Crossman et al., 2013). Further changes in land systems might then result from ensuing decision-making processes at different levels as a response to global changes, ranging from local land owners choices (e.g. farmers changing management practices), to regional/national spatial planning policies (e.g. designation of nature protection areas) and global trade agreements (e.g. certification schemes for sustainable production of commodities) (Lambin et al., 2006, Verburg et al., 2013a). Hence, changes in land systems are simultaneously cause and consequence of global environmental change resulting from socio-ecological processes operating at multiple spatial and temporal scales, as well as a possible local strategy of mitigation and adaptation to global environmental change (Verburg et al., 2015).

For land systems to be sustainable, the concerns over the losses of certain ecosystem services of global importance (e.g. carbon sequestration, biodiversity) have to be balanced with the benefits of other potentially conflicting services (e.g. food production, raw material
extraction, provision of housing) (Lambin and Meyfroidt, 2011). Therefore, it is crucial to have a good understanding of the trade-offs between the provision of services under alternative land uses, taking into account their synergetic effects and complementarities (Crossman et al., 2013; Müller et al., 2016).

2. Agricultural land systems: past, present and future

Among all human activities, agriculture has been the major mode of anthropogenic transformation of land systems. In order to meet human needs for food, feed and fibres, agricultural areas have expanded into forests, savannas and grasslands in all parts of the world (Chhabra et al., 2006), with more than a third of the total ice-free land surface being currently used for growing crops (ca. 12%) or grazing animals (ca. 26%) (Ramankutty et al., 2008; Foley et al., 2011). Alongside the conversion of natural areas, the introduction of intensive land management practices and technological innovations (e.g. high-yielding cultivars, chemical fertilisers and pesticides, mechanisation, irrigation and transportation) has contributed to increasing yields, reducing production costs and enabling transportation of perishable products over large distances, thus allowing agricultural production to be feasible in previously unsuitable locations (Tilman et al., 2002; Chhabra et al., 2006). That has enabled a spectacular increase in agricultural productivity over the last decades, which has greatly contributed to food security in most regions of the world despite a doubling of the total population (Bindraban and Rabbinge, 2012).

However, agricultural expansion and intensification have also come at the expense of extensive environmental damage (Matson et al., 1997; Matson and Vitousek, 2006), often with implications for agricultural production itself. Examples of such negative impacts include the degradation of water resources due to increased use of fertilisers and biocides (Bennett et al., 2001), soil erosion and reduced fertility, overgrazing, soil salinisation due to irrigation (Wood et al., 2000) and degradation of important ecosystem services (e.g. pollination) due to loss of habitat (Kremen et al., 2002; Ricketts et al., 2004). Moreover, agriculture has also been contributing to climate change through the release of potent greenhouse gases into the atmosphere, namely methane from livestock digestion processes and stored animal manure, and nitrous oxide from organic and mineral nitrogen fertilisers (Smith et al., 2008). In addition, the use of peatlands (a large sink of greenhouse gases) for agricultural land uses such as livestock grazing may also contribute to soil oxidation in these areas, leading to further increased CO₂ and N₂O emissions (Oertel et al., 2016). In turn, climatic changes are expected to globally affect crop yields (Parry et al., 2004; Rosenzweig et al., 2014) and water availability for irrigation (Gerten et al., 2011; Elliot et al., 2014). Even though mid- and high-latitude regions might experience positive impacts in some crops as a consequence of higher temperatures and CO₂ levels (Wolfe et al., 2008; Wolf et al., 2011), most impacts are expected to be strongly negative, particularly those resulting from more frequent extreme weather events (e.g. heat waves, droughts and high precipitation) and related emergence of
pests and diseases (Rosenzweig et al., 2002; Porter and Semenov 2005; Wolfe et al., 2008; Gregory et al., 2009; Soussana et al., 2010; Iglesias et al., 2012, Porter et al., 2014). Hence, one could argue that, despite of having greatly alleviated undernourishment worldwide, modern intensive agriculture may have traded relatively short-term increases in crop yields for long-term overall losses in productivity (Foley et al., 2005; Matson and Vitousek, 2006).

Future food security is a major global concern (Schmidhuber and Tubiello, 2007; Ericksen et al., 2009; Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011). This concern is mainly fuelled by the estimated growth of the global population to over 9 billion in 2050 (UN, 2015) and rising incomes, specially in emerging market countries that are leading to an increase in food consumption per capita, particularly land- and water-intensive animal-based products such as meat and dairy (OECD/FAO, 2016). As a result, global crop demand is expected to increase by 100-110% from 2005 to 2050 (Tilman et al., 2011). Food security is not determined by food availability alone; other aspects such as food access, stability of food supply, food safety and quality are also relevant (Schmidhuber and Tubiello, 2007; Ericksen et al., 2009). Nonetheless, land-based production still provides its major biophysical basis and therefore, further increases in food production—either by expanding agricultural area or increasing per-area productivity – will be crucial to guarantee future food security (Ericksen et al., 2009; Verburg et al., 2013b).

Around 20% of the world’s total land surface is estimated to be suitable for crop production, with more than a half of this area being already under cultivation (Bruinsma, 2003; Ramankutty et al, 2008). Since the majority of the remaining potentially suitable land corresponds to tropical forest areas, further agricultural expansion is highly undesirable, not only due to its pervasive land-use change impacts (Gibbs et al., 2010; Smith, 2013) but also due to the high costs of providing the required infrastructure (Smith et al., 2010;). At the same time, agriculture is expected to face increasing competition for land with other uses. For instance, a larger and more affluent population implies that increasing shares of land will be used for expanding settlements, infrastructure, amenity services and recreational uses (DeFries et al., 2010; Smith et al., 2010; Seto et al., 2011; Van Vliet et al., 2017). The demand for forest products is also foreseen to keep increasing, although at somewhat lower rates than in the last decades (Ajani, 2011).

On top of that, food production may also have to compete for land with biofuel production (Rathmann et al., 2010; Harvey and Pilgrim, 2011). The production and use of biofuels is generally regarded as an advantageous alternative for the following reasons (Chhabra et al., 2006, OECD/IEA, 2007): i) it is a renewable resource, in contrast to finite fossil fuels; ii) it may further improve energy security, by diminishing the dependency of oil supply from unstable foreign markets; iii) it is seen as a potentially carbon neutral source of energy that may help to mitigate climate change, as since biofuel combustion emits CO₂ that has been previously absorbed during plant growth; iv) it is regarded as an opportunity to provide additional sources of income and foster rural economic development. In the last decade, several
countries have, therefore, implemented governmental measures to promote the production and use of biofuels for transportation, mainly in the form of tax reductions/exemptions and mandatory blending targets for transportation fuels (Sorda et al., 2010). As a result of these policies, the deployment of biofuels is expected to continue increasing in forthcoming years (OECD/IEA, 2011).

A range of different sources of biomass feedstock are available for the production of biofuels (Hamelinck and Faaij, 2006; Petrou and Pappis, 2009), including first-generation biofuels produced from food crops such as starch crops (e.g. maize), sugar crops (e.g. sugarbeet, sugarcane) and oilseeds (e.g. sunflower, soybeans); and second-generation biofuels produced from ligno-cellulosic feedstocks such as crop residues, fast-growing perennial grasses (e.g. miscanthus and switchgrass) and short-rotation coppice trees (e.g. poplar, willow). Despite its promising prospects, the large-scale deployment of biofuels has recently come under severe criticism. Given the current maturity level of available technologies, commercially available biofuels have so far employed almost exclusively food crops as feedstock (OECD/IEA, 2008; UN, 2013). The ensuing diversion of crops from food markets has raised concerns about the adverse effects of biofuel production on reducing potential food supply and contributing to temporary food shortages and price volatility, consequently undermining food security in poorer regions (Banse et al., 2008; RFA, 2008; Müller et al., 2008). Furthermore, expanded production of biofuel feedstocks has often come at the expense of tropical rainforest areas, either through direct land-use change (Eickhout et al., 2008; Wicke et al., 2011) or indirect land-use change processes, i.e. land clearing resulting from displacement of food production to new areas (Bowyer, 2010; Lapola et al., 2010; Meyfroidt et al., 2013). Not only can this contribute to a decline in biodiversity (Van Oorschot et al., 2010), but also the greenhouse gas emissions resulting from such changes may well exceed any possible gains from replacing fossil fuels (Searchinger et al., 2008; Fargione et al., 2008).

It is thus advocated that the search for beneficial biofuels should instead focus on promoting feedstock options that avoid these impacts, such as producing second-generation biofuels from low-input perennial grasses cultivated in marginal/degraded lands (Tilman et al., 2006; Tilman et al., 2009). However, the deployment of second-generation biofuels has been rather incremental, with major technical and economic barriers still having to be overcome until they become fully commercial and widely deployed (OECD/IEA, 2008; Janssen et al., 2013). Therefore, first-generation feedstock are expected to remain the main biofuel option for years to come.

The anticipated increased competition for land would, at first, suggest a Malthusian catastrophic scenario, in which the limited availability of suitable land would lead to a strict competition between different types of land use and eventually result in a shortage of land for the provision of different functions, thus creating several negative welfare impacts (Lambin, 2012). However, competition for land and global land availability could also be understood through a Ricardian view (after the economist David Ricardo), according to which it would
become feasible to produce more from the available stock of suitable land on account of the following mechanisms (Lambin, 2012). First, increased prices of land-based commodities put more (marginal) land under use, as it becomes profitable to invest in land conversion, restoration or productivity enhancement. Second, different types of land use do not strictly compete for the same land areas, as they have specific requirements in terms of climate, soil, and topographic characteristics. Moreover, the geographic distribution of land use adjusts overtime through a progressive learning process, to better match land quality and consequently achieve an increase in agricultural production while decreasing land area under use (Mather and Needle, 1998). This mechanism has been observed in several countries, where agricultural abandonment in marginal areas has occurred together with a simultaneous concentration of intensive agriculture in the most fertile and accessible areas, leading to a net reforestation at a national scale (Rudel et al., 2005; Meyfroidt and Lambin, 2011). Finally, the expansion of transport infrastructure and the rapid increase in global trade in wood and food commodities now allows the spatial reallocation of land use to take place at a global scale. This makes large tracts of land available to be used more efficiently, particularly through regional specialisation in the production of the crops for which local suitability is the highest (Godfray et al., 2010).

The Malthusian and Ricardian views of land are not fundamentally incompatible as they both recognise limits to the expansion of land use. However, despite some empirical evidence of increasing land scarcity (e.g. the recent peaks in land prices (Nickerson et al., 2012; Cordonnier, 2012; The Economist, 2012) and large-scale cross-border land transactions by transnational corporations (Anseeuw et al., 2013; Messerli et al., 2014)), the Malthusian view of land as a finite resource might be too narrow, as it ignores many factors such as the role of international trade and the room to adjust the geographic distribution of land use (Lambin, 2012). On the other hand, the Ricardian view might be overoptimistic, as it somewhat ignores the large economic, environmental and social costs associated with shifting land-use regimes across world regions and the irreversible socio-ecological consequences of converting pristine carbon-rich ecosystems, indigenous lands, ecological corridors, and other lands providing important services (Lambin, 2012).

Hence, we can conclude that, rather than hinging on the mere availability of cultivable land, future global food security should revolve around finding strategies that allow to increase productivity in current agricultural land while simultaneously preserving essential ecosystem services (Foley et al., 2011; Lambin, 2012). Technological innovations such as improvements in crop genetics are expected to continue pushing crop yields upward, but limits to productivity growth will eventually be imposed, due to a combination of factors such as climate change, water scarcity, limits to biological productivity, declining effects of additional application of different types of input and the need to reduce their negative externalities (Chhabra et al., 2006; Gornall et al., 2010; Licker et al., 2010; Foley et al., 2011; Running, 2012; Ray et al., 2012; Ray et al., 2013). Nonetheless, recent analyses have found large geographic variations in current crop and livestock productivity, even among regions with similar biophysical conditions (Licker et al., 2010; Neumann et al., 2010; Godfray et al., 2010; Mueller et al., 2012),
suggesting the existence of yield gaps, i.e. differences between the realised productivity and
the yield potential under optimal management practices. Yield gaps can be explained by the
(lack of) technical knowledge and capacity of farmers to invest, access and/or use inputs and
technology, by the unavailability of infrastructure to store and transport the commodities
to consumer markets, or simply because high input costs and low marginal returns from
increased production make it economically suboptimal to raise production to the maximum
technically attainable at current crop market prices (Godfray et al., 2010).

Significant opportunities to increase yields have been identified across many parts the
world, particularly in Africa, Latin America and Eastern Europe, where nutrient and water
limitations seem to be large (Foley et al., 2011; Mueller et al., 2012). New agronomic approaches
will need to be deployed though, in order to prevent the environmental degradation usually
associated with conventional intensive agriculture. A diverse portfolio of so-called sustainable
intensification approaches is available that would allow for increasing productivity while
improving resource- and inputs-use efficiency (Godfray et al., 2010; Smith, 2013), such as
site-specific crop management (a.k.a. precision agriculture), integrated pest management
and zero/ reduced soil tillage for improved soil conservation. Closing the existing yield
gaps through sustainable intensification is thus regarded has having the largest potential
for improving long-term global productivity while minimising both pressure on land and
environmental externalities (Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011; Smith,
2013; Verburg et al., 2013b). However, finding the solutions that can best facilitate sustainable
agricultural production is highly site-specific, depending on the local characteristics of the
existing production systems, political and socio-cultural contexts, prevalent risks and the
means to offset them (Pretty et al., 2006; Godfray et al., 2010; Verburg et al., 2013b).

To summarize, in the coming decades agricultural land systems will be facing a complex
food-energy-environment trilemma: matching the rapidly growing and changing global
demands for food and transport energy, while also attempting to simultaneously increase
productivity, cope with a growing set of climate-related risks and reduce the environmental
impacts of agricultural activities, in a context of increasing competition for land. 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 local land-use decisions made by farmers and on the ensuing spatio-temporal land-use
change dynamics (Verburg et al., 2013a; Verburg et al., 2013b; Van Vliet et al., 2015). 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 decision-making processes and help designing robust strategies that are able
to cope with the impending challenges.
3. Understanding the spatial patterns of agricultural land systems

3.1. How do agricultural land-use patterns develop over space and over time?

When making land-use decisions, farmers have to evaluate the viability of possible production alternatives and resource allocation options, for instance, which crops to grow, which machinery and inputs to use or which long-term investments to make (Rae, 1977; Öhlmér et al., 1998). The combination of multiple individual land-use decisions over time and across space ultimately leads to the emergence of spatial patterns of agricultural land use (Balmann, 1997; Berger, 2001; Verburg, 2006; Bakker et al., 2011). These decisions are influenced by numerous factors operating simultaneously at different spatial and temporal scales (Lambin et al., 2001; Hesperger and Bürgi, 2007). A fundamental distinction can be made between proximate and underlying factors (Geist and Lambin, 2002). Proximate factors entail those driving forces that play a role on the local suitability for different activities, such as the local biophysical conditions determining the potentials and constraints for agricultural production, available infrastructure, and agglomeration effects. Underlying factors constitute the systemic conditions in socioeconomic systems that influence the level of production and consumption of commodities and ecosystem services, thus inducing the trajectory of land and resource use. Hence, underlying factors can be associated with the amount of land area that is required for different purposes, while proximate factors determine the locations where land-use change processes are more likely to occur.

The interplay between proximate and underlying factors appears to drive land-use decisions in a synergetic way, with large variations caused by location-specific conditions and activities, and specific contexts at the local, regional and global levels (Geist et al., 2006; Verburg et al., 2015). For instance, the local biophysical suitability for cultivating different crops largely determines the potential yields that are feasible to achieve with different technological options (Van Velthuizen et al., 2007; Fischer et al., 2012). Within the restraints of their knowledge, available opportunities, risks and access to resources, capital and markets, farmers evaluate different production options taking into account their required investments, costs incurred in field operations and logistics, expected revenues from selling the commodities and eventual policy incentives (Rae, 1977; Öhlmér et al., 1998). These decisions may not only be affected by local conditions but also by spatial externalities emanating from neighbouring farms that can result in the clustering of agricultural land-use choices (Lewis et al., 2008), for instance: environmental externalities due to the movements of materials such as water, soil, plant, pest, pollen, and contaminants; social externalities due to learning, information spillovers or poorly defined property rights.

Concurrently, underlying factors such as demography, income and diet largely determine the global demand for agricultural commodities (Verburg et al., 2008). Price formation processes are established in agricultural commodity markets according to the supply and costs of agricultural production from different world regions and the global demand for agricultural...
commodities. A trade balance and structure eventually emerges in global agricultural markets, as result of comparative economic advantages between regions, transportation costs and trade policy measures (Miljkovic, 1999; Meijl et al., 2006; Eickhout et al., 2007).

Socioeconomic developments, technological innovations, new trade agreements/barriers, deployment of infrastructure, changes in the price of production inputs, reform of policy and spatial planning regimes, changes in institutional arrangements, climatic change and weather variability may subsequently affect the conditions determining the costs of production, supply, demand and prices of agricultural commodities. Farmers and consumers will then consider adjusting their preferences as a response to these variations, depending on the magnitude and/or duration of their effects. Sudden perturbations do not necessarily have to result in an immediate change in the structure of agricultural land systems though. For instance, in case of a temporary fall in the prices/productivity of a certain crop or introduction of a subsidy promoting a new crop, farmers might decide to first wait a few years in order to gain better information before changing their cropping system. Such choices may, for example, depend on the investments already made and the degree of flexibility to reverse their decisions (Isik and Yang, 2004; Song et al., 2011; Regan et al., 2015). Farmers can also adopt distinct strategies to capitalise opportunities and avoid risks, depending on their entrepreneurship profile, perceptions, traditions and communication networks, among other socio-cultural traits (Willock et al., 1999; Lauwere, 2005; Schmit and Rounsevell, 2006; Guillem et al., 2012).

The net effect of the aggregated changes resulting from farmers’ adjustments in their land management practices may then feedback into the conditions surrounding agricultural production or in the trade balance of agricultural commodity markets, which in turn can affect ensuing decision-making processes (Verburg, 2006; Verburg et al., 2013b; Rounsevell et al., 2014). Agricultural land systems can thus be interpreted as complex adaptive systems (Parker et al., 2003) manifesting non-linear behaviour, inertia to change, path-dependency of system evolution, feedback loops and spatial interactions in which local developments affect and are affected by conditions in neighbouring and distant locations (Verburg et al., 2002; Liu et al., 2013; Verburg et al., 2015). Therefore, changes in land systems cannot be simply explained as the equilibrium result of a set of driving forces at a certain moment in time (Verburg et al., 2006).

3.2. Explaining and simulating the spatial patterns of agricultural land systems

Agricultural land-use patterns have been continuously changing over time as a response to variations in proximate and underlying factors (Tilman et al., 2002; Bakker et al., 2011). Further changes can be expected in the future as a result of anticipated changes in climate and socioeconomic systems. Spatial analysis and land-use modelling can be used as explorative tools to better understand the apparent interplay between these factors and provide information on the possible future states of land systems (Verburg et al., 2004a; Koomen et al., 2008a). Spatial analysis allows to transform different types of spatial data into meaningful information,
revealing patterns and suggesting causal relationships between proximate factors and the observed spatial patterns of land use (Anselin and Getis, 1992; Verburg et al., 2004a; Lesschen et al., 2005). Spatially-explicit land-use models can integrate proximate and underlying factors in order to capture both the spatial distribution and amount of land claimed for different land-based activities, thus allowing for the exploration of potential future developments in land systems following alternative scenarios of socioeconomic developments, climatic changes and/or policy reform (Alcamo et al., 2006; Koomen et al., 2008a; Lavalle et al., 2011a).

Since experiments in real land systems are neither feasible nor ethically acceptable, land-use models can be used as learning tools to test hypothesis and formalise knowledge on understanding land systems (Verburg et al., 2006). 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 (for an overview, see e.g. Koomen and Stillwell, 2007). A broad distinction can be made between empirical and theory-based approaches (Irwin and Geoghegan, 2001; Verburg et al., 2006; Overmars et al., 2007a). 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. Such approaches usually also rely on the use of geographic information systems (GIS) to process, convert into a regular grid and overlay spatial datasets depicting the observed patterns of land-use with relevant proximate factors in a study area. In such a setting, the study area can be regarded as a statistical population where each gridcell constitutes an individual observation with certain attributes that are specific to its location.

Empirical spatial analysis approaches have demonstrated to be capable of quantifying the explanatory power, direction and intensity of different proximate factors on explaining the spatial patterns of agricultural land systems across a multitude of regions (see e.g. Verburg et al., 2004b; Bakker et al., 2005; Van Doorn and Bakker, 2007; Bakker et al., 2011; Hatna and Bakker, 2011). Logistic regression is the most commonly applied statistical method in land-use change analysis (Lesschen et al., 2005). Logistic regression is a multivariate generalised linear model that aims to predict a discrete outcome from a set of explanatory variables. Since land-use change is usually represented as a discrete change from one land-use type to other (Feranec et al., 2010), logistic regression is deemed appropriate to analyse land-use change processes (Millington et al., 2007). These findings can then be implemented in the calibration of land-use models, in order to extrapolate historical land-use trends into the future (Schneider and Pontius Jr, 2001; Verburg et al., 2008; Hoymann, 2010; Lavalle et al., 2011b). Empirical land-use modelling approaches have been extensively used, for instance, to explore the effect of policies in agricultural land systems in Europe (e.g. Sheridan et al., 2007; Verburg et al., 2008; Verburg and Overmars, 2009; Verburg et al., 2010; Britz et al., 2011; Lavalle et al., 2011a).

In contrast with empirical approaches, theory-based (or deductive) approaches apply a structured theory to real case studies, using logic deductive reasoning to guide the characterisation
of land-use change processes and explain the casual relationships between decisions on land use and their outcomes (Verburg et al., 2006; Overmars et al., 2007a). Theory-based approaches typically assume that landowners attempt to maximise the utility derived from land, with functional form and explanatory variables in the models based on economic theory (Irwin and Geoghegan, 2001). In economics, land is a special asset that can be regarded both as a production factor and as a consumption good, providing space for locating economic activities, infrastructure and dwellings, as well as ecosystems services, amenities and aesthetic value (see e.g. Hubacek and Van den Bergh, 2002 for an overview on the role of land in economic theory from a conceptual and historical perspective).

Three interrelated concepts are instrumental in explaining the allocation of land among competing uses: land rent, i.e. the reward paid for the use of land to its owner/user (Barlowe, 1972); land price, i.e. the payment that is made to acquire the property rights over a land parcel (Buurman, 2003); land value, i.e. how individuals value the goods and services that they enjoy from land, including their financial and non-financial aspects (Bateman, 2009). Land value represents the willingness-to-pay of each economic agent in the land market and thus can differ among individuals depending on their preferences, whereas land price is determined in the land market and therefore is the same for everyone (Buurman, 2003). Ricardo (1817) explained the existence of land rent by differences in soil fertility and land scarcity, while Von Thünen (1842) focused on the importance of spatial location, distance to markets and transportation costs to explain land use and differences in land prices. More recently, Alonso (1969) brought Von Thünen's theory to an urban context and formulated the bid-rent theory, that explained the relationship between land prices and land use. He assumed a competitive land market in which land-users seek to maximise their utility. This implies that land is being purchased or rented by the bidder offering the highest bid, i.e. the potential land-user able to derive the highest rent from land. As a result, both the revenue of the sellers and the utility of the buyers are maximised (Martinez, 1992).

Land is thus expected to be used for the purpose which brings the greatest utility, taking into account the relative benefits of alternative land uses (Fujita, 1989). This generally implies that urban development tends to outcompete agriculture. Thus, higher revenue activities such as commerce and services tend to concentrate at the city center, while industrial and housing functions select locations in its surroundings. A similar process can be observed within the agricultural sector, where capital and resource intensive types of farming, such as horticulture, normally outcompetes arable farming and husbandry activities (Bakker et al., 2011).

Measuring land value and land-derived utility is not a straightforward endeavour though. First of all, the provision of non-marketable life-support ecosystems services and the existence of intrinsic non-use values (e.g. the value one might hold for the continued existence of a pristine natural area, even if one does not intend to visit it) makes it virtually impossible to objectively assess the total value of land (Bateman, 2009). Furthermore, utility might differ among similar economic agents, depending on their intended use of land, their preferences
for specific objectives and the degree to which those objectives can be achieved (Keeney, 1969). For instance, farmers may have certain objectives that they aim to achieve while engaging in agricultural production, such as increasing profit/income levels, expanding business, or having more leisure time. Some of these objectives might be overwhelmingly more important than others; for example, increasing leisure time might only be taken into consideration if beforehand a minimum income level is secured (Rae, 1977).

Notwithstanding this complexity, several economic valuation methods have been developed that rely on surrogate measures to assess particular aspects of land-derived utility:

- **contingent valuation methods**, which estimate the willingness-to-pay of individuals for goods and services that do not have a market price, for instance, in nature areas and open spaces (see e.g. Tyrväinen and Väänänen, 1998; Ruijgrok, 1999; Moon and Griffith, 2011);

- **the travel cost method**, in which the value of a site is determined by the costs people incur while travelling to visit the site, particularly used for the valuation of recreational areas (see e.g. Clawson and Knetsch, 1966; Layman et al., 1996; Rosenberger and Loomis, 1999);

- **the hedonic pricing method**, which attempts to derive a value for non-market goods from goods that have a market price and have internalised some of the attributes of the non-market goods (Buurman, 2003). Hedonic prices can be regarded as the implicit prices of attributes, that are revealed from the behaviour of economic agents. Such studies typically rely on observed prices of differentiated products and the specific amounts of attributes associated with them (Rosen, 1974). In the case of land, the hedonic price of a parcel can be determined by valuing the attributes of land parcels, through the identification of differences in land prices that can be explained by differences in attributes (for different applications of hedonic pricing to land valuation, see e.g. Geoghegan et al., 1997; Tyrväinen and Miettinen, 2000; Bell and Bockstael, 2000; Mahan et al., 2002; Buurman, 2003; Dekkers and Rietveld, 2011);

- **spatially-explicit cost-benefit analysis and capital budgeting methods**, which evaluate the economic viability of land uses according to the cash flows (revenues and costs) resulting from their specific land-based activities (Rossiter, 1995). For instance, farms can be regarded as long-term economic enterprises that involve capital budgeting decisions according to the required investments (e.g. in facilities and commodity-specific machinery) and expected future revenues (Barlowe, 1972; Plantinga, et al., 2002; Schatzki, 2003; net present value assessment is a standard method used in capital budgeting to appraise long-term projects by measuring discounted time series of expected cash flows. This method has often been applied to value land in agricultural land systems (see e.g. Van der Hilst et al., 2010; Ustaoglu et al., 2016; Andrée et al., 2017).

These methods of economic valuation are useful for calibrating land-use models and can be implemented using spatial analysis techniques similar to those applied in empirical
approaches. The resulting theory-based land-use models are then able to determine the optimal configuration of (agricultural) land systems and the location of related land-based activities, by applying mathematical optimization techniques for different, and even divergent, objectives (see e.g., Balmann, 1997; Geoghegan et al., 1997; Bell and Irwin, 2002; Rounsevell et al., 2003; Koomen et al., 2005; Benke et al., 2011).

Both empirical and theory-based approaches have their merits and limitations in explaining and forecasting (agricultural) land-use patterns. Empirical approaches are popular because they rely on standardised statistical methods that are easily reproducible and tend to perform relatively well in reproducing existing spatial patterns (Overmars et al., 2007a). However, the reduced-form nature of the often applied statistical methods makes it difficult to distinguish between correlation and causation (Lewis et al., 2008). Therefore, empirical approaches do not seem to be able to fully explain the causality between land-use change factors and processes and the human behaviour leading to decisions on land use (Irwin and Geoghegan, 2001; Overmars et al., 2007a).

Theory-based approaches should, in principle, allow to formalise and test hypothesis on the causal relationships driving land-use change processes, since they explicitly incorporate assumptions on the behaviour and preferences of economics agents in the model’s functional form. However, the realism of the conventional concepts of rational behaviour and utility maximisation informing these assumptions remains debatable. This is partly due to the stated difficulty that people have in evaluating their own preferences, the short-run preferences of many to pursue immediate gratification or, conversely, the habit of others to pursue other goals than self-interest (Rabin, 2002; Verburg et al., 2004a). Furthermore, the ability of theory-based approaches to actually reproduce existing land-use patterns has been rarely investigated through model validation. In fact, in one of the few occasions where empirical and theory-based approaches have been validated and compared, it was found that the incorporation of an economic framework has not lead to an improvement of the model’s predictive power (Overmars et al., 2007b). However, such findings may be specific to that particular case study and, therefore, any inference on the comparative ability of these approaches would thus be far-fetched.

In fact, the preference for using one type of approach over the other usually seems to be more related to the disciplinary background of the researchers involved, 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, we can conclude that there is still a poor understanding on the comparative ability of empirical and theory-based approaches to explore, explain and simulate the spatial patterns of agricultural land systems.
4. Research questions and dissertation structure

The goal of this dissertation is to examine how different spatial analysis and land-use modelling approaches can contribute to understanding spatio-temporal patterns of agricultural land systems. In particular, the ability of empirical and theory-based approaches to explain observed agricultural land-use patterns is investigated, as well as their aptitude for simulating and exploring future developments in agricultural land systems.

To study this topic, the following research questions and sub-questions are 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?
   
   • Q1.1. To what extent are empirical approaches able to explain observed agricultural land-use patterns?
   
   • Q1.2. To what extent are theory-based approaches able to explain observed agricultural land-use patterns?
   
   • Q1.3. How do empirical and theory-based approaches compare in explaining observed agricultural land-use patterns?

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?
   
   • Q2.1. To what extent are empirical approaches able to simulate future agricultural land-use patterns?
   
   • Q2.2. To what extent are theory-based approaches able to simulate future agricultural land-use patterns?
   
   • Q2.3. How can empirical and theory-based approaches be combined to simulate future agricultural land-use patterns?

These research questions are addressed in Chapters 2 through 7. Table 1.1 provides an overview of the chapters and research questions addressed.
A number of case studies applying empirical and theory-based approaches are presented in order to provide evidence on the comparative strengths and limitations of these approaches in explaining and simulating the spatial patterns of agricultural land systems. The empirical approaches are based on a standardised, widely applied statistical method, the logistic regression analysis. The theory-based approaches are based on a standard capital budgeting method, the net present value approach. These approaches are implemented in pixel-based tools for spatial analysis and land-use modelling relying on raster data. The case studies presented here are not intended, by any means, to be exhaustive in regard to the large variety of approaches currently available. Instead, there was a deliberate decision towards selecting only a very limited number of well-established methods that can clearly illustrate the fundamental principles behind each type of approach, thus allowing to infer on the ability and appropriateness of empirical and theory-based approaches to investigate specific aspects of agricultural land systems.

Table 1.1: Overview of the research questions addressed in each chapter

<table>
<thead>
<tr>
<th></th>
<th>Q.1. Explaining current patterns</th>
<th>Q.2. Simulating future patterns</th>
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<tbody>
<tr>
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<td>Empirics-based</td>
<td>Theory-based</td>
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<td>Ch. 6</td>
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<tr>
<td>Ch. 7</td>
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The ability of the selected approaches to explain and simulate agricultural land-use patterns is evaluated according to the following elements of (spatial) data analysis (Anselin and Getis, 1992; Koomen, 2008; Shmueli, 2010):

- **exploratory data analysis**, i.e. the ability of a given approach to reveal structural patterns and suggest related processes;

- **explanatory data analysis**, i.e. the ability of a given approach to construct causal explanations of patterns and processes;
• **modelling/simulation**, i.e. the ability of a given approach to test theories by applying their formal causal relationships for the purpose of reproducing and/or forecasting observations of patterns and processes.

The presented case studies address several prominent challenges and opportunities in agricultural land systems, for instance: agricultural expansion, intensification, extensification and abandonment (Chapter 2). In addition, most chapters incorporate the interrelationships with other land-use change processes including the competition for land with other types of land use and the competition for land among different agricultural production systems. This latter type of competition is studied specifically in the context of introducing bioenergy crop production (Chapter 5 and 7) where direct and indirect land-use change impacts are a concern (Chapter 7). Additional topics addressed in this thesis include: multifunctionality and the provision of ecosystem services from 2nd generation biofuel crops (Chapter 5); adaptation of agricultural land systems to climate change and more frequent extreme weather events (Chapter 6); and land availability resulting from increased productivity in agricultural systems (Chapter 7).

Table 1.2 provides an overview of which topics are addressed in each chapter.

**Table 1.2: Overview of the topics addressed in each chapter**

<table>
<thead>
<tr>
<th>Topics relevant to agricultural land systems</th>
<th>Chapters</th>
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<tr>
<td>Expansion, intensification, extensification and abandonment</td>
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</tr>
<tr>
<td>Competition with other land-use types</td>
<td></td>
</tr>
<tr>
<td>Competition among agricultural production systems</td>
<td>x</td>
</tr>
<tr>
<td>Introduction of biofuel crop production</td>
<td></td>
</tr>
<tr>
<td>Multifunctionality and provision of ecosystem services</td>
<td>x</td>
</tr>
<tr>
<td>Adaptation to climate change</td>
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</tr>
<tr>
<td>Land availability resulting from increased productivity</td>
<td></td>
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</tbody>
</table>

A number of complementary study areas were selected for these research topics:

• **Portugal**, a country experiencing simultaneous processes of land-use change, such as farming intensification; increased migration to urban centers; expansion of tourism-related activities in coastal areas; marginalization of traditional agricultural and grazing practices and the consequent abandonment of agricultural land;

• **the Netherlands**, a country with a high pressure on land and an advanced agricultural sector with a high value per hectare; and
Argentina, one of the main global exporters of agricultural commodities and a key player in the biofuel markets.

The thesis starts with the chapters that focus on explaining current agricultural land-use patterns (Part II). Chapter 2 studies the observed land-use change processes in Portugal between 1990 and 2006, applying an empirical approach of spatial analysis to analyse the effects of different factors in shaping (agricultural) land-use patterns during that period. The subsequent chapter presents an economic theory-based land-use modelling framework that explains the causal links between economic decisions and resulting spatial patterns of agricultural land use, which is then operationalised and validated in a case study in the Netherlands. Chapter 4 goes on to present an integrated framework for land-use modelling which is able to incorporate both empirical and theory-based approaches in a unified assessment of local land suitability. This modelling framework is operationalised in a case study in the Netherlands in order to compare the ability of the model to reproduce existing land-use patterns according to different modelling approaches.

Chapter 5 starts a new part of the thesis (Part III) that focuses on simulating future agricultural land-use patterns. It applies an economic theory-based land-use modelling approach to explore the potential of reed as a bioenergy feedstock that can be combined with water and nature management objectives. This study simulates the local competition between reed and grassland used for dairy farming in the Netherlands. The next chapter presents a theory-based approach for spatial analysis to assess the future local economic impacts of more frequent extreme weather events in arable farming systems in the Netherlands. In addition, it explores the economic feasibility of adopting adaptation measures at the local level. Chapter 7 combines an explanation of observed agricultural land-use patterns with simulating future patterns. It presents a land-use modelling framework combining empirical and theory-based approaches to determine the economic potential of biofuel production avoiding indirect land-use changes (iLUC) resulting from land competition with other functions. The empirical approach explores future developments in food and feed production to determine land availability and the technical potential of biofuel production. The theory-based approach assesses the economic performance of biofuel crops on the surplus land in comparison with other production systems and determines the economic potential of biofuel production. The framework is demonstrated for a case study in Argentina to determine the development of biofuel potential from soy and switchgrass up to 2030.

Finally, Chapter 8 summarises and evaluates the findings from the thesis. It provides answers to the research questions, highlights the possibilities and limitations of the methods and data used, and gives recommendations for further research.

All analytical chapters that comprise this dissertation have been published in peer-reviewed scientific journals, as is detailed in Table 1.3.
Table 1.3: Overview of the publications related to the chapters of this dissertation

<table>
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<tr>
<th>Part</th>
<th>Introduction</th>
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<tr>
<td>Chapter 1</td>
<td>Unpublished</td>
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**Part II** Explaining observed agricultural land-use patterns

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<th>Chapter</th>
<th>Publication Details</th>
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</table>

**Part III** Simulating future agricultural land-use patterns


**Part IV** Conclusions

| Chapter 8 | Unpublished |