Explaining agricultural intensity at the European and global scale

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This research was conducted under the auspice of the C.T. de Wit Graduate School for Production Ecology and resource Conservation (PE&RC).

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Thesis
submitted in fulfillment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Monday 4 October 2010
at 4 p.m. in the Aula

Kathleen Neumann
Explaining agricultural intensity at the European and global scale, 168 pages.

Thesis Wageningen University, The Netherlands (2010)
With references, with summaries in Dutch and English

ISBN 978-90-8585-709-9

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Chapter 1

General introduction

1.1 Background

Humans alter their environment. They convert land cover by deforestation, urbanization, agricultural abandonment, or expansion of agriculture (Foley et al., 2005; GLP, 2005). But humans also alter the environment by changes in land management. Land management comprises all kind of activities to maintain the use and development of land resources. Agricultural land management does not necessarily lead to a conversion of the land cover but rather to its modification. One of the most significant forms of land cover modification is agricultural intensification (Lambin et al., 2000). Agricultural intensification is the process of increasing inputs per unit land (e.g., irrigation, fertilizer, labor) or outputs per unit land (e.g., crop yields) (Keys and McConnell, 2005). In the previous decades agricultural intensification led to strong increases in agricultural production, more than was achieved by agricultural expansion (Matson et al., 1997; Wood et al., 2000). Agricultural intensification is, however, not only a crucial step towards increased food production but it also poses enormous challenges for the world's ecosystems (Kendall and Pimentel, 1994; Cassman, 1999; Tilman et al., 2002; Foley et al., 2005). Agricultural intensification is therefore a key variable in global integrated environmental assessments (IPCC, 2000; UNEP, 2007).

Today, agriculture occupies approximately 34% of the world's ice-free surface (Ramankutty et al., 2008). Given the land scarcity in many cropping regions agricultural expansion is projected for only some regions in Central America, South America, and Africa. Agricultural intensification, however, is expected to remain crucial for accommodating increasing food demand of the world's growing population (Gregory and Ingram, 2000; Kirchmann and Thorvaldsson, 2000). Agricultural intensification takes different forms, which are determined by different types of land management. Agricultural land management may be specified as the interplay of production mix, production techniques (e.g., intercropping), mechanization, chemical technology, water management, labor, or other capital investments. Figure 1.1 shows for two exemplary agricultural land use types possible management types. The figure illustrates that arable land may be managed by mechanization, fertilizer application, and irrigation. Each of these land management practices may be applied to a different degree (i.e., application rate of land management). Hence, while a particular crop type may be cultivated with extensive fertilizer application it may be less intensively irrigated. The interplay of agricultural land management types and their application rates determine land use intensity.

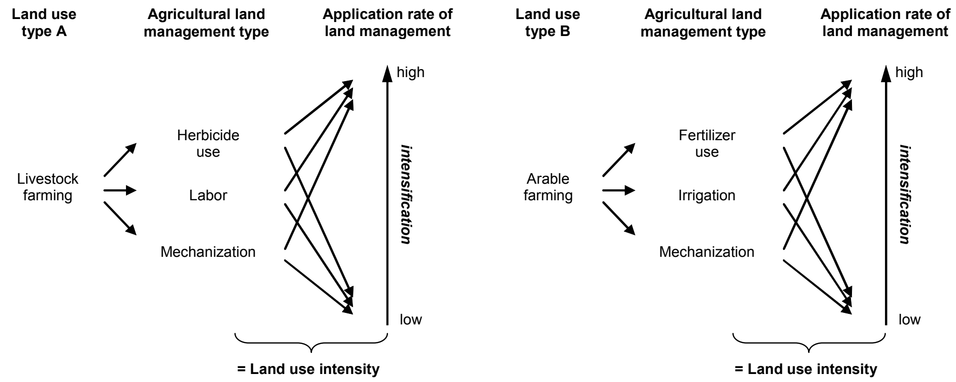

Figure 1.1: The relation between land use type and land use intensity illustrated for two exemplary agricultural land use types.

Agricultural land management and land use intensity differ across the globe but their causes are not well understood at the continental or global scale. One of the few large scale studies done was conducted by Keys and McConnell (2005) who synthesized a number of case studies in the tropics to assess the various factors driving agricultural intensification. The authors conclude that the relative contribution of these factors varies greatly between regions. For Europe, Herzog et al. (2006) developed an overall intensity index which was applied to twenty-four test-sites using site-specific information on Nitrogen inputs, pesticide applications, and livestock intensity. Results show that agricultural intensities are highly diverse amongst these sites and therefore cannot simply be extrapolated to entire Europe.

The urgency of better understanding land cover modifications, especially agricultural intensification is stressed by Lambin et al. (2000). The authors remark that more and more scientists have realized the need to investigate more subtle land changes, and that these need more attention. Agricultural intensification, however, cannot entirely be understood without understanding the determinants of agricultural land management. This thesis aims to explore some determinants of agricultural land management and land use intensity as described in Section 1.3.

1.2 Overview of methodological approaches in continental and global scale land use change studies

Agricultural land management, land use intensity, and agricultural intensification have been extensively studied at the farm scale (Ahmed and Sanders, 1998; Shriar, 2000; Keys and McConnell, 2005; Herzog et al., 2006; Pascual and Barbier, 2006; Tittonell et al., 2009). At the global and continental scale, however, comprehensive information on the different agricultural land management practices and land use intensities is scarcely available (GLP, 2005). This section will therefore address two main aspects. First, how are agricultural land management and land use intensity represented in current continental scale mapping efforts; and second, how are the processes of agricultural land management and intensification considered in current continental and global modeling approaches.

The first global land cover maps were produced some twenty years ago (Koomanoff, 1989; DeFries and Townshend, 1994). These first attempts have since then been supplemented by many other more sophisticated datasets (Hansen et al., 2000; Loveland et al., 2000; Bartholome and Belward, 2005; Defourny et al., 2006). The first attempts at mapping agricultural land uses and land management practices at the continental or global scale have, however, only recently been made. FAO (2007) has mapped the spatial distribution of livestock across the globe. This was accompanied by an earlier effort by Kruska et al. (2003) who mapped livestock-oriented production systems for developing countries. Ramankutty et al. (2008) and Monfreda et al. (2008) mapped global cropland areas for which several authors have identified the extent of irrigation at the global or continental scale (Siebert et al., 2005; Thenkabail et al., 2009; Wriedt et al., 2009; Portmann et al., 2010) and fertilizer inputs (Potter et al., in press). The methodologies applied for generating all these datasets range from land surveys to remote sensing techniques and spatial modeling. These studies also illustrate the limited availability of global and continental spatially explicit information on agricultural land management practices and land use intensity.

A common technique when studying land use changes over a particular period rather than describing a momentary situation is land use modeling. Land use modeling is an important technique to explore land use dynamics and possible future developments, to describe the spatial and temporal relationships between land use change drivers and resulting land patterns, and to provide decision support in broad policy making contexts (Veldkamp and Lambin, 2001). However, continental and global scale land use models hardly exist (Heistermann et al., 2006) and land use modelers face a broad range of challenges, amongst others the explicit consideration of land management and land use intensity (Lambin et al., 2000). Modeling crop yields, which are often used as a measure of agricultural land use intensity, is probably one of the better elaborated concepts. Global scale crop yields were modeled by several authors (Cassman, 1999; Bondeau et al., 2007; Stehfest et al., 2007). Livestock farming, which plays an important role in land change processes, is, however, hardly considered as a distinct land use type in current continental and global land use models, mainly due to limited data availability. Global integrated modeling approaches, therefore, often either rely on aggregated livestock information to conduct environmental impact assessments (Darwin, 1999; Sands and Leimbach, 2003) or apply simple disaggregation mechanisms to distribute national livestock projections to grid cells (Bouwman et al., 2005; Schaldach and Koch, 2009). Continental or global scale modeling of agricultural land management practices, such as fertilizer or pesticide application, is even more challenging. This can be traced back to a lack of both consistent data and a detailed understanding of the driving forces for particular management practices. Agricultural land management and land use intensity are addressed differently in current modeling approaches; if they are addressed at all. In a simple approach land management practices are considered as a distinct land use type, for example 'irrigated arable land'. In such a case irrigation may be dynamically modeled by simulating changes of the location of irrigated arable land or by simulating land use changes due to (no) irrigation water availability. Other aspects of irrigation, for example the amount of applied water are usually disregarded (Alcamo et al., 1998; Overmars et al., 2007). While the first issue could be treated equally as land use conversion the latter issue addresses the quantity of change, i.e., the amount of water, which in fact is a measure for intensity (Lambin et al., 2000). Such more process oriented approaches were developed at the continental and global scale by Heistermann (2006) and Lotze-Campen et al. (2008). However, many land use modeling approaches focus on biophysical drivers, given good data availability, while case studies (for examples see de Koning et al., 1998; Boardman et al., 2003; Keys and McConnell, 2005; Long et al., 2007) have indicated the important role of socio-economics and policy implementation in driving land use changes.

Integrated assessment models probably have the largest potential for improving the understanding of land use change processes including agricultural intensification (Lambin et al., 2000). Compared to other model types integrated models have better capabilities to consider intensification in a simplistic way as a function of resource management under biophysical and socio-economic constraints. For example, the global integrated assessment model IMAGE considers intensification as a region inherent characteristic that is mainly influenced by the global food demand.

Intensification is closely linked to crop and livestock productivity and is expressed in a region-specific management factor. At the grid cell level IMAGE aims to explore the consequences of the regional intensification, for example land use changes (Alcamo et al., 1998). Another example is the MAgPIE model which simulates land use and water use pattern at the global scale (Lotze-Campen et al., 2008). MAgPIE is coupled with the dynamic vegetation model LPJmL (Bondeau et al., 2007) to integrate information on potential crop yields and irrigation water with socio-economic information on population, income, food demand, and production costs. The LandSHIFT model, which so far operates only for Africa, considers intensification as a function of biophysical constraints and population density. LandSHIFT explicitly addresses spatially-explicit changes in land use intensity, which are mainly linked to livestock densities, and simulates them as a dynamic process (Schaldach and Koch, 2009).

Modeling agricultural land management and intensification requires a thorough understanding of its socio-economic and biophysical causes and constraints. Hence, the drivers of intensification and factors explaining current agricultural land management need to be identified first. However, at the continental and global scale, where consistent and reliable data are scarce and land related processes are complex, a sound explanation of these factors is a big challenge and represents a major gap in current land use studies. Consequently, there is only a small number of spatially explicit large scale land use modeling approaches that specifically address land management aspects. Improving the understanding of agricultural intensification drivers and their robust linkage to land cover models is a main challenge for the land use research community and is addressed in this thesis.

1.3 Objectives

At the global scale, land use and land cover changes are responsible for greenhouse gas (GHG) emissions, which are a major cause of climate change. However, the understanding of land dynamics and their characteristics at the global scale is still a challenge (GLP, 2005). With this thesis a contribution shall be made at reducing this knowledge gap. The main objective of this thesis is to explore spatial diversity in agricultural land management and land use intensity and to explain its variability across the globe. To meet this objective a variety of quantitative methodologies were developed and applied at different spatial scales. Because there is little consensus regarding an applicable approach for identifying agricultural intensity (Shriar, 2000; Roschewitz et al., 2005), this thesis targets selected aspects of agricultural land management and land use intensity including livestock farming, efficiency of grain production, and irrigation. These aspects were selected because they represent three important issues of land use intensity and agricultural land management. The research was conducted at the European and global scale.

Four research questions were formulated:

1. How can the current livestock pattern in Europe be explained?
2. How can future changes in the European livestock sector be explored?
3. How can determinants of efficiency in current crop production be identified and how do these differ between regions?
4. What are the local and national level determinants of currently irrigated cropland?

1.4 Outline of the thesis

This thesis comprises six chapters, including the introduction. Each chapter addresses at least one of the research questions presented in Section 1.3. In Chapter 2 an explanatory analysis is done to determine the spatial distribution of five different livestock types (dairy cattle, beef cattle, sheep, pigs, and poultry) within Europe. For this an empirical and an expert-based approach are applied. Empirical approaches test hypotheses by using observed or experimental data. Expert-based approaches use assumptions based on case study evidence and system understanding. The purpose of the study is to assess the importance of several land- and climate-related factors as determinants of the spatial livestock distribution.

In the third chapter the results obtained in Chapter 2 are integrated in a multi-scale modeling approach to explore future developments of the European livestock sector. The aim of the study is to explore changes in the European livestock sector by integrating a broad range of processes related to livestock farming while accounting for drivers at different spatial scales. Both quantity and spatial distribution of different livestock types are simulated over the 2000-2030 period for four contrasting scenarios.

The research presented in Chapter 2 and 3 is done at the European scale. Yet, Chapter 3 also considers socio-economic processes occurring at the global scale (e.g., changes in consumer behavior and global trade). Chapter 4 and 5 focus on the global scale. In Chapter 4 an empirical analysis is made to analyze actual yields of wheat, maize, and rice production at both the regional and global scale accounting for biophysical and land management-related factors. A stochastic frontier production function is applied to calculate maximum attainable grain yields, yield gaps, and efficiencies of grain production.

Chapter 5 addresses several aspects of global irrigation. A multilevel analysis is applied to explore the determinants of current global irrigated cropland at grid cell level and at country level. Multilevel analysis is a statistical approach for analyzing hierarchically structured data. While biophysical information is considered at grid cell level socio-economic and political information are primarily accounted for at country level. Based on the identified variables and their importance, a map of potential for irrigation expansion is generated and discussed.

Table 1.1 summarizes Chapter 2-5 with respect to the studied land use aspect, the addressed research question presented in Section 1.3, and the spatial scales which are taken into account in each chapter. The synthesis of Chapter 2-5 is presented in Chapter 6. This chapter discusses the main findings of this thesis and assesses different perspectives for land use intensity research in land science and policy making.

Table 1.1: Outline of Chapter 2-5.

Land use aspect	Research question	Scale of observation	Scale of analysis	Chapter
Europe				
Livestock farming	Identification of location factors	NUTS region	Grid cell (1 km)	2
	Exploration of future changes	Grid cell (1 km)	Grid cell (1 km), country	3
Globe				
Crop production	Determinants of efficiency in crop production	Grid cell (5 arc-minute)	Grid cell (5 arc-minute), world-region, globe	4
Irrigation	Local and national level determinants	Grid cell (5 arc-minute)	Grid cell (5 arc-minute), country, globe	5

Chapter 2

Modeling the spatial distribution of livestock in Europe

Livestock remains the world's largest user of land and is strongly related to grassland and feed crop production. Assessments of environmental impacts of livestock farming require detailed knowledge of the presence of livestock, farming practices, and environmental conditions. The present European-wide livestock distribution information is generally restricted to a spatial resolution of NUTS 2 (province level). This chapter presents a modeling approach to determine the spatial distribution of livestock at the landscape level. Location factors for livestock occurrence were explored and applied to consistent and harmonized European-wide regional statistics to produce a detailed spatial distribution of livestock numbers. Both an expert-based and an empirical approach were applied in order to disaggregate the data to grid level. The resulting livestock maps were validated. Results differ between the two downscaling approaches but also between livestock types and countries. While both the expert-based and empirical approach are equally suited to modeling herbivores, in general, the spatial distribution of monogastrics can be better modeled by applying the empirical approach.

Based on: Neumann, K., Elbersen, B., Verburg, P., Staritsky, I., Pérez-Soba, M., de Vries, W. and Rienks, W., 2009. Modelling the spatial distribution of livestock in Europe. – Landscape Ecology 24, 1207-1222.

2.1 Introduction

Most studies in land change science are focused on land cover change while paying limited attention to land use and livestock. However, livestock is an important component of land use and is intricately related to natural, economical, political, and social conditions. Few studies have explicitly addressed the spatial dynamics of livestock (Verburg and Keulen, 1999; Kruska et al., 2003). To better integrate livestock within integrated models of land change and to assess the environmental impact of livestock, it is crucial to know where livestock are located and what the determinants for their spatial distributions are. In Europe, the importance of livestock farming varies greatly between regions and livestock types. Beef and dairy cattle are the most important European livestock types in terms of total numbers and economic value. 83% of the European Union's (EU's) dairy cows are found in the Netherlands, England, parts of Scotland, Western France, Northern Italy, Sweden, Finland, Northern Spain, Denmark, and Germany (Arendonk and Liinamo, 2003). The highest pig concentrations occur in North Rhine-Westphalia, Jutland, South-East of the Netherlands, East Anglia, Emilia Romagna, and Brittany (Bolsius, 1993). These regions developed around harbors supplying low cost cereal substitutes and soybean as a cheap vegetable protein source. Large concentrations of poultry farming occur in the Netherlands, parts of Denmark, France, Germany, Italy, and the UK. At the local scale poultry production, like pig production, is often situated in or near regions of cereal production as well as close to harbors in order to receive imports of feed ingredients (EC, 2004; FAOSTAT, 2006). Some 74% of the European sheep are kept in five member states, specifically UK, Spain, Greece, France, and Italy (FAOSTAT, 2009a).

Different livestock concentrations and different livestock types have different environmental impacts, such as pollution of air and water resources by leaching and runoff of nitrogen or erosion by overgrazing. Environmental impacts of livestock have been discussed and assessed for different scales and by several authors. Two of the most prominent studies carried out at the global scale are; the assessment of various impacts of livestock on the environment by Steinfeld et al. (2006) and de Haan et al. (1997). Both authors discuss the environmental challenges of livestock farming, evaluate its environmental impact, and present potential technology and policy options for mitigation. In addition to these global studies, several studies have been published for the European or regional scale, studying, for example, the impacts of different livestock types on the environment and policy scenarios on ammonia emissions and nitrogen leaching and runoff (Hooda et al., 2000; Nielsen and Kristensen, 2005; Oenema et al., 2007; van Groenigen et al., 2008).

Policy instruments, such as the EU Common Agricultural Policy (CAP) Health Check, the CAP Cross Compliance, the Water Framework Directive and the new Rural Development Regulation (RDR) support instruments, all require integrated impact assessments. Spatially detailed and European-wide consistent livestock data are essential for these ex-ante assessments. Data are, however, currently not available and consequences of livestock farming can only be assessed in an approximate manner. Present EU-wide livestock distribution information only provides data on livestock types and numbers at administrative regional levels (e.g., Nomenclature of Units for Territorial Statistics (NUTS) 2). Administrative boundaries often cut through different environmental zones such as river basins, mountain areas and landscapes and it can be assumed that livestock are not evenly spread within the territories.

More detailed insight into the spatial variation of livestock can be achieved by disaggregating livestock statistics. However, downscaling livestock data for Europe remains challenging as some livestock types have lost their relationship with the land and local fodder production. Furthermore, there are very few consistent European-wide datasets on farm management, feed composition and manure management that describe European livestock farming with detailed spatial resolution. Given these limitations, only a few attempts have been made to disaggregate sub-national livestock data to a high spatial resolution. A first attempt at disaggregating European livestock data from regional to grid level, applying expert rules, was carried out in the European Livestock Policy Evaluation Network (ELPEN). In this study, dairy systems within the EU-15 were located at NUTS 2 level by examining differences in the area of land used by the different dairy systems in different countries (Perez-Soba et al., 2001; Petit and Elbersen, 2009). European farm information data, although not solely livestock, from the Farm Accountancy Data Network (FADN) was downscaled in the CAPRI-Dynaspat and SEAMLESS projects (Elbersen et al., 2006; Kempen et al., 2006) At the global scale, the Food and Agricultural Organization of the United Nations (FAO) has downscaled livestock types to 3 arc-minute resolution based on empirical analysis (FAO, 2007). At the regional scale Hellsten et al. (2008) have disaggregated parish level pig and poultry data to 1 km^2 for the UK. These studies show that different approaches can be used to determine spatial livestock distribution and that the results give valuable insights into the spatial patterns of livestock distribution. However, a comparison of different methodologies was beyond the scope of the studies mentioned above and results were not validated.

This chapter presents a newly developed method to model the spatial distribution of livestock at the 1 km^2 resolution within the EU-27 based on consistent regional livestock statistics. The purpose of the study is to study the importance of several land-related and climatic factors as livestock location determinants. The originality of the approach that was developed lies in its integration of an expert-based and an empirical approach. The results are validated by comparing the simulated patterns with spatially detailed census data for a number of countries. Furthermore, the suitability of the approach is determined by comparing the results with a random distribution model.

2.2 Methodology

2.2.1 Overall downscaling method

A downscaling framework was developed to disaggregate livestock data to 1 km grid level (Figure 2.1). Five different livestock types were considered: 1) dairy cattle, 2) beef cattle, 3) sheep, 4) pigs, and 5) poultry. Probabilities for livestock occurrence were identified by applying two different methodologies: an expert-based approach (based on expert knowledge of the authors) and an empirical approach. The purpose of using the two different approaches was to study the robustness of the methodology.

In the expert-based approach (the base approach), land-related suitability rules were specified for herbivores and monogastrics based on case study evidence and system understanding. The extent to which these suitability rules lead to realistic livestock distributions at the European scale was tested. In the empirical approach, statistical analyses were employed to test (for a set of land-related and climatic factors) how much of the present day European livestock distribution could be explained by these factors. The empirical approach is based on detailed livestock statistics as available for a number of countries. Empirical-statistical approaches are frequently applied in land use modeling studies to determine driving forces of spatial land use dynamics (Mertens et al., 2002; Aspinall, 2004; Overmars and Verburg, 2005). Although this approach is very data intensive, it allows determination of livestock type and country-specific location factors for livestock. Given the limited data availability, the empirical approach could only be applied to a selection of countries for which sufficient information could be obtained (Denmark, Germany, the Netherlands, and Portugal).

Based on either the expert-based suitability rules or statistical relationships, grid cell-specific probabilities for livestock distribution were calculated (see Figure 2.1). An allocation mechanism was developed to disaggregate the livestock statistics based on these livestock probabilities. Livestock types were individually allocated to land use types starting with the grid cell with the highest probability.

The allocation mechanism takes two different hierarchies of distribution into account. The first is the order of livestock type allocation. Allocation of herbivores starts with dairy cattle, followed by beef cattle and finally sheep. This means that if all herbivore types are competing for the same piece of land, it is assumed that dairy cattle have the highest chance of being allocated to the best land because of their economic importance. Beef is assumed to be kept on good, medium and marginal land and sheep are assumed to occur more often on marginal land; e.g., steeper slopes, lower productive grasslands and semi-natural lands. When allocating monogastrics, pigs have a higher priority than poultry and are allocated first without consideration of the presence of herbivores in a cell. Hence, no competition is assumed between herbivores and monogastrics for the same location. Second, herbivores are always allocated to pasture first and if there is no land left they are shifted to arable land. Since rotational

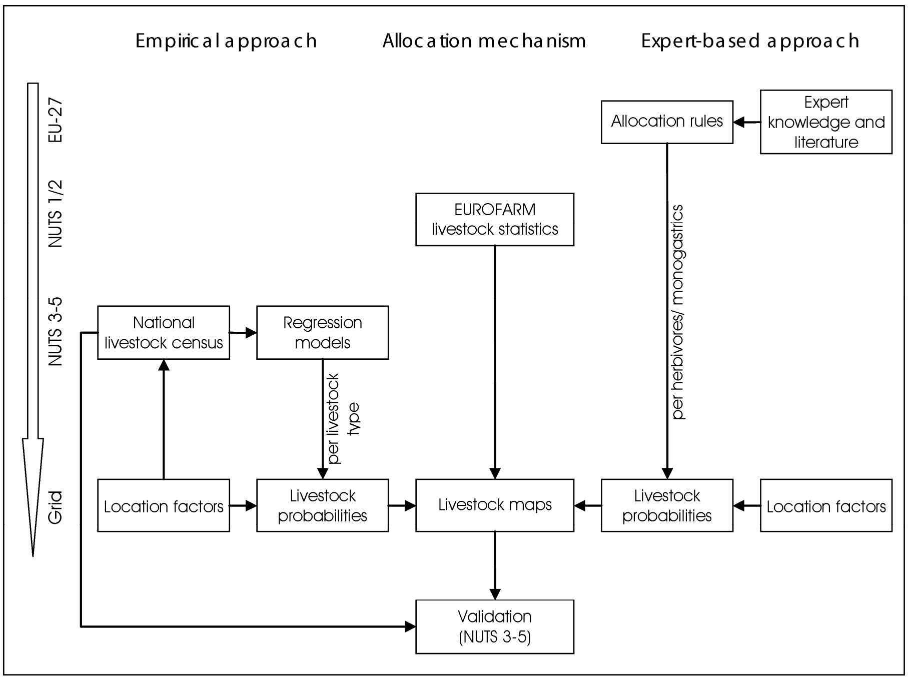

Figure 2.1. Downscaling methodology.

grassland is part of the arable land class this is a reasonable assumption. Semi-natural land has the lowest priority in the allocation procedure. Monogastrics are firstly allocated to arable land (due to limitations in area availability) before shifting to pasture and eventually permanent crop land. Probabilities for livestock allocation are furthermore randomly increased for some grid cells to account for chance events in livestock production systems.

The results are displayed as maps showing the spatial distribution of each livestock type for EU-27 with a spatial resolution of 1 km^2. While the EU-27 could be fully covered by the expert-based approach, the empirical approach could only map livestock for those countries for which sufficient data were available (see Section 2.3.2). The maps were validated by comparing the retrieved patterns with both spatially detailed national census data and a random distribution model.

2.2.2 Data

Maps of livestock distribution for the year 2000 were generated using European census data. Livestock was grouped as dairy cattle, beef cattle, sheep, pigs, and poultry. Consistent EU-wide regional statistics on these livestock types, their numbers, and their distribution over land use types, were obtained from the EUROSTAT EUROFARM database (Eurostat, 2007) (Table 2.1). The EUROFARM database contains harmonized statistical information on structure of agricultural holdings collected through national agricultural surveys. Livestock data are available at the level of NUTS 1 or NUTS 2 regions, and is mostly national level for the smaller EU Member States and province or autonomy level for the larger countries. Data were collected for the years 2000 to 2003 depending on the available variables and their administration level per country. The aim was to use information at the most spatially and thematically detailed level possible.

Table 2.1 EUROFARM livestock statistics.

Livestock category	Livestock types	Land use types
Herbivores	Dairy cattle, beef cattle, sheep	Hectare of fodder land, permanent grassland, rough grazing used per livestock type per NUTS region
Monogastrics	Pigs, poultry	Hectare of arable, permanent grassland, and permanent crops used per livestock type per NUTS region

A categorization of livestock into herbivores and monogastrics was carried out as the spatial distribution of each group is driven by different factors. Herbivores are assumed to obtain a large part of their feed requirements (roughage and concentrates) from the farmland where they are kept either by actual grazing or by feeding with hay and forage from the surrounding land, while being in the housing system. Livestock productivity therefore depends on the quality of the surrounding land. The higher the grassland productivity the higher is the expected livestock productivity (e.g., tons of milk or meat). Monogastrics are primarily fed by concentrates which are not necessarily locally produced but often partly or fully imported from outside the region. Monogastrics are thus assumed to be detached from the land and its actual productivity (Barnard and Nix, 1979). These are of course very rough assumptions that ignore the large diversity of farming systems in Europe. However, for a European-wide study, and taking data availability into account, this simplification was necessary.

2.2.3 Implementation of the downscaling method

Land use harmonization

The overall downscaling methodology as presented in Section 2.2.1 was implemented for the EU-27. Before determining location factors of livestock types, the land use information (as used from different sources) was harmonized. Land area requested by each livestock type within a NUTS 1/2 region is given per EUROFARM land use type. For instance, the data represents the number of dairy cattle at ‘total permanent grassland and meadows’ within a NUTS region. This statistical information is not always consistent with the land cover information of the CORINE Land Cover 2000 data which was used for the spatial allocation of livestock (EEA, 2005). A translation of the respective EUROFARM land use classes to the most similar CORINE land cover classes was performed (Table 2.2). Hence, it could be determined which CORINE classes were used within every EUROFARM region by the different livestock types.

The translation of EUROFARM land use classes to the respective CORINE classes was done as carefully as possible, however, one-to-one relationships do not exist in all instances. Where there was insufficient area for a particular CORINE class to allow allocation of all EUROFARM based land use requirements for a certain livestock category, this land claim was shifted to another land cover class according to the procedure given in Section 2.2.1.

Table 2.2. Link between EUROFARM land use categories and CORINE land cover categories.

EUROFARM land use category	CORINE land cover categories
Arable fodder production area, and fodder roots and brassicas including forage plants (incl. temporary grass, green maize)	- Non-irrigated arable land - Land principally occupied by agriculture, with significant areas of natural vegetation - Complex cultivation patterns
Total permanent grassland and meadow	- Pastures - Land principally occupied by agriculture, with significant areas of natural vegetation
Rough grazing	- Natural grasslands - Sclerophyllous vegetation - Transitional woodland-shrub - Land principally occupied by agriculture, with significant areas of natural vegetation - Heather and moorlands
Permanent crops	- Vineyards - Olive groves - Fruit trees and berry plantations - Annual crops associated with permanent crops - Agro-forestry areas

Determining location factors: Expert-based approach

Herbivores

Simple suitability rules for livestock distribution were formulated in this study (based on expert knowledge of the authors) to test how much of the current herbivore distribution across Europe they could explain. In order to guarantee consistency, no region-specific suitability rules were applied as the data and information availability on location factors for herbivores are limited. Only those factors that are available for the whole of Europe and have a causal relation with livestock density were used. First, the EUROFARM data provide information on herbivore numbers per land use type per region (Table 2.1). These land use types were used to define suitability rules. Second, several studies emphasize the importance of slope as a determinant of herbivore distribution, with flat areas being more suited to keeping livestock than steep areas (Mueggler, 1965; Cook, 1966; Harris and Kennedy, 1999). For this reason slope was considered as an additional location factor. Third, grassland productivity was taken into account as a location factor affecting the carrying capacity of locations, as areas with higher grassland productivity can feed more animals.

The suitability rules are summarized in Table 2.3. Suitability rules were formulated for each land cover type, eventually resulting in different probabilities for each possible combination of variables. Based on these expert rules, a probability map was generated to identify the herbivore occurrence for each 1 km grid cell. In a later step, these grid cell-specific probability values were used by the downscaling algorithm to allocate the livestock numbers.

Table 2.3. Suitability rules and related data sources for downscaling herbivores.

Location factor	Suitability rule	Source
Land use	Livestock only occurs on agricultural land: permanent grassland, non-irrigated arable, semi-natural grassland, and moors and heathlands	Simplified CORINE Land Cover 2000 (based on EEA (2005))
Slope	- 0-6% slope: grazing unconstrained, highest stocking densities possible - > 6-12% slope: some grazing constrains, lower stocking densities - > 12-24% slope: large grazing constraints, low stocking densities - > 24% slope: little grazing possible	Derived from USGS GTOPO30
Potential grassland production	- High productive grassland: highest stocking densities possible - Medium productive grassland: medium stocking densities - Low productive grassland: low stocking densities	MARS database (Boogaard et al., 2002; Micale and Genovese, 2004)

Monogastrics

Monogastrics in Europe are much less connected to the immediate environment than herbivores and are characterized by large (spatial) variation in local concentrations of pigs and poultry. Pig and poultry farms often emerge from other agricultural production systems such as dairy cattle farming and are located within agricultural areas on land associated with these farms (Bolsius, 1993). Distance to harbors is an important location factor for pig and poultry farming in Western Europe, but not necessarily for central and Eastern Europe. The occurrence of pig and poultry farming in Europe is often related to local historic developments and is de-coupled from local agricultural production conditions making an explanation of the distribution very complex. Therefore, it was decided to use the information from the EUROFARM statistics providing NUTS level information on livestock numbers for pigs and poultry in combination with land use information. The combined livestock-land use information was linked to the best matching CORINE land cover classes to calculate the grid cell-specific probabilities (see Table 2.2). As monogastric farming has often evolved from arable and dairy farming, pigs and poultry were assumed to occur on arable land, grassland and permanent cropland. This does not necessarily mean that these land use types provide fodder products to these livestock systems.

Determining location factors: empirical approach

In the empirical approach, statistical relationships were established between observed livestock numbers, derived from national level data sources and independent variables for a selection of countries. A wide range of variables that could potentially explain livestock distribution was incorporated in the statistical analysis, e.g., soil type, climate, geomorphology and population distribution (Table 2.4). Detailed national livestock census data at a higher spatial resolution than the data available from EUROFARM were obtained for the Netherlands, Denmark, Germany and Portugal (Table 2.5). These detailed data were related to the selected variables (Table 2.4) to identify those that were significant and to derive quantitative empirical relationships with livestock distribution.

First, Pearson correlation coefficients were calculated to assess relations between all variables in Table 2.4 and livestock locations. Where variables were highly correlated (≥0.7), selected variables were excluded from further statistical analysis to avoid multicollinearity. Second, multiple linear regressions were used to identify the extent to which the selected variables could explain the location of individual livestock types. A forward stepwise regression was applied (statistically significant at the 0.05 level). Standardized regression coefficients of each variable were derived from the regressions. As an example, Table 2.6 shows the estimated parameters for dairy cattle and pig locations in Germany. It shows that the spatial distribution of dairy cattle can be largely explained by environmental factors such as topography, climate and distribution of grassland. Although the spatial distribution of pigs is also related to environmental factors such as climate and topography, economic variables such as distance to cities and ports, and locations of maize and wheat production are also important location factors. Based on the statistical results, livestock probabilities were calculated by applying the estimated regression models to all individual grid cells within the country. Contrary to the expert-based approach these maps show country-specific probabilities of livestock occurrence per livestock type. Probabilities as calculated with the expert-based and empirical approach were used to downscale the EUROFARM data as described in Section 2.2.1.

Table 2.4. Selected independent variables used for the empirical analysis of spatial livestock distribution.

Variable	Spatial resolution	Source
Socio-economic variables		
Travel time to cities/ ports	1 km^2	Accessibility analysis based on GISCO database infrastructure
Population density	1 km^2	Derived from LandScan (http://www.ornl.gov/sci/gist/landscan)
Soil-related variables		
Soil types	1:1 mln	The EU Soil Geographic database contained in the MARS database
Percentage soil clay content	Polygons converted to 1 km^2	European Soil Database of the Joint Research Centre (JRC) of the EU
Organic carbon content in top soil	1 km^2	Map of Organic Carbon in Topsoils in Europe, Joint Research Centre (JRC) of the EU
Soil depth	Polygons converted to 1 km^2	European Soil Database of the Joint Research Centre (JRC) of the EU
Land use		
Land use type	1 km^2	Simplified CORINE Land Cover 2000 (based on EEA (2005))
Crop types	1 km^2	Capri-Dynaspat
Potential grassland productivity	1:1 mln	MARS database (Boogaard et al., 2002; Micale and Genovese, 2004)
Climatic variables		
Accumulated rainfall	1 km^2	Worldclim (http://www.worldclim.org/)
Mean yearly temperature	1 km^2	RIVM (mean temperature 1961-1990)
Number of months a year with average temperature below 0 degrees C	1 km^2	Derived from CRU (http://www.cru.uea.ac.uk)
Number of months a year with average temperature above 15 degrees C	1 km^2	Derived from CRU (http://www.cru.uea.ac.uk)
Environmental zones	Polygons converted to 1 km^2	Metzger et al. (2005)
Geomorphology		
Elevation (DEM)	1 km^2 (using 90m DEM)	Derived from 1000m DEM from SRTM3 data
Average height difference	1 km^2	Derived from 1000m DEM from SRTM3 data
Slope	1 km^2 (using 90m DEM)	Derived from 1000m DEM from SRTM3 data

Table 2.5. National livestock census data used to establish statistical relationships between observed livestock occurrence and other variables.

Country	Detail of EUROFARM data	Detail of census data, source	Year	Dairy cattle	Beef cattle	Sheep	Pigs	Poultry
Denmark	NUTS 1 (n=1)	NUTS 5 (n=277) (Det Jordbrugsvid-enskabelige Fakultet, 2000)	2000	x	x		x	x
Germany	NUTS 1 (n=14)	NUTS 3 (n=439) (Statistisches Bundesamt, 2001)	2001	x			x	x
Netherlands	NUTS 1 (n=4)	NUTS 4 (n=488) Statistics Netherlands, further processed by Naeff (2006)	2003	x	x	x	x	x
Portugal	NUTS 2 (n=5)	NUTS 3 (n=28) (Instituto Nacional de Estatística, 1999)	1999			x	x	x

2.2.4 Validation

A validation of all simulated livestock maps was performed using detailed national livestock census data for 12 European countries. These countries were chosen in such a way that they represent diverse land use patterns and environmental conditions. Furthermore, national census data, providing comparable and spatially explicit information about each livestock category on a high spatial resolution, were available for these 12 countries. The level of detail of the census data (in terms of livestock classes and spatial detail) differs from country to country (Table 2.7).

Table 2.6. Linear regression models for distribution of dairy cattle and pigs in Germany (all variables are significant at 0.05 level).

Dairy cattle ($r^2 = 0.48$)				Pigs ($r^2 = 0.42$)			
	Unstand. Coeff.		Stand. Coeff.		Unstand. Coeff.		Stand. Coeff.
Variables	B	Std. Error	Beta	Variables	B	Std. Error	Beta
(Constant)	0.108	0.026		(Constant)	-2.573	0.293	
Accumulated rainfall	<0.001	<0.001	0.434	Accumulated rainfall	0.004	<0.001	0.502
Average height difference	-0.016	0.001	-0.429	Average height difference	-0.140	0.010	-0.379
Land use pasture	0.001	<0.001	0.242	Travel time to large cities	<0.001	<0.001	0.346
Mean yearly temperature	-0.022	0.002	-0.190	Maize	<0.001	<0.001	0.211
Travel time to ports	<0.001	<0.001	0.123	Travel time to small cities	<0.001	<0.001	-0.173
Percentage soil clay content	-0.001	<0.001	-0.108	Land use non-irrigated arable land	0.005	0.001	0.167
Soil type crystalline rocks	-0.033	0.006	-0.099	Soil type sands	0.462	0.054	0.162
Land use complex cultivation pattern	0.001	<0.001	0.095	Common wheat	<0.001	<0.001	-0.159
Grassland	<0.001	<0.001	0.089	Travel time to ports	<0.001	<0.001	-0.150
Travel time to small cities	<0.001	<0.001	0.081	Mean yearly temperature	0.133	0.023	0.116
Soil type sands	-0.019	0.005	-0.068	Non-permanent industrial crops	-0.001	<0.001	-0.113
Non-permanent industrial crops	<0.001	<0.001	-0.068	Land use pasture	-0.004	0.001	-0.101
Organic carbon content in top soil	-0.001	<0.001	-0.066	Barley	<0.001	<0.001	0.095
Maize	<0.001	<0.001	0.063	Population density	<0.001	<0.001	-0.080
Travel time to large cities	<0.001	<0.001	-0.061	Soil depth	-0.003	0.001	-0.062
Soil type glaciofluvial deposits	-0.069	0.023	-0.045	Soil type organic materials	0.326	0.121	0.050
Soil suitability for grassland production	0.006	0.002	0.043	Organic carbon content in top soil	-0.009	0.004	-0.047
Land use agriculture mixed with natural vegetation	<0.001	<0.001	0.034	Urban areas	0.196	0.086	0.045
Urban areas	-0.014	0.007	-0.032	Arable land	0.348	0.137	0.040
				Soil suitability for grassland production	-0.047	0.024	-0.036
				Soil type volcanic rocks	-0.436	0.208	-0.033
				Soil type calcareous rocks	0.120	0.071	0.029

An independent validation was carried out for the expert-based approach as the national livestock census data were independent from the EUROFARM statistics used for allocating livestock. To validate the empirical approach the national livestock census data used for validation were also used to identify the location factors for livestock distribution (Figure 2.1). It was therefore not an independent validation but rather a measure of goodness of fit.

To validate the downscaling results, the livestock densities per administrative unit as retrieved from the detailed national livestock census, were compared with the livestock densities resulting from the downscaling procedure (aggregated from 1 km^2 to the same administrative unit). This comparison was done in a correlation analysis. While the EUROFARM statistics used for downscaling were available at NUTS 1/2 level, the validation was done at NUTS 3 level or, if available, at a higher resolution (Table 2.7). Hence, the validation does not address the full resolution of the results but rather addresses the division over administrative units that fall within the units used as base data.

A comparison was made with results of a random distribution model (referred to here as "the reference model"). The reference model allocates livestock to randomly selected grid cells evenly across all available land in order to evaluate if, and how much, more information can be gained by applying a downscaling mechanism instead of a random distribution. For the reference model it was assumed that all locations have the same probability of having livestock kept on them. Comparison with a random model is one of a number of available techniques to validate spatially explicit models (Pontius et al., 2004).

2.3 Results and validation

2.3.1 Results: Spatial livestock distribution

Figure 2.2 shows the results for dairy cattle, beef cattle and pigs resulting from the expert-based approach. For better visualization, the downscaled 1 km^2 resolution data were aggregated to NUTS 3 level which was also used as the spatial resolution for validation. Livestock numbers were translated into Livestock units (LSU) to make them comparable Europe wide. Also the boundaries of the NUTS 1/2 regions from which the livestock statistics were downscaled are shown.

The maps show that dairy cattle are found all over Europe. European hotspots of dairy farming such as Northwest Germany and the Netherlands, Bavaria, Po valley in Italy, Ireland and Brittany are clearly visible. Variations within the NUTS 1/2 region are clearly shown on the downscaled high resolution maps (Figure 2.2, Map 1). Intra-regional differences in dairy cattle farming are, for example, remarkable in Northwest Germany, Bavaria, central UK, Ireland, and wide areas of France. To a large extent this can be explained by the assumption that dairy cattle distribution is linked to a high preference for grasslands. Furthermore, the exclusion of areas that are unsuitable for keeping livestock, such as the wetlands in the Southwest of Ireland or land with a steep slope, causes further differentiation within regions. Beef cattle are also spread over the whole of Europe. Compared to dairy cattle, there are remarkably large livestock concentrations in Scotland/ North England, Ireland, and Central France. Beef cattle farming has a long history in these regions. Results show a broad variability of stocking densities within the respective NUTS 1/2 regions, especially for regions with higher beef cattle densities (Figure 2.2, Map 2). In most parts of Eastern Europe the patterns are different. There are relatively low densities of beef cattle with a fairly homogenous spatial distribution. With the exception of a few regions, sheep farming plays a minor role in Europe. Average stocking densities are often low. However, in regions characterized by sheep farming, such as Scotland, Wales, and Greece, there is clear spatial variation in livestock distribution within the NUTS 1/2 regions (not shown). European hotspots of pig farming are the central and southern part of the Netherlands, North-West Germany, North-East Spain and Brittany. Variations in stocking density within the respective NUTS 1/2 regions can be seen clearly on Figure 2.2 and Map 3. The high density of pigs in the Po valley coincides with the spatial pattern of dairy cattle distribution in this region. The increasing demand for parmesan cheese, which started about 40 years ago, caused an expansion of dairy farming in the region and the whey (a by-product of Parmesan cheese production) was fed to the pigs explaining the coincidence (Bolsius, 1993). In other regions of intensive livestock farming, such as in Finland and Sweden, spatial variations within the NUTS 1/2 regions are also seen. The same is true for poultry farming which has high densities in Eastern Europe, North and Central France, North-East Spain, the Netherlands, parts of UK, Denmark, and in the Po valley (not shown).

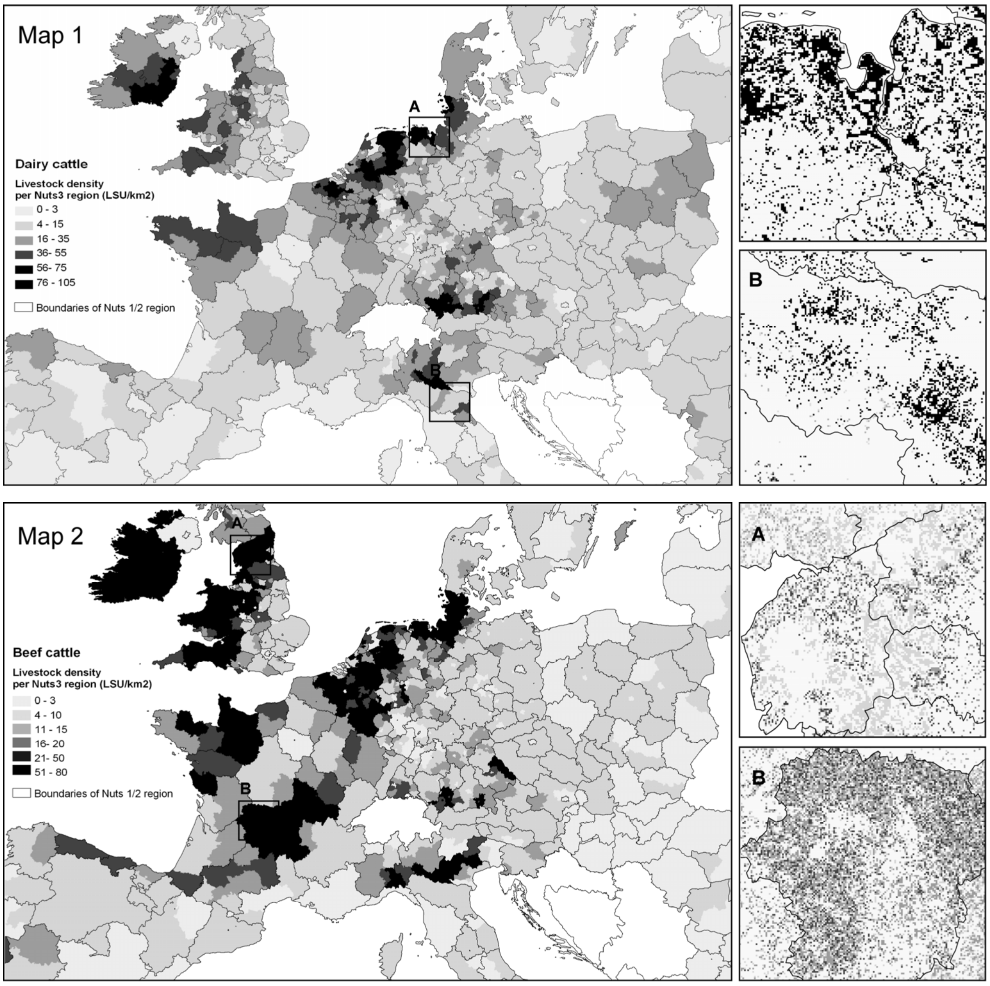

Figure 1.2. Map 1: Downscaling results aggregated to NUTS 3 level for dairy cattle and on a 1 km grid level for selected regions. Map 2: Downscaling results aggregated to NUTS 3 level for beef cattle and on a 1 km grid level for selected regions.

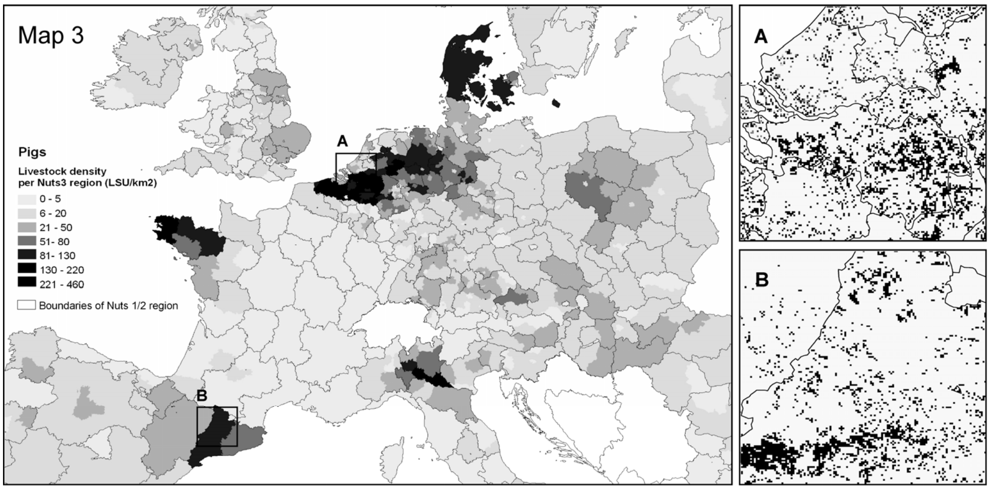

Figure 1.2. Map 3: Downscaling results aggregated to NUTS 3 level for pigs and on a 1 km grid level for selected regions.

2.3.2 Validation of livestock distribution

Herbivores

Results differ remarkably between livestock types and countries (Table 2.7). Overall, good results for herbivores can be achieved with both the expert-based and the empirical approach, particularly for dairy cattle. Comparing the downscaling results with the results of the random distribution model proves that the downscaling assumptions explain part of the variation in livestock distribution, especially for dairy cattle. An exception is Denmark for which the best dairy and beef cattle distribution is modeled by the random distribution model. For Denmark, neither the expert-knowledge approach nor the empirical approach disaggregated data more accurately than the random distribution model. This means that the processes underlying livestock distribution in Denmark were not captured by our approach. Denmark has a rather homogenous land use (mainly arable land) with little variation in altitude. The expert-knowledge approach therefore spreads herbivore distribution evenly across the whole of Denmark negating to capture local characteristics. The empirical approach takes further land-related and climatic factors (such as soil variables) into account. Soil variables have been shown, by local experts, to be an important variable in explaining Danish cattle distribution (pers. comm. Inge Kristensen). Compared to dairy cattle, the distribution of beef cattle is less accurate. This is due to the fact that nowadays distribution of beef cattle is less influenced by biophysical than socio-economic factors, making it more difficult to capture variability with the approaches and spatial data used here. Furthermore, in continental Europe, for example in Germany, beef cattle is also bred for dual purposes, i.e., meat and milk production. This factor has to be taken into account when assessing the different results for dairy cattle and beef cattle.

The situation for sheep is different and the random distribution model gives (in general) better results than the expert-based downscaling approach. Sheep are often kept under harsh conditions in areas with relatively low grassland productivity and steep slopes.

Monogastrics

For monogastrics, especially poultry, in general low levels of correspondence between the allocation results and the national livestock census data are found (Table 2.7). Overall, it can be concluded that the empirical approach is better able to explaining the spatial distribution of monogastrics than the expert-based approach for the following reasons: The expert-based approach assumes the spatial variation of pigs and poultry is based solely on land use information, however, this explains only a small part of their spatial variation. Often their feed is imported from overseas which decouples them from local agricultural production. Furthermore, traditions in farming and historic developments have had a stronger impact on livestock occurrence then biophysical factors. For instance, extremely large populations of pigs and poultry are held on a few farms in Emilia-Romagna (Italy) (FADN, 2003), a result of the traditional markets located in this region (e.g., production of Parma ham).

The occurrence of these extreme populations cannot be explained by environmental conditions but can be related to the historic development of livestock farming and associated infrastructure and market conditions in the region. The challenges involved in downscaling the distribution of monogastrics are noted in a livestock downscaling study produced by the FAO (FAO, 2007).

Table 2.7. Correspondence (r^2) between national census data and livestock maps per administrative unit applying a downscaling procedure (d) and a random distribution model (r).

Country	Spatial detail of EUROFARM data	Spatial detail of national census data	Year of national census data	Dairy cattle		Beef cattle		Total cattle		Sheep		Pigs		Poultry	
Expert-based approach															
				d	*r*	*d*	*r*	*d*	*r*	*d*	*r*	d	r	d	r
Austria*	NUTS 1 (n=3)	NUTS 2 (n=9)	2001-2003**	-	-	-	-	0.86	0.68	0.82	0.85	0.96	0.55	0.96	0.83
Belgium*	NUTS 1 (n=2)	NUTS 3 (n=43)	2002	-	-	-	-	0.71	0.57	0.10	0.20	0.40	0.35	0.29	0.34
Denmark	NUTS 1 (n=1)	NUTS 5 (n-277)	2000	0.47	0.59	0.57	0.63	-	-	0.29	0.05	0.63	0.54	0.05	0.05
Finland	NUTS 2 (n=4)	NUTS 3 (n=20)	2002	0.77	0.10	-	-	0.79	0.10	0.32	0.47	0.81	0.27	0.79	0.33
Germany	NUTS 1 (n=14)	NUTS 3 (n=439)	2001	0.86	0.54	-	-	0.86	0.61	0.42	0.37	0.38	0.38	0.29	0.28
Hungary	NUTS 2 (n=7)	NUTS 3 (n=20)	2003	0.61	0.57	-	-	0.72	0.68	0.73	0.75	0.77	0.73	0.06	0.08
Ireland*	NUTS 2 (n=2)	NUTS 3 (n=7)	2003	-	-	-	-	0.40	0.29	0.33	0.60	0.01	0.46	0.09	0.25
Netherlands	NUTS 1 (n=4)	NUTS 4 (n=488)	2003	0.74	0.47	0.13	0.35	-	-	0.31	0.18	0.25	0.39	0.22	0.28
Portugal*	NUTS 2 (n=5)	NUTS 3 (n=28)	1999	-	-	-	-	0.30	0.33	0.90	0.87	0.04	0.11	0.03	0.08
Romania*	NUTS 2 (n=8)	NUTS 3 (n=42)	2002	-	-	-	-	0.58	0.73	0.34	0	0.46	0.22	0.25	0.27
Spain	NUTS 2 (n=17)	NUTS 3 (n=50)	2001	0.69	0.71			0.49	0.49	0.73	0.85	-	-	-	-
Sweden	NUTS 2 (n=8)	NUTS 3 (n=21)	2003	0.92	0.86	0.92	0.91	-	-	0.67	0.37	0.91	0.83	0.65	0.52
Empirical approach															
Denmark	NUTS 1	NUTS 5	2000	0.54		0.28		-		-		0.56		0.03	
Germany	NUTS 1	NUTS 3	2001	0.74		-		-		-		0.74		0.43	
Netherlands	NUTS 1	NUTS 4	2003	0.81		0.20		-		0.21		0.64		0.14	
Portugal	NUTS 2	NUTS 3	1999	-		-		-		0.87		0.65		0.52	

* Given constraints in data availability evaluation could be done for one aggregated cattle category only

** Statistics from 2001, 2002, and 2003 were used for the evaluation (calculation of average of the three years)

2.4 Discussion and conclusions

2.4.1 Location factors

Knowledge of the spatial distribution of livestock is essential to any assessment of the environmental impact of their production, for example pollution of water by nitrogen leaching and soil erosion caused by overgrazing. Unlike earlier studies (FAO, 2007), the downscaling framework presented here provides a two-way methodology applying both an expert-based and an empirical approach. The results indicate that land-related and climatic factors can, to a certain extent, explain the current spatial livestock distribution in Europe. The results furthermore indicate and quantify the spatial distribution of livestock within the landscape. In general it can be concluded that downscaling livestock data is feasible. However, obtaining good results for all livestock types for the whole of Europe remains a challenge.

Disaggregating coarse scale livestock data is challenging for several reasons. First, the spatial distribution of livestock in Europe is not solely shaped by land-related and climatic factors. Although historically the spatial distribution of livestock has been shaped by biophysical circumstances influencing the agricultural production capacity of the land, the importance of biophysical factors has diminished over time as livestock production has moved towards confined systems. Other considerations have emerged depending on the region and livestock type. Factors such as socio-economic development, demographic changes in farmer population, farming traditions, religions, farm sizes, specialization trends, regional and local politics, policy implementation and subsidies, Protected Designation of Origin (PDO) initiatives, and attractiveness of other sector employment are often even more influential and must not be neglected when attempting to explain the spatial livestock pattern in present day Europe. These very heterogeneous livestock farming location factors, their limited data availability as well as the frequent occurrence of chance events and bottom-up effects make it rather challenging to define European-wide and simplified assumptions as an underlying base for downscaling livestock. Second, comparable and consistent EU-wide data that provides accurate and spatially detailed information able to explain livestock distribution is limited. This means that even if the livestock location factors are correct, it is a challenge to use them in a distribution approach in order to obtain the correct livestock distribution pattern.

2.4.2 Allocation mechanism

The core of the livestock modeling framework is the allocation mechanism. The allocation mechanism is based on several assumptions. Hierarchies between herbivores and between monogastrics probably do exist. The applied hierarchies are based on the overall economical importance of the individual livestock type but the extent to which these hierarchies can be applied to whole of Europe is questionable. Possible hierarchies between herbivores and monogastrics are not considered here for two reasons. Firstly, it is challenging to define (at the European scale) whether herbivores or monogastrics are economically more important. Secondly, herbivores and monogastrics are not expected to compete for the same sources of feed.

The results are strongly determined by the probability maps. In the expert-based approach one probability map was used for all herbivores and one for all monogastrics. Livestock allocation is therefore sensitive to the allocation hierarchies which favor dairy cattle and pigs the most. For dual-purpose cattle farming it may be more appropriate to assign no hierarchies between dairy and beef cattle. However, only a few regions of Europe are characterized by dual-purpose cattle farming which makes such an approach unsuitable to use at the European scale.

Conversely, the empirical approach allows the calculation of probability maps per livestock type. The most suitable areas for livestock allocation differ with livestock type and the chance that several livestock types will compete for the same piece of land is small. Hence, the allocation hierarchy itself has less influence on the spatial livestock allocation than in the expert-based approach. Accounting for full competition between all livestock types within the allocation remains challenging but could be considered if the triggers for competition are known. Those triggers are, for example, policies or other financial stimuli endorsing certain livestock types. In addition, cultural factors such as the history of a region and its farming traditions, can explain the dominance of certain livestock types in specific regions. However, including these factors in the allocation mechanism would require large datasets and a more regional approach.

Other issues arise when peri-urban systems (which are increasing for monogastrics and herbivores) are considered. In peri-urban areas livestock farming is shaped primarily by socio-economic factors such as multifunctional land use and settlement structures. Peri-urban livestock farming was therefore not considered in the livestock allocation mechanism.

2.4.3 Validity of the results

The results show remarkable differences between livestock types, countries, and approaches. Although in some cases correspondence values for herbivores differ notably between the expert-based and the empirical approach, no judgment can be made on which approach is more valid. Both approaches seem to miss relevant location factors for herbivores. Socio-economic location factors as discussed above probably explain a significant part of current herbivore distribution. This fact was not captured by either approach, probably due to the fact that spatially explicit information on such factors is not available. While both the expert-based and the empirical approach confirm the common perception that cattle is primarily found on high productive agricultural land, this assumption holds only partly true for sheep. Hence, the assumptions made to describe the probability of herbivore occurrence used in the expert-based approach, which were based on assumptions for cattle, only partly describe conditions for sheep. Although sheep farming is strongly related to the land, sheep can be kept under harsh conditions characterized by unfavorable steep slopes and low productivity semi-natural areas.

Despite the low levels of correspondence for both downscaling approaches when applied to monogastrics, both approaches give better results than a random distribution for pigs for almost all countries. This leads to the conclusion that pig farming and the pig populations are, to a certain extent, coupled with the land. Our initial assumption that pigs are located on agricultural land can therefore be partially confirmed. The random distribution model often leads to equally accurate or even more accurate poultry maps than the expert-knowledge approach. This supports the observation that the European-wide suitability rules used here have only a limited value when applied to poultry farming. Identifying location factors for poultry is demanding and for disaggregating poultry data it is recommended that an empirical approach is used, if possible including socio-economic aspects. Overall, it can be concluded that both the expert-based and the empirical approach are equally suited to modeling herbivores, particularly dairy cattle. The spatial distribution of monogastrics can be better modeled by applying the empirical approach.

2.4.4 Relevance of the approach

The exploration of location factors of livestock makes a valuable contribution to the understanding of Europe's present day spatial livestock distribution. In the case of herbivores, the location factors identified here can be used as basis for environmental impact assessment and may, for example, be considered as proxies for diverse risks associated with livestock production, such as environmental loads or the likelihood of livestock disease outbreak and transmission to humans. Such risk proxies may be used as criteria in decision making processes for shaping strategies and gearing investments for risk mitigation.

Improvement of livestock distribution information to a level that is meaningful for environmental assessments and integrated modeling approaches of land change could, until now, only be reached by using detailed national data (if available). However, this leads to inconsistent data use, complicating a consistent EU-wide assessment of the impacts of farming on the environment on the one hand and hampering modeling of land systems on the other. It can therefore be concluded that there is an urgent need to collect European-wide data at a higher spatial and thematic resolutions. Greening the CAP cannot be accomplished in Europe by changes in policy alone but should rather be accompanied by improved statistical data collection and monitoring systems which take account of the wider regional diversity in farming systems and the environment.

Understanding factors and processes that determine spatial livestock distribution are of crucial importance to the exploration of the dynamics of livestock distribution in the future. This study makes a contribution to our future understanding. Based on the location factors identified here, in combination with appropriate scenarios, simulating spatial-temporal dynamics of European livestock farming becomes more feasible.

Chapter 3

Multi-scale scenarios of spatial-temporal dynamics in the European livestock sector

The European livestock sector has changed rapidly in the recent past and further changes are expected in the near future due to reforms in the European Common Agricultural Policy (CAP), increasing environmental concerns and changing consumer awareness. To explore possible environmental impacts due to changes in livestock density a robust understanding of the detailed spatial dimensions of livestock farming and their dynamics is required. We developed a multi-scale modeling approach for exploring spatial and temporal dynamics of livestock distribution by accounting for drivers at different spatial scales. Assessment of change in both quantity and location was made for six livestock types for four contrasting scenarios. The national level livestock numbers were calculated by a macro-economic model. These livestock numbers were spatially distributed at the landscape scale according to the scenario assumptions. Results indicate for most of the old European Union (EU) member countries a decrease in livestock numbers. In the new EU member countries sheep, goats, and pigs are expected to decline while beef cattle and poultry are expected to grow. Livestock densities are expected to increase both within and outside current livestock hotspot regions in absence of environmental legislations. Environmental pressure as result of high livestock densities may, however, also remain in regulated scenarios where environmental policies are implemented and income support remains stable over time due to path dependencies in the livestock sector. But contrary to the non-regulated scenario it is less likely that new areas with high risk of negative environmental impacts will develop.

Based on: Neumann, K., Verburg, P.H., Elbersen, B., Stehfest, E. and Woltjer, G.B.: Multi-scale scenarios of spatial-temporal dynamics in the European livestock sector. – Agriculture, Ecosystems & Environment (under review).

3.1 Introduction

Over the past 20-30 years European livestock farming and the spatial distribution of livestock across Europe has been largely shaped by far-reaching reforms of the European Common Agricultural Policy (CAP), animal diseases, increasing environmental concerns and changed consumer awareness (Hasha, 2002; Hermansen, 2003; EC, 2004; EC, 2006). These issues are still influencing the livestock sector and are anticipated to be trend-setting for the near future. The European livestock sector is expected to remain dynamic in the forthcoming years (EC, 2009).

Changes in the livestock systems go together with changes in their spatial distribution. Livestock distribution is driven by several processes operating at multiple scales, such as changes in (global) markets and trade, regional variations in land suitability, production conditions and technology as well as local environmental constraints and both agricultural and environmental policies. Shaped by these processes European livestock distribution is very heterogeneous, being characterized by regional concentrations which potentially conflict with environmental targets such as those set under the Nitrates and Water Framework Directives. The impact of different livestock types on the environment has been explored at several scales and especially its impact on the nitrogen cycle is judged as one of the most critical issues threatening the functioning of the earth system (Rockström et al., 2009). Steinfeld et al. (2006) provide an environmental impact assessment of livestock at the global scale. The authors discuss the environmental challenges of livestock farming, evaluate its environmental burden, and discuss potential policy options for alleviating these. At the European scale, Halberg et al. (2005) discuss a number of assessment tools for determining the environmental impact of various livestock types. Oenema et al. (2007) have studied nutrient losses from manure management for the EU-27 and have concluded large differences between European Union (EU) member countries. However, the spatial resolution of the study is limited to regions (NUTS 2; Nomenclature of Territorial Units for Statistics (NUTS)). At the regional to local scales several authors have studied a broad range of environmental concerns related to livestock farming in Europe (Hooda et al., 2000; Nielsen and Kristensen, 2005). In addition to these environmental impact assessments, numerous studies have also been published studying the impacts of policy scenarios on ammonia emissions, nitrogen leaching and runoff from animal production systems (Berntsen et al., 2003; Oenema, 2004; Gömann et al., 2005; van Groenigen et al., 2008). These studies are, however, either very data-intensive which restricts their applicability to single farms and relatively small regions, or they use a simplified aggregated approach to permit a

European-wide application. But since many environmental impacts depend on the location, the accuracy of such aggregated assessments is low by definition.

To explore possible environmental impacts of livestock farming across Europe but also to be able to make ex-ante assessments of environmental policies, a robust understanding of spatial dimensions of livestock farming and their spatial dynamics is required. Current EU-wide livestock density data only provide information on livestock types and numbers at administrative level (e.g., NUTS 2). To deal with the limitations of such aggregated data the Food and Agricultural Organization of the United Nations (FAO) has downscaled livestock types to a 3 arc-minute resolution using empirical analysis (FAO, 2007). However, the spatial patterns obtained were not validated. At the European scale, Elbersen et al. (2006) and Neumann et al. (2009; Chapter 2) have disaggregated farm types and livestock types, respectively, from NUTS 1/2 level to higher resolution raster data (1 km). Neumann et al. (2009; Chapter 2) showed that such downscaling was successful for cattle and sheep but especially difficult for poultry. Such downscaling approaches are only valid for the current situation and do not allow for an assessment of future changes in spatial livestock pattern in response to policies and other conditions. Only a few attempts were made to simulate spatial changes in future livestock distribution. At the global scale, Bouwman et al. (2005) have modeled spatial dynamics of both pastoral and mixed livestock systems based on FAO projections till 2030. Spatial livestock distributions are strongly linked to the presence of grassland and feed requirements while socio-economic aspects were not taken into account. Biophysical land characteristics and feed requirements were also considered by Koch et al. (2008) to assess impact of grazing on land use dynamics in the Jordan River region. For China, Verburg et al. (1999) linked a land cover change model with a livestock module to investigate near-future changes on the livestock distributions. Dalgaard et al. (2002) have modeled agricultural activity for different Danish (livestock) farm types to explore consequences of the Agenda 2000 reform. These authors have applied the agricultural model ESMERALDA to simulate changes in agricultural activities, such as livestock farming, for estimating changes in manure-N. While the methodology clearly illustrates the impact of the CAP, other factors influencing the spatial distribution of livestock, such as environmental legislations, demand for livestock products and changes in biophysical conditions were beyond the scope of the study. The mentioned studies illustrate the limited number of efforts made to simulate spatial-temporal dynamics of livestock farming. Their strength lies on exploring some specific aspects of changes in livestock farming, however, interactive processes at the global, international and local scale are disregarded. The limited availability of research approaches for livestock systems contrasts with the wide availability of land cover change models (Verburg et al., 2009).

In this chapter we present a novel multi-scale modeling approach for simulating spatial and temporal dynamics of livestock distribution. The aim of the study was to explore changes in the European livestock sector by integrating a broad range of processes related to livestock farming while accounting for drivers at different spatial scales. Both quantity and spatial distribution of six different livestock types was simulated over the 2000-2030 period for the entire extent of the EU for four contrasting scenarios.

3.2 Livestock in Europe – status quo and recent developments

The importance of livestock farming in Europe strongly varies between regions and livestock types (Neumann et al., 2009; Chapter 2). In many European countries beef and dairy cattle are the most important livestock types in terms of numbers and economic value (FAOSTAT, 2009a). Together, Germany, France and the UK account for almost half of all European cattle and are also leader in EU dairy production. According to Arendonk and Liinamo (2003) more than 80% of the EU dairy farming systems account for intensive farming systems, characterized by relatively large average herd size, specialized dairy farms, young average herd age and high stocking rates. These intensive systems are mainly found in the Netherlands, England, parts of Scotland, Western France, Northern Italy, Sweden, Finland, Northern Spain, Denmark, and Germany (Arendonk and Liinamo, 2003). However, dairy and beef cattle numbers have fallen significantly over the last twenty years throughout much of Europe, mainly due to implementation of the CAP reform and a change in consumption due to animal diseases, namely Bovine Spongioform Encephalapathy (BSE).

Past development of pig farming shows high spatial diversity. Some of the main pork producers, such as France, Spain and Denmark, have experienced a steady increase of production over the past 30 years. Germany and Poland that also contribute to the lion share of European pork production showed a rather unsteady development over the past years, mainly as result of the economic collapse after 1990 (EC, 2004; FAOSTAT, 2009a). Highest pig concentrations nowadays can be found in North Rhine-Westphalia, Jutland, South-East Netherlands, and Brittany (Eurostat, 2009). Contrarily to the European beef and dairy cattle sector the pig sector has been more market-oriented since years as the EU has offered only limited market support to pig producers. The CAP reforms therefore had less impact on the pig sector (EC, 2004).

Poultry numbers have significantly increased in Western Europe and Poland over the past fifteen years mainly as a consequence of diet shifts from red meat towards white meat. Large concentrations of poultry farming are found in the Netherlands and parts of Denmark, France, Germany, Italy, and the UK (EC, 2004; FAOSTAT, 2009a).

Sheep farming is of relatively small importance for the overall European economy. However, it has an important impact on land use in a number of regions. Some 74% of the European sheep are kept in the UK, Spain, Greece, France, and Italy (FAOSTAT, 2009a). Within these key countries, the population has declined since the 1990s in the UK, France, and Italy but is quite stable in Spain and Greece. Compared to other European agricultural sectors income levels in the sheep sector are one of the lowest while facing rising commodity prices. This process can explain most of the decrease together with the recent occurrence of the Blue Tongue disease in major producing regions (EC, 2009).

Goats play a marginal role in the European livestock sector accounting for 1% of the total European livestock only (EC, 2004). Approximately 40% of all European goats are kept in Greece, followed by Spain (22%) and France (9%) (FAOSTAT, 2009a). Table 3.1 gives an overview of the recent developments of livestock numbers for the EU-27.

In the near future the European livestock sector is expected to be further influenced by the CAP reform. EU ministers of agriculture adopted a fundamental reform in June 2003 which entailed the introduction of a system of decoupled payments per farm (Single Farm Payment (SFP)), meaning that subsidy payments were no longer linked to volume of production (EC, 2009). Moreover, a cross-compliance instrument was introduced to accompany this system making the payments conditional on all

Table 3.1. Changes of livestock numbers per livestock type and decade between 1970 and 2000 expressed in percent for the EU-27 (excluding Estonia, Latvia and Lithuania) (FAOSTAT, 2009).

Livestock type	1970 - 1980	1981 - 1990	1991-2000
Cattle	10	-6	-19
Sheep	4	12	-20
Goats	-4	34	0
Pigs	37	6	-8
Poultry	24	5	1

statutory management requirements (SMR) in the field of environmental, animal welfare and public health requirements as well as standards of good environmental and agricultural condition (GEAC). This new policy has been implemented in the old EU member countries since the 1st of January 2006. Especially regions that are characterized by high livestock densities are anticipated to show a decrease in livestock number within the coming years. Whether this decrease will also take place in the new member countries where the SFP system has also gradually been introduced as from 2008 has to be awaited (Ciaian and Swinnen, 2006). The starting situation is generally different as most of these countries have shown an enormous decline in livestock numbers after the communist system collapsed. It is still to be seen whether the recovery to the pre-1990s level of livestock numbers will be stronger than the influence of the introduced SFP system. The development within Eastern Europe is very diverse. A rather successful development can be documented in Poland and Hungary: both countries have regained their former positions as net meat exporters. Agricultural development in other countries, such as in Romania, is lacking behind because of incomplete reforms that led to a fracturing of production into either very small, mainly subsistence units or large, quasi-state-owned enterprises (Bjornlund et al., 2002).

However, European livestock farming, namely high density farming, is not only shaped by agricultural policies but also by environmental legislations, such as the Nitrates Directive. The Nitrates Directive delineates Nitrate Vulnerable Zones (NVZs) aiming to reduce water pollution from nitrogen compounds, which are largely produced by livestock. NVZs are regions with a high risk for nitrogen leaching and the Nitrates Directive requires legally binding rules to reduce nitrogen losses from agriculture to the environment (EC, 1991). There is also an increased consumer awareness of food safety and animal welfare issues. This awareness was mainly stimulated by outbreaks of several animal diseases during the 1990s and early 2000s which abruptly disrupted the long-term trends in the EU livestock sectors. These diseases had strong impact on livestock numbers in the South of the UK (BSE), the UK, Ireland, France and the Netherlands (foot-and-mouth disease (FMD)), and Germany, the Netherlands and Spain (swine fever). As a result of these developments the organic farming sector was documented to show a large growth resulting for some countries in a market share of up to 9% for some major product groups (Hermansen, 2003; Hovi et al., 2003; Borell and Sorensen, 2004).

3.3 Exploration of future livestock distribution

3.3.1 The multi-scale modeling framework

Understanding land use and land cover change processes requires an integrated approach accounting for socio-economic and biophysical driving forces (Turner II et al., 1995; Lambin et al., 2001). Many case studies were conducted to gain understanding of the complex interactions between human and natural systems (Lambin et al., 2003; Mottet et al., 2006; Overmars and Verburg, 2006). An integrated approach also requires integration of different spatial scales at which land use change drivers act. Its importance for modeling land use changes has been emphasized by several authors (Veldkamp et al., 2001a; Jantz and Goetz, 2005; Verburg et al., 2008). These studies have indicated that land use is the result of several processes operating at different spatial scales. Yet, the influence of each of these processes on land use differs between scales. Therefore, processes often do not behave linearly across different scales which makes their aggregation difficult (Easterling, 1997). Simply applying knowledge about land use driving processes from one scale to another scale results in wrong conclusions about the land use system. Observations of land use can often only explain a part of the entire multi-scale land use system as the observations depend on extent and resolution of their measurements. From this understanding we can conclude that land use change models should account for the hierarchical structure of land use change drivers and be based on observations valid at the scale of analysis.

Based on these considerations we developed a multi-scale modeling framework to simulate spatial and temporal dynamics of livestock in Europe considering biophysical, human, and political driving factors. The modeling framework therefore combines a set of models operating at multiple scales, each tackling specific drivers and processes that affect land use and livestock distribution at the scale of analysis. Figure 3.1 gives an overview of the modeling framework.

3.3.2 Models

Changes in livestock numbers at national level were determined by a modeling procedure that links the Global Trade Analysis Project Model (GTAP) (Hertel, 1997) to the Integrated Model to Assess the Global Environment (IMAGE) (Meijl et al., 2006). By using this model framework the demand for agricultural land as well as

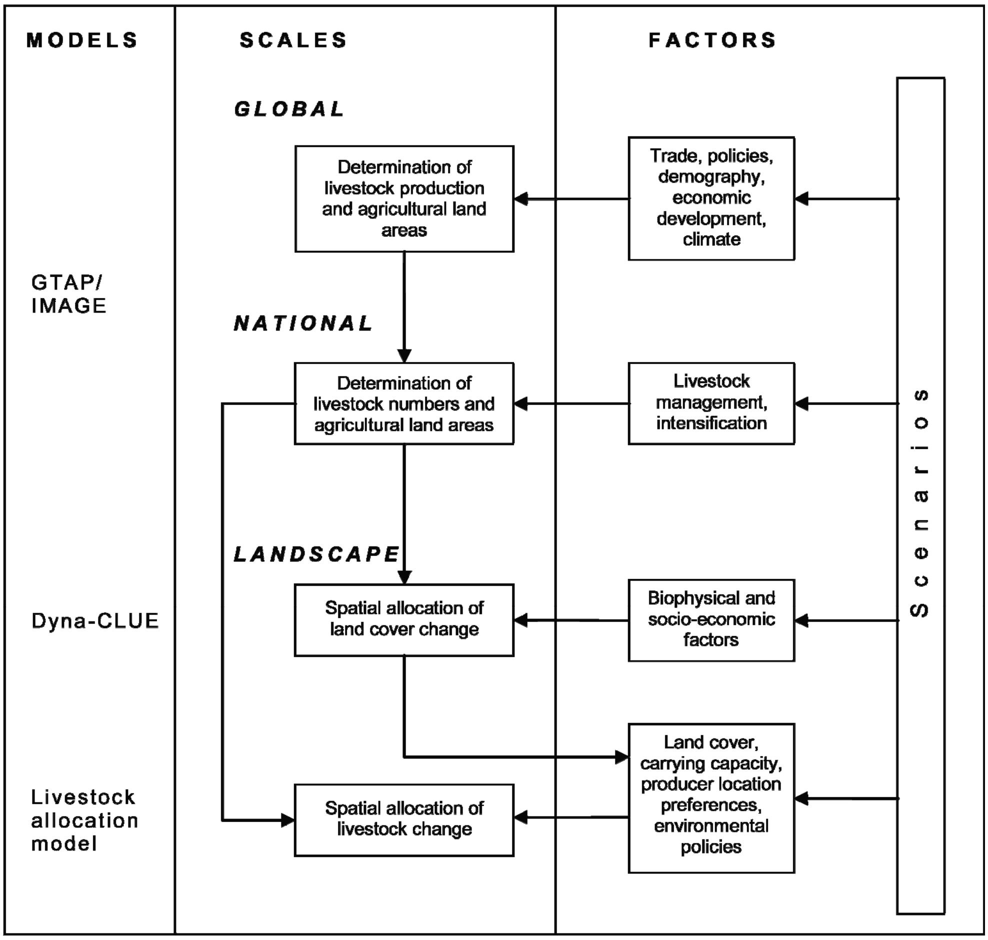

Figure 3.1. Multi-scale modeling framework for livestock distribution.

livestock numbers were calculated for each country of the EU-27 for 2010, 2020 and 2030. GTAP is a general equilibrium model with (for this study) a spatial resolution of world-regions outside Europe and countries within Europe. The model uses regional and national level input–output tables to explicitly link industries in a value added chain from primary goods to the final assembling of goods and services for consumption. Changes in production, consumption and trade of agricultural commodities are calculated based on change in consumer demand, technological change, land supply, market prices, international trade regulations, and policies that aim at influencing international trade flows and local production conditions. GTAP is based on the assumption that land is heterogeneous between countries. Since the model assumes that imports and domestic commodities are imperfect substitutes in demand a special function (Armington) is used to describe the substitution possibilities between these goods. In this way the bilateral livestock commodity trade is modeled (Meijl et al., 2006).

Livestock production is used by IMAGE to specify the livestock numbers. IMAGE is a global ecological-environmental model to explore environmental long-term consequences of human activities. IMAGE simulates land cover changes and greenhouse gas emissions on the basis of regional production of food, livestock products, timber as well as local climatic and terrain properties (Alcamo et al., 1998; MNP, 2006). IMAGE calculates how many animals are needed to meet the livestock production and how much feed they require. Given specific diet assumptions in IMAGE specified per world-region, i.e., how much grass and how much crops are needed by the livestock, the area of grassland was determined. In this way the calculation of livestock numbers is in line with the calculation of land area demand (Bouwman et al., 2005; Meijl et al., 2006). Consumption and trade are primarily driving livestock production per country, where both depend on population, GDP per capita and agricultural policy.

At the landscape scale we used the Dyna-CLUE model to spatially allocate these changes in land area for the 2000-2030 period (Verburg and Overmars, 2009). Dyna-CLUE simulates land cover changes using empirically quantified relations between land cover and its underlying driving factors in combination with dynamic modeling. Land cover types are allocated at a spatial resolution of 1 km^2 for the entire EU with a yearly resolution. Agricultural land cover types distinguish rainfed arable land, irrigated arable land, permanent crops and permanent grassland.

3.3.3 Livestock allocation model

We developed a spatial allocation model to simulate possible changes in spatial distribution of livestock in Europe. The model assumes that livestock distributions are steered by the initial spatial livestock pattern, carrying capacities, and producer location preferences. The carrying capacity is, in this study, the maximum number of animals that can be found at a certain location. The carrying capacity is determined by the capability of the location to provide fodder, to cope with manure, and by the environmental legislations. In general, locations with sufficient fodder production and limited environmental restrictions have higher carrying capacities. Producer location preferences delineate regions for livestock farming as favored by livestock producers under a certain scenario. Producer location preferences were defined to indicate the preferences for livestock allocation consistent with the overall scenario storylines. The allocation of livestock to a 1 km^2 grid is done per country using livestock units. This translation of livestock numbers into livestock units was necessary as the carrying capacity of the location defines the total amount of livestock that could be sustained rather than distinguishing between different livestock types. We furthermore considered competition for the same land resources between different herbivore types and between monogastrics.

The livestock allocation model is a stepwise procedure (Figure 3.2). Upon changes in carrying capacity, for example as result of the implementation of new environmental policies, a correction is made proportional to the initial livestock numbers for all locations where the current livestock density exceeded this capacity. Based on the decrease in animal numbers, due to a decrease of carrying capacity, the national change in livestock numbers as calculated with GTAP/IMAGE was corrected. The grid cell-specific producer location preferences indicate locations where changes in livestock density are likely. In case a livestock type is growing, i.e., its numbers are increasing, the extra animals are allocated at locations with the highest producer location preferences. In turn, if a livestock type is characterized by a decrease the livestock density will first decrease at the least preferred locations before livestock densities also drop at the locations with higher preferences for livestock production. The amount of change in livestock density at the location is determined by the initial density of herbivores or monogastrics, the carrying capacity and the competitive strength of each livestock type. The competitive strength is the relative change in livestock numbers per livestock type; therefore, it is an indicator for the competition between livestock types. The competitive strength of a particular livestock type determines the hierarchy of livestock type allocation. First, decreases in livestock numbers are allocated for the livestock type with the largest decrease at the national level. These changes are accounted for in further steps since land resources may have become available. Increases are allocated starting with the livestock type with the strongest growth. Due to the different dynamics of livestock types we enable competition between them. The temporal dynamics in livestock type numbers together with changes in availability of land resources due to changes in livestock density, allow for shifts in dominant livestock types. This way we simulate a gradual change of one livestock type to less preferred areas due to strongly increasing numbers of another livestock type competing for the same land resources. Figure 3.3 illustrates the mechanism for livestock density changes for two exemplary livestock types for four different cases.

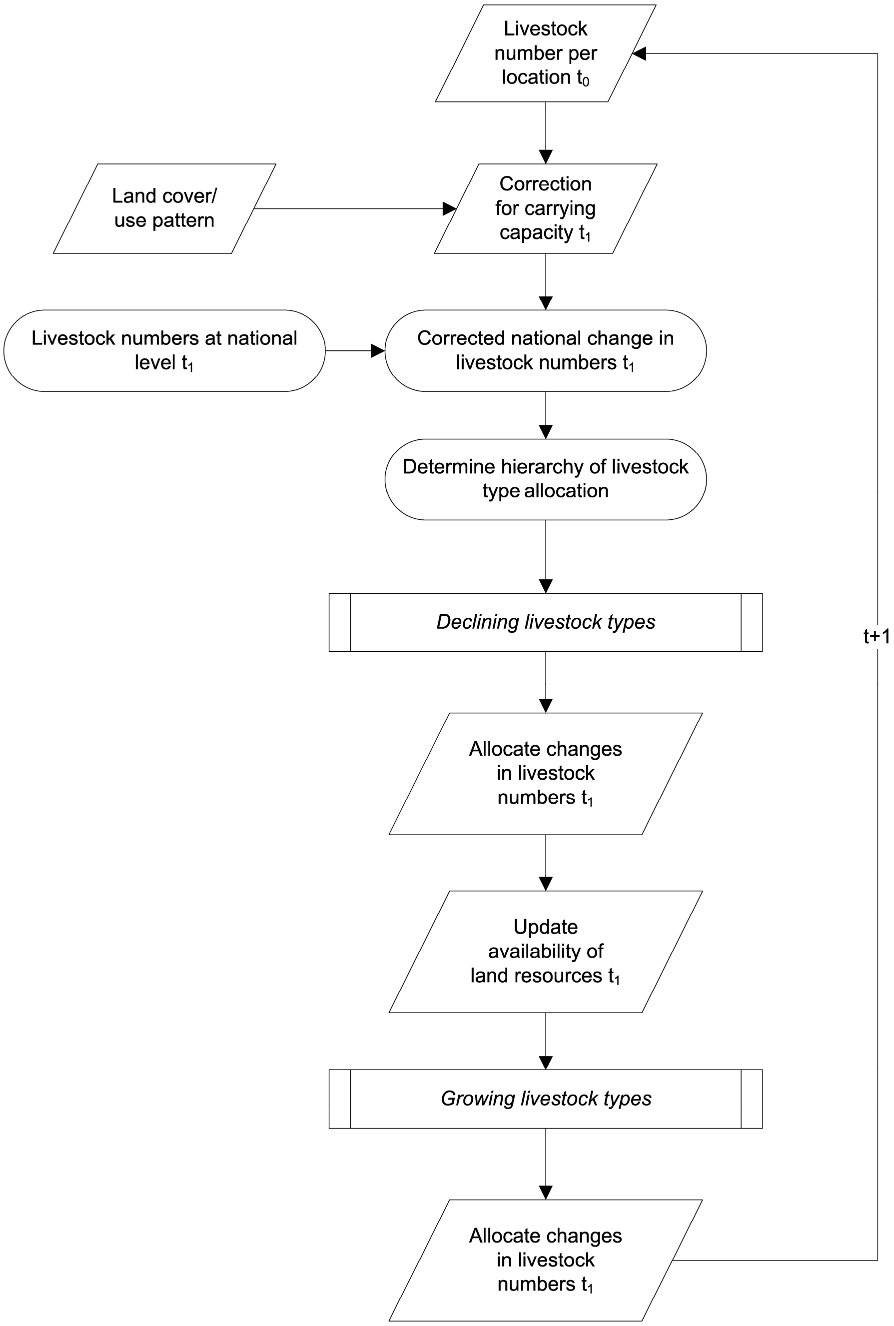

Figure 3.2. The livestock allocation model.

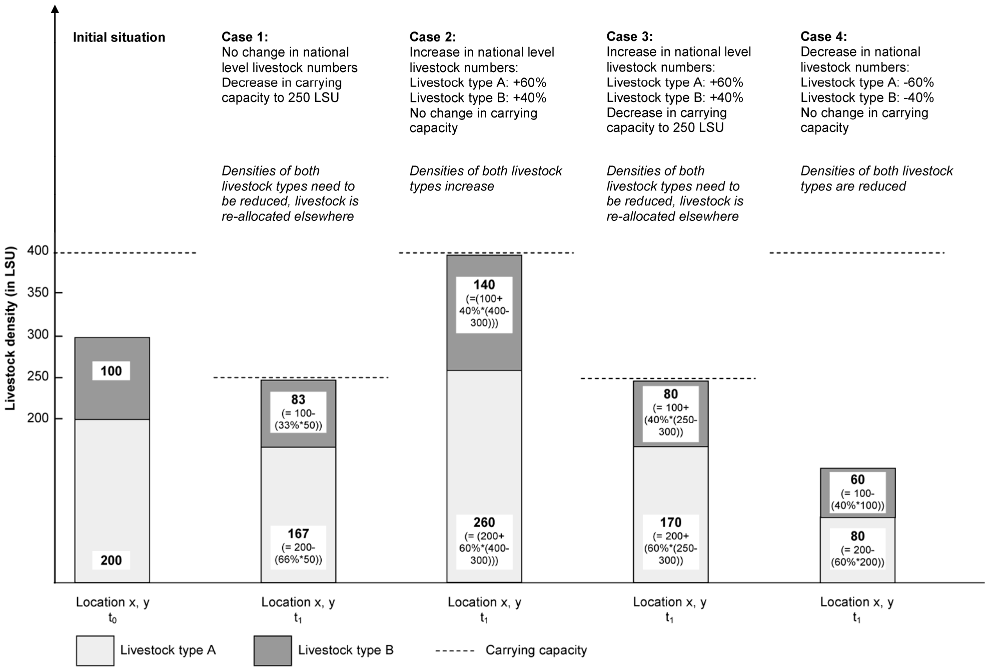

Figure 3.3. Mechanism of local livestock density changes for two exemplary livestock types for four different cases.

3.3.4 Model implementation

For the simulation of changes in the livestock distribution we considered the initial spatial livestock pattern to account for path dependencies in the livestock farming sector. We used the livestock maps for dairy cattle, beef cattle, sheep, goats, pigs, and poultry as produced and validated by Neumann et al. (2009; Chapter 2). These maps show livestock densities at 1 km^2 grid level for the situation around the year 2000 covering the entire EU-27. In this study we classified dairy cattle, beef cattle, sheep, and goats as herbivores and pigs and poultry were classified as monogastrics. This classification was carried out because the spatial distribution of herbivores and monogastrics is driven by different factors. Herbivores were assumed to obtain a large part of their feed requirements from the farmland where they are grazing or by receiving hay and forage from the surrounding land, while being in the stable. Contrarily, we assume all monogastrics are kept in housing systems receiving concentrates which are not necessarily locally produced but often partly or fully imported from outside the region (Neumann et al., 2009; Chapter 2). Herbivores can therefore be assumed to be more dependent on local land resources than monogastrics. The first can be referred to as land-dependent and the latter as land-less livestock. Herbivores and monogastrics were allocated separately since we did not consider a direct competition between both.

Producer location preferences are assumed for both herbivores and monogastrics for each scenario based on a selection and weight of location factors that were chosen according to the scenario storylines (Table 3.4). An important location factor is the initial livestock density. Overall, we assume a higher producer location preference for regions with an initial high livestock density because these regions have established infrastructure, manufacturing industry, economies of scale, and well-skilled labor. Presence of large scale grassland areas is considerably attractive for herbivores since we expect these to derive most of their feed requirements from the local region. Continuous grassland areas were therefore assigned to have a higher location preference. Monogastrics primarily depend on fodder production and are therefore assigned a higher location preference for continuous production areas of maize, soy and other fodder products. To import fodder and transport products the accessibility to markets plays a crucial role. Higher producer preferences for monogastrics were therefore assigned close to towns and harbors. To account for chance events in location decisions the producer location preferences were randomly modified to represent the local variations in conditions and the arbitrariness in some of the decisions. Such a perturbation leads to a more realistic spatial distribution pattern. We considered producer location preferences as being static over time.

We assumed that future livestock densities are to be constrained by the carrying capacity. The carrying capacity is quantified scenario-specific for both herbivores and monogastrics (Table 3.3). The carrying capacity strongly depends on landscape characteristics such as land cover type and its change. Herbivores are assumed to be fed from arable land, grassland, semi-natural vegetation, recently abandoned arable land and grassland as well as heather and moorlands. Monogastrics can be fed from arable land, grassland and permanent cropland. A change of land cover may also cause a change in the carrying capacity. For example, if grassland is abandoned and converts into urbane areas the carrying capacity for livestock drops to zero as we assume urban areas is not capable to fulfill feed requirements for the considered livestock types. In this way we allowed to dynamically change the carrying capacity as result of changes in land cover. Environmental legislations, for example, the Nitrates Directive with the delineation of NVZs may further impact the carrying capacity of the location. For all regions outside the NVZs differences in slope and other environmental features, such as climate and geomorphology, captured in the environmental typology of Metzger et al. (2006) were considered to stratify the carrying capacity. Table 3.2 gives an overview of all data used for the model implementation. These drivers were modeled for four contrasting scenarios which are further elaborated in the following section (3.3.5 Scenarios).

Changes in spatial distribution of livestock were simulated at grid level (1 km) and account for differences in carrying capacities, changes in land cover, pressure on land resources, producer location preferences as well as spatial policies aimed at reducing negative environmental impacts.

Table 3.2. Data sources for defining carrying capacities and producer location preferences.

Variable	Description	Source
Carrying capacity		
Land cover	17 discrete land cover classes	Derived from simplified CORINE Land Cover 2000 (http://dataservice.eea.eu.int.)
Environmental zones	Stratification of Europe into 13 zones based on environmental conditions	(Metzger et al., 2006)
Slope	Categorization into no slope (0-6%), little slope (> 6-12%), medium slope (> 12-24%) and steep slope (> 24%)	Derived from 1000m DEM from SRTM3 data
Nitrate Vulnerable Zones (NVZ)	Spatial delineation of NVZ where N input is legally bound to not exceed 170 kg N per hectare and year	(JRC, 2006)
Livestock excretion rates	Nitrogen excretion for European livestock in kg N per livestock type per year	(Van der Hoek, 1998)
Producer location preferences		
Density of dairy cattle, beef cattle, sheep, goats, pigs and poultry in 2000	Density per livestock type in livestock units (LSU) per km^2	(Neumann et al., 2009; Chapter 2)
Potential grassland productivity	Categorization into high, medium and low productive grassland	MARS database (Boogaard et al., 2002; Micale and Genovese, 2004)
Large scale grassland areas	Large continuous grassland areas with at least 40% grassland within a radius of 8km	Derived from simplified CORINE Land Cover 2000 (http://dataservice.eea.eu.int.)
Large scale fodder production areas	Large continuous fodder (maize, soya and other fodder on arable land) areas with at least 40% fodder within a radius of 8km	Derived from Capri-Dynaspat (http://www.agp.uni-bonn.de/agpo/rsrch/dynaspat/dynaspat_e.htm)
Travel time to cities	Travel time to towns with more than 100.000 inhabitants which are accessible within 3.600 seconds	Accessibility analysis based on GISCO database infrastructure (Verburg et al., 2006)
Travel time to harbors	Travel time to harbors with freight of at least 15.000 kton per year which are accessible within 5.000 seconds	Accessibility analysis based on GISCO database infrastructure (Verburg et al., 2006)

3.3.5 Scenarios

In order to deal with uncertainties of future developments of societal, demographic and political dimensions, four contrasting scenarios were analyzed. These scenarios are based on EURURALIS scenarios which are an EU elaboration of the IPCC SRES scenarios (Westhoek et al., 2006). The first axis distinguishes the scenario ranges from globalization to regionalization. The second axis represents the dominant steering philosophy, ranging from a world with low regulation levels and dominance of market forces to a world with a higher degree of governmental regulation. In that way four scenarios were applied which are called Global economy (A1), Global co-operation (B1), Continental markets (A2), and Regional communities (B2). The generated livestock scenarios elaborated these overall scenarios in terms of expected development of the livestock sector and livestock related policies and attitudes. For this we distinguish between a regulated and non-regulated world by applying low carrying capacities in the first and high carrying capacities in the latter (Table 3.3). The different levels of carrying capacity illustrate the implementation of environmental legislations, such as the NVZ, in a regulated world. Applying different carrying capacities has a direct impact on the spatial dynamics of livestock distribution. The distinction between a globalized and regionalized world is based on different producer location preferences. In a globalized world we have assigned high preferences for large scale resources while we assume stronger preferences on regional livestock production systems in a regionalized world.

The A1 scenario implies a globalized world without strong environmental concerns or restrictions. Strict environmental legislations, such as the Water Framework or Nitrates Directives, are not implemented. Agricultural policies, such as market support, income support and the less favored areas (LFA) support are abolished and due to structural changes in agriculture there is a trend towards allocating agricultural land in areas with relatively high potential productivity (Verburg et al., 2006 ; Eickhout and Prins, 2008). Consumer awareness of food safety as well as animal health and welfare were not considered to be very important. Elimination of almost all trade barriers implies intensive livestock farming. We assume that a considerable share of feed is provided from other regions and manure can be transported over long distances. The A2 scenario describes another world without strong environmental regulations. Both the A2 scenario and the A1 scenario assume high carrying capacities and therefore suppose further concentration of livestock in areas with initially high densities given the monetary efficiency of such systems (Table 3.3). Opposed to the

Table 3.3. Carrying capacities for different scenarios.

	A1 + A2 scenario	B1 + B2 scenario	
	Carrying capacity	Carrying capacity inside NVZ[1)]	Carrying capacity outside NVZ
Herbivores			
Arable land	Maximum observed herbivore density on arable land per environmental zone and slope class in 2000[2)]	190 LSU/km^2 limitation on sloping grounds[3)]	50% of the maximum observed herbivore density on arable land per environmental zone and slope class in 2000
Grassland	Maximum observed herbivore density on grassland per environmental zone and slope class in 2000[2)]	190 LSU/km^2 Derogations (in LSU/km^2) apply for Austria (260), The Netherlands (280), Germany (260), Ireland (280), and Denmark (260) limitation on sloping grounds[3)]	50% of the maximum observed herbivore density on grassland per environmental zone and slope class in 2000
Semi-natural vegetation, recently abandoned arable land and grassland and heather and moorlands	Maximum observed herbivore density on semi-natural vegetation per environmental zone and slope class in 2000[2)]	50% of the observed maximum density on semi-natural vegetation per environmental zone and slope class in 2000 limitation on sloping grounds[3)]	50% of the maximum observed herbivore density on semi-natural vegetation per environmental zone and slope class in 2000
All other land cover types	0 LSU/km^2	0 LSU/km^2	0 LSU/km^2
Monogastrics			
Arable land, grassland, permanent crops	Maximum observed monogastric density on arable land, grassland and permanent crops per environmental zone and slope class in 2000[2)]	450 LSU/km^2 limitation on sloping grounds[3)]	25% of the maximum observed monogastric density on arable land and grassland per environmental zone and slope class in 2000
All other land cover types	0 LSU/km^2	0 LSU/km^2	0 LSU/km^2

[1)] We assume nitrogen excretions from herbivores are directly emitted to the environment while excretions from monogastrics are partly captured (e.g. with biogas installations). We therefore allow monogastrics exceeding the 170kg N per ha for 25%. These assumptions together with livestock type specific excretion rates (Van der Hoek, 1998), slope and livestock conversion factors (FAO, 2009b) result in the presented carrying capacities.

[2)] Europe was stratified into thirteen homogenous environmental zones (Metzger et al., 2006) considering four different slope classes. For each of the resulting fifty-two zones we identified the maximum density of herbivores and monogastrics per land cover type as observed in Neumann et al. (2009; Chapter 2). This maximum livestock density was defined as the land cover type specific carrying capacity.

[3)] Steep slope (>24%): 50% reduction of LSU, intermediate slope (>12-24%): 25% reduction of LSU, slight slope (>6-12%): 5% reduction of LSU (after (Velthof et al., 2007)).

A1 scenario the A2 scenario, however, emphasizes regional production systems and resources by different location producer preferences.

The B1 scenario and the B2 scenario are characterized by extensive production systems, stagnating technology, and stronger governmental regulations which are also reflected in high environmental standards characterized by an implementation of environmental policies, particularly the Nitrates Directive with the NVZs. This European directive allows a maximum amount of 170 kg nitrogen per hectare per year applicable with livestock manure within the NVZs (EC, 1991). Carrying capacities within the NVZs are determined according to this restriction. Carrying capacities are also kept relatively low outside the NVZ in order to allow livestock stocking densities to be in line with animal welfare considerations. The major difference between the B1 scenario and the B2 scenario is their market orientation. In the B1 scenario the level of CAP subsidies and trade barriers are expected to be gradually reduced (Eickhout and Prins, 2008). Hence, the distance to trading centers for livestock fodder becomes more important represented by the producer location preferences (Table 3.4). Contrarily, in the B2 scenario, as well as in the A2 scenario, we assume a high preference for local and regional products. Agricultural markets are protected against competing products to avoid cheap imports and many mature European industries are protected from outside competition through trade barriers. LFA support is sustained to stimulate maintenance of arable agriculture and managed grasslands in these areas.

Table 3.4. Location factors and their weights used for determining scenario specific producer location preferences.

Location factors	A1 + B1 scenario	A2 + B2 scenario
Herbivores		
Density of dairy cattle, beef cattle, sheep and goats in 2000	large	very large
Large scale grassland	large	none
Potential grassland productivity	large	large
Chance events (random value)	very small	very small
Monogastrics		
Density of pigs and poultry in 2000	small	very large
Large scale fodder production	small	very small
Travel time to cities	large	small
Travel time to harbors	large	none
Chance events (random value)	very small	very small

3.4 Results

3.4.1 Development of livestock numbers

Scenario-specific livestock numbers for 2010, 2020, and 2030 were calculated with GTAP/IMAGE. Overall, all four scenarios state similar trends in livestock numbers with often remarkable differences between old and new EU member countries. In most of the EU-15 member countries[1] almost all livestock decreases with a strong decline for herbivores and a smaller decline or even an increase for monogastrics. For the EU-12 member countries[2] sheep, goats, and pigs are expected to decline while numbers for beef cattle and poultry are expected to grow. For all scenarios beef cattle is projected to become the most dynamic livestock type within both the EU-15 and EU-12, although with an opposing trend. Table 3.5 shows the expected changes in livestock numbers for the EU-15, EU-12, and EU-27 for the four scenarios.

Table 3.5. Expected changes in livestock numbers (in percent) between 2000 and 2030 for four scenarios.

	A1			A2			B1			B2		
	EU-15	EU-12	EU-27	EU-15	EU-12	EU-27	EU-15	EU-12	EU-27	EU-15	EU-12	EU-27
Dairy cattle	-4.3	17.1	3.7	-10.1	-2.8	-7.4	1.4	8.1	3.9	-8.1	-5.1	-7.0
Beef cattle	-29.7	38.6	-4.1	-21.6	35.3	-0.3	-45.0	16.2	-22.1	-35.7	8.7	-19.1
Sheep	-20.1	1.1	-12.2	-10.2	-0.9	-6.7	-37.8	-15.3	-29.3	-26.4	-20.6	-24.2
Goats	-17.1	1.1	-10.3	-8.7	-0.9	-5.8	-32.4	-15.3	-26.0	-22.7	-20.6	-21.9
Pigs	-1.9	-2.8	-2.3	8.7	-1.6	4.9	-6.7	-8.3	-7.3	0.5	-10.6	-3.7
Poultry	-5.9	12.1	0.8	4.1	13.9	7.7	-10.6	6.0	-4.4	-4.0	3.6	-1.2

In the A1 scenario the old EU member countries are expected to experience a decrease of all livestock types. The projected decline can mainly be traced back to far-reaching reforms of the CAP, primarily with respect to market support such as reduction of coupled payments. The expected decline is the most drastic for beef cattle as this sector has obtained most of the recent CAP support compared to all other livestock types. Livestock production, namely beef and poultry, are expected to move to countries

[1] The EU-15 comprises the 15 member countries of the European Union before the expansion in 2004.

[2] The EU-12 comprises the 12 member countries that joined the European Union in 2004.

with lower production costs, such as Brazil (beef) and the new EU member countries (beef and poultry). Furthermore, CAP market price and income support, although phased out by 2020, initially trigger more livestock production in the new EU member countries due to newly obtained access to these support instruments in 2004.

The A2 scenario indicates for the EU-15 a moderate decrease of all herbivores. This continuation of the recent trends can be explained by the constant market and income support which is assumed in the A2 scenario. The same instruments may mitigate the consequences of the economic collapse of the Eastern European countries after 1990. For the new EU member countries only a slight decline in livestock numbers is projected. The projected increase of beef and poultry in the new EU member countries can, similar as in other scenarios, partly be traced back to lower commodity prices as compared to the EU-15 (Fuller et al., 2000).

In the B1 scenario the abolishment of market and income support explains part of the strong decreases of livestock numbers in the EU-15. Moreover, an expected decrease of meat consumption of 10% reinforces the downtrend, which is remarkably severe for red meat. The liberalization of the (agricultural) markets moves the new EU member countries in an advantageous situation due to lower production prices than in the old EU member countries. However, also in the EU-12 a decrease of meat consumption of 10% is expected which offset these production advantages to some extent.

In the B2 scenario an overall decline of livestock numbers is expected. The assumed population decrease, low macro-economic growth as well as a diet change towards 10% less meat explains a good portion of this development. The continuation of export subsidies and import tariffs as well as the preference for local products may slow down this trend but cannot compensate for it.

3.4.2 Spatial distribution of livestock

Figure 3.4 presents total livestock densities at HARM[3] level indicating large differences across Europe. Overall, it can be seen that the major livestock distribution patterns remain similar in all four scenarios. Remote regions with disadvantageous livestock farming conditions and initially low livestock densities, such as large areas of Sweden, Finland, Central and Southern Italy, North-Eastern France but also regions in Southern France remain of lower importance for livestock farming compared to other European regions. In contrast, the main hotspots of livestock farming such as Brittany, the Po-valley, the Netherlands, and Belgium are expected to persist in all four scenarios. The relatively steady pattern at the HARM level is not surprising as many driving forces do not necessarily cause a change in livestock over administrative regions but rather at the local scale to which the effect of the most important socio-economic and biophysical driving forces is assumed to be linked, for example local land cover changes due to demographic developments. However, if we zoom to a higher spatial resolution for livestock farming regions, both hotspots of livestock farming and regions with less intensive livestock farming, we see more dynamics. Regions show clear differences between the four scenarios. A detailed analysis of the results can therefore only be made at landscape level by looking at each livestock type separately.

In the globally oriented A1 and B1 scenarios most increase in livestock numbers is found through intensification in regions with large scale grassland and fodder areas. Locations being easily accessible from harbors for importing feed but also towns for processing industry and consumers are preferred new locations for intensive livestock production of monogastrics. The lower carrying capacities in the B1 scenario cause, however, in some regions a spread of livestock. Figure 3.5 shows such concentration and spread tendencies as a result of the interplay of changes in livestock numbers, land cover change, location preferences, and carrying capacities. This is illustrated by the example of sheep farming in Portugal. The concentration effects in the global scenarios appear stronger in the B1 scenario than in the A1 scenario, mainly as a result

[3] HARM regions are harmonized administrative units integrating NUTS regions at different hierarchical levels (NUTS 1, 2, and 3).

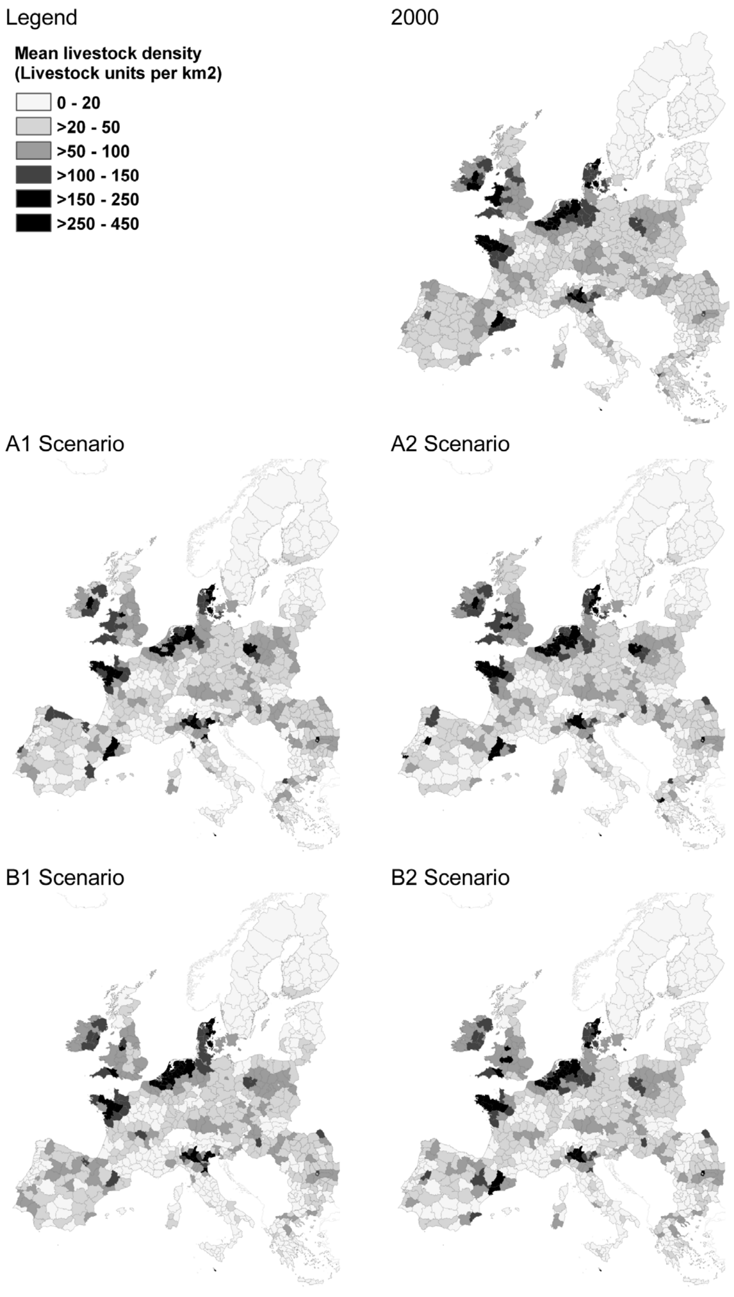

Figure 3.4. Mean livestock density at HARM level in 2000 and 2030 for the four scenarios.

of the tremendous decrease of livestock numbers in the B1 scenario for entire Portugal (-39%). Regions with marginal sheep farming, such as the Algarve, tend to become even less important. Contrarily, regions with high attractiveness for global markets and high sheep densities in 2000, such as the Central-Eastern part of Portugal, are characterized by a larger spread of sheep due to the lower carrying capacities. The largest spread can be seen in the B2 scenario. But considering the strong decrease in sheep numbers (-27%) emptying tendencies in marginal sheep farming areas are expected to occur simultaneously.

In the B1 and B2 scenarios spread from the most densely populated regions towards regions with high development potential is seen. This effect is strongest in the NVZs where policy measures are assumed to have drastically limited the maximum stocking rates. Furthermore, animal welfare considerations and preference for less intensive systems lead to more spread of livestock throughout regions (in large countries) or even throughout entire countries (in small countries). Figure 3.6 illustrates the impact of the implemented NVZs for two European hotspots of livestock: pigs in Brittany and dairy cattle in the Netherlands. The enforced decline of maximum stocking rates in the NVZs according to the policy restrictions causes a spread of livestock within the designated areas. The example of Brittany shows that pig densities have to be reduced up to 80% at some locations if the strict Nitrate Directive restrictions are applied in the NVZs. Such drastic decreases are exceptional for some hotspot regions. Remarkable for Dutch dairy cattle is that even with an expected decreasing number of animals (-8% between 2000 and 2030 in the B2 scenario) new dairy cattle farming will develop in the neighborhood of already established dairy cattle farming. Hence, an expected overall decrease does not necessarily prohibit the growth of new livestock farming locations. Results of the A1 scenario show for both examples a trend towards livestock concentration. One reason is the high maximum stocking densities which endorse local livestock density growth. Furthermore, the simulated slight decrease of pigs (-0.4% between 2000 and 2030) and dairy cattle (-2.3% between 2000 and 2030) in France and the Netherlands, respectively, is expected to affect the marginal livestock areas. Especially small scale livestock farming in regions outside the major livestock farming regions with limited fodder resources and disadvantageous market distance are expected to disappear. The agglomeration of new pig farming in the surrounding of Nantes as shown in Figure 3.6 has been stimulated by an projected increase in pig production in France between 2000 and 2010 (+0.5%) combined with strong producer location preferences for towns with strong market influence.

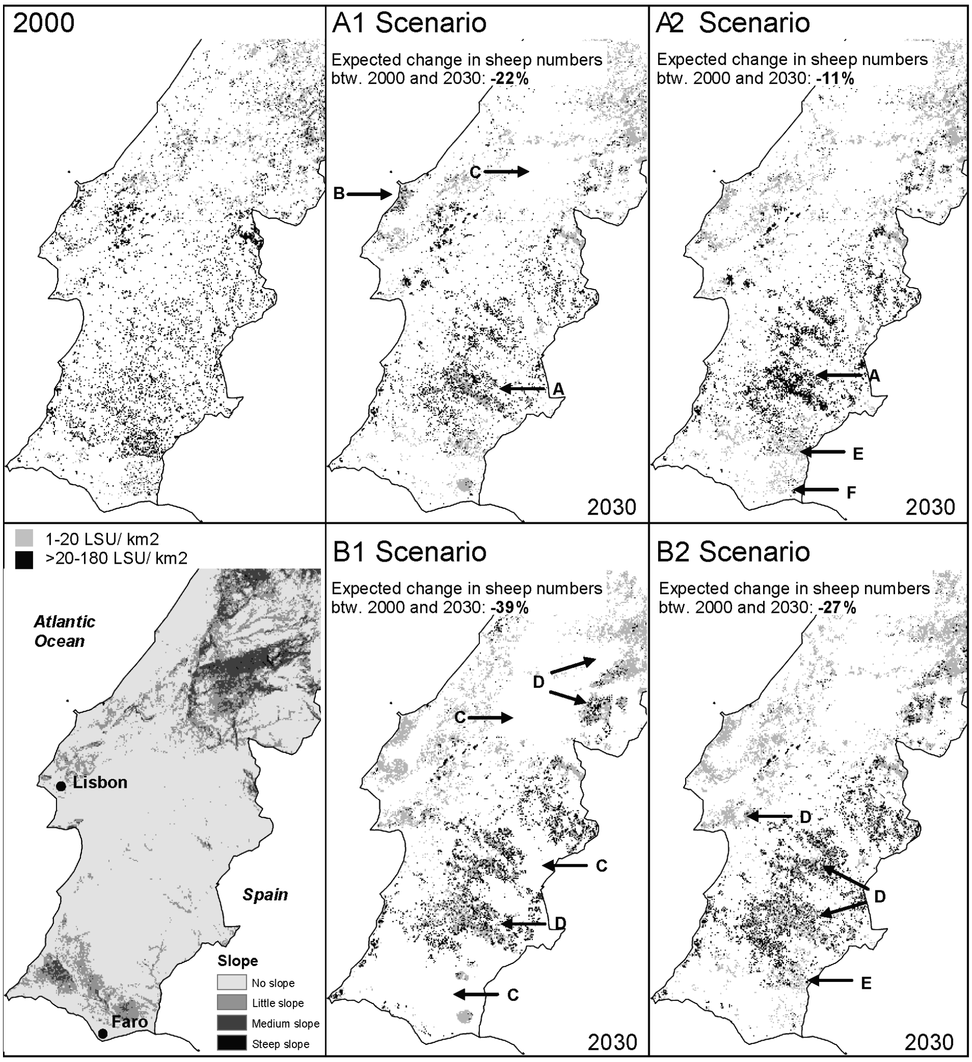

Figure 3.5. Comparison of scenario results for development of sheep in Portugal. A) Concentrations in highly productive grassland areas, B) Concentrations in large-scale grassland areas, C) Decline in marginal livestock keeping areas with low producer preferences, D) Spread due to decreased carrying capacity, E) Livestock persist in regions with an initial high density, F) Sheep remains spread outside the major livestock regions.

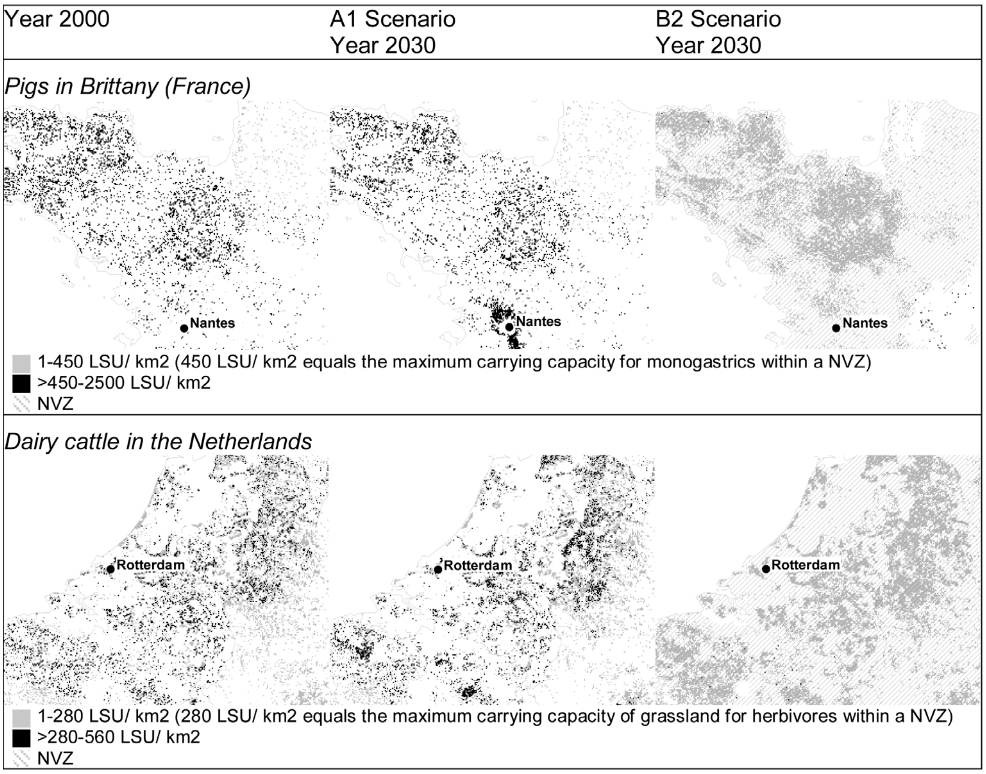

Figure 3.6. Simulated changes of pig farming in France and dairy cattle farming in the Netherlands in the non-regulated A1 scenario and the regulated B2 scenario.

A comparison of the results with the year 2000 situation shows that without implementation of environmental legislations and an ongoing income and market support at the current level (A2 scenario) livestock densities are expected to increase in current livestock hotspots such as South Brittany, South West England, and North-Rhine Westphalia. But also outside the current centers of livestock farming, namely in some regions of Poland, the Baltic republics, Hungary, Slovenia, and Romania an increasing livestock density compared to the current situation is expected. Hence, environmental pressure does not only continue in current livestock hotspot regions but may also emerge in regions that are not yet faced with those risks. However, environmental pressure of livestock farming may also remain in regulated scenarios where environmental policies are implemented (B1 and B2 scenario). Though, in the regulated scenarios the livestock densities in most livestock hotspot regions are restricted according to the requirements of the Nitrates Directive, they remain high compared to other regions. This observation can largely be traced back to the path dependency of livestock farming. Contrarily to the A2 scenario an expansion or origin of new risk areas is, however, less likely to occur in the regulated scenarios. The smaller likelihood is due to the low carrying capacities (B1 and B2 scenario) and the preference for small scale regional livestock production areas (B2 scenario).

3.5 Discussion

3.5.1 Validity of methodology

The presented modeling framework illustrates how different modeling approaches can be consistently linked across spatial scales to simulate the future spatial-temporal dynamics in the European livestock sector. The strength of the framework lies in its integrative setup of linking simulations at different spatial scales with the corresponding driving factors and processes. While such an approach was already applied successfully to land cover change analysis (Verburg et al., 2008), actual land use and management have so far been ignored. The approach presented indicates that it is possible to make scenario analyses for livestock densities, which is an important aspect of land management and characterizes different land use systems. However, some discussion points regarding the validity of the approach remain.

Firstly, data availability for calibration and validation of the model is constrained by the limited possibilities to observe livestock at a high spatial resolution, as it is done via remote sensing techniques for land cover data (Pontius et al., 2008). Due to the absence of spatial data the model could not be validated. Given the complexity of the European livestock sector as well as the limited data availability on present livestock distribution and on biophysical and socio-economic conditions influencing livestock dynamics, we had to rely partly on expert knowledge and scenario assumptions. Herbivores and monogastrics are allocated independently from each other since we assume that both livestock categories do not compete for the same fodder sources and that manure is managed differently so that no interactions of constraints occur. This holds true for the majority of European livestock farming. Yet, for some regions farming of a particular livestock type has evolved from another livestock type such as in the Po valley where pig farming emerged from dairy cattle farming (Bolsius, 1993). In such cases it becomes desirable to account for full competition between all livestock types. However, those cases are rather exceptional while accounting for full competition across entire Europe remains challenging due to the need for additional assumptions (concerning socio-economic development, demographic changes in farmer population, traditions, religions, farm sizes, specialization trends, regional and local politics, etc.). Including such factors is not possible at the European scale.

Secondly, a related issue arises with the producer location preferences which were identified for herbivores and monogastrics and applied to the whole of Europe. Producer location preferences may be determined for individual livestock types per country given the different requirements of different livestock types. However, Neumann et al. (2009; Chapter 2) have shown that identifying country and livestock-specific location factors is difficult since livestock location factors are only to some extent related to land and environmental constraints. We, therefore, decided to apply a more generalized approach as presented in this study.

Thirdly, simple model assumption had to be applied for the allocation mechanism. Within the presented modeling framework we prohibit exceeding the specified carrying capacities. These carrying capacities may sometimes exceed a sustainable use of resources, for example due to overgrazing. The carrying capacities are therefore not necessarily reflecting the environmental constraints but rather the maximum livestock capacity accepted under the scenario conditions.

Finally, it should be emphasized that the simulation results cannot be validated with real data since they refer to a future situation which is still unknown. The simulations should therefore be seen as plausible and alternative futures which are needed as a basis for exploring the possible environmental impacts of changes in livestock patterns driven by alternative policies and market developments. Plausibility of the results therefore depends on the consistency and transparency of the approach and methodology, the plausibility of assumptions, and the use and quality of input data.

3.5.2 Scenarios

Uncertainties of the future can only be explored to a limited extent with the commonly used baseline scenario approach. We therefore applied four contrasting reference scenarios whereby every scenario illustrates a coherent and consistent development of the livestock sector between 2000 and 2030. Exogenous drivers differ between the scenarios as well as the implementation of agricultural and environmental policies. Policies that we considered are CAP support, LFA support and the Nitrates Directive with the implementation of NVZs. While the first two were used to determine the livestock numbers at country level the NVZs were considered when spatially allocating the animal numbers within each country. In this way we could capture economic and environmental constraints in a quantitative and qualitative manner. Spatial environmental policies have a macro-level effect through the price effects of these constraints. This feedback was, however, not considered in the macro-level simulations. The incorporation of spatial feedbacks in aggregated, macro-level models would require a further integration of the different models applied in this study. Besides the positive effects of such a further integration all encompassing models run the risk of unmanageable complexity.

We believe having considered the policies with the most influence on the European livestock sector. A number of other policies, which are not considered here, may have an effect on the livestock sector as well. For example, High Nature Value Farmland (HNV) areas may be considered for sustaining low-intensive livestock farming. However, further work is required for completing and refining the HNV datasets and a political debate on the development of possible HNV support measures is still ongoing (Paracchini et al., 2008).

3.6 Conclusions

Our study presents a novel multi-scale modeling framework to explore detailed spatial and temporal dynamics of different livestock types. The approach requires the application of a range of complex models. More simple approaches would not have sufficed because the European livestock farming sector is very dynamic. This dynamic can primarily be traced back to recent changes in the European economy, politics, and consumer behavior. Elaboration of spatial and temporal changes in livestock distribution requests a thorough understanding of these dynamics, including socio-economical, political, and biophysical conditions as well as traditions, but also the ability to translate these factors into a net change. Livestock farming systems strongly differ across Europe in terms of their level of intensity, degree of mechanization, type of management, labor intensity, farm size, and other parameters. These heterogeneous livestock characteristics make it a challenge to define valid European-wide but simplified assumptions as underlying base of the modeling framework. Capturing this diversity in livestock farming at the landscape level is, however, crucial for a proper environmental impact assessment. Comparable and consistent data that provides (spatially) detailed information on the present European livestock sector are hardly available. Such data limitations pose an extra challenge for modeling the complexities and dynamics of European livestock in the future. Given these considerations and constraints the presented methodology illustrates how an integrated modeling approach can be used to elaborate dynamics in temporal and spatial livestock distribution. The projected livestock pattern can be used for both environmental impact assessment and an evaluation of agricultural and environmental policies. Results may furthermore be used as proxies for livestock production related risks such as livestock disease outbreaks.

Chapter 4

The yield gap of global grain production: A spatial analysis

Global grain production has increased dramatically during the past 50 years, mainly as a consequence of intensified land management and introduction of new technologies. For the future, a strong increase in grain demand is expected, which may be fulfilled by further agricultural intensification rather than expansion of agricultural area. Little is known, however, about the global potential for intensification and its constraints. In the presented study, we analyze to what extent the available spatially explicit global biophysical and land management-related data are able to explain the yield gap of global grain production. We combined an econometric approach with spatial analysis to explore the maximum attainable yield, yield gap, and efficiencies of wheat, maize, and rice production. Results show that the actual grain yield in some regions is already approximating its maximum possible yields while other regions show large yield gaps and therefore tentative larger potential for intensification. Differences in grain production efficiencies are significantly correlated with irrigation, accessibility, market influence, agricultural labor, and slope. Results of regional analysis show, however, that the individual contribution of these factors to explaining production efficiencies strongly varies between world-regions.

Based on: Neumann, K., Verburg, P.H., Stehfest, E. and Müller, C. (2010): The yield gap of global grain production: A spatial analysis. – Agricultural Systems, vol. 103, 316–326.

4.1 Introduction

Human diets strongly rely on wheat *(Triticum aestivum* L.*)*, maize *(Zea mays* L.*)*, and rice *(Oryza sativa* L.*)*. Their production has increased dramatically during the past 50 years, partly due to area extension and new varieties but mainly as a consequence of intensified land management and introduction of new technologies (Cassman, 1999; Wood et al., 2000; FAO, 2002b; Foley et al., 2005). For the future, a continuous strong increase in the demand for agricultural products is expected (Rosegrant and Cline, 2003). It is highly unlikely that this increasing demand will be satisfied by area expansion because productive land is scarce and also increasingly demanded by non-agricultural uses (Rosegrant et al., 2001; DeFries et al., 2004). The role of agricultural intensification as key to increasing actual crop yields and food supply has been discussed in several studies (Ruttan, 2002; Tilman et al., 2002; Barbier, 2003; Keys and McConnell, 2005). However, in many regions, increases in grain yields have been declining (Cassman, 1999; Rosegrant and Cline, 2003; Trostle, 2008). Inefficient management of agricultural land may cause deviations of actual from potential crop yields: the yield gap. At the global scale little information is available on the spatial distribution of agricultural yield gaps and the potential for agricultural intensification. There are three main reasons for this lack of information.

First of all, little consistent information of the drivers of agricultural intensification is available at the global scale. Keys and McConnell (2005) have analyzed 91 published studies of intensification of agriculture in the tropics to identify factors important for agricultural intensification. They emphasize that a plentitude of factors drive changes in agricultural systems. The relative contribution of them varies greatly between regions. This problem was confirmed by a number of studies that have investigated grain yields, and tried to identify factors that either support or hamper grain production at different scales (Kaufmann and Snell, 1997; Timsina and Connor, 2001; FAO, 2002b; Reidsma et al., 2007). These studies also indicate that most of these factors are locally or regionally specific, which makes it difficult to derive a generalized set of factors that apply to all countries. A second reason for the absence of reliable information on the global yield gap is the limited availability of consistent data at the global scale. Especially land management data are lacking. When it comes to quantifying potential changes in crop yields often only biophysical factors, such as climate are considered while constraints for increasing actual crop yields are often neglected or captured by a simple management factor that is supposed to include all factors that cause a deviation from potential yields (Alcamo et al., 1998; Harris and Kennedy, 1999; Ewert et al., 2005; Long et al., 2006). Finally, lack of data also leads to another difficulty. Many yield gap analyses have in common that they apply crop models for simulating potential crop yields which are compared to actual yields (Casanova et al., 1999; Rockstroem and Falkenmark, 2000; van Ittersum et al., 2003). Potential yields, however, are a concept describing crop yields in absence of any limitations. This concept requires assumptions on crop varieties and cropping periods. While such information is easily attainable at the field scale it is not available at the global scale. Moreover, different simplifications of crop growth processes exist between the models. This may result in uncertainties of globally simulated potential yields, and makes an appropriate model calibration essential for global applications. Comparing simulated global crop yields to actual yields therefore bears the risk of dealing with error ranges and uncertainties of different data sources (i.e., observations and simulation results) which might even outrange the yield gap itself. Consequently, available knowledge about the yield gap is rather inconsistent and regional and global levels of agricultural production have hardly been studied together.

The aim of this chapter is to overcome some of the mentioned shortcomings by analyzing actual yields of wheat, maize, and rice production at both the regional and global scale accounting for biophysical and land management-related factors. We propose a methodology to explain the spatial variation of the potential for intensification and identifying the nature of the constraints for further intensification. We estimated a stochastic frontier production function to calculate global datasets of maximum attainable grain yields, yield gaps, and efficiencies of grain production at a spatial resolution of 5 arc-minute (approximately 9.2 x 9.2 km on the equator). Applying a stochastic frontier production function facilitates estimating the yield gap based on the actual grain yield data only, instead of using actual and potential grain yield data from different sources. Therefore, the method allows for a robust and consistent analysis of the yield gap. The factors determining the yield gap are quantified at both the global and regional scale.

4.2 Methodology

4.2.1 The stochastic frontier production function

Stochastic frontier production functions originate from economics where they were developed for calculating efficiencies of firms (Aigner et al., 1977; Meeusen and Broeck, 1977). Since agricultural farms are a special form of economic units this econometric methodology can also be used to calculate farm efficiencies and efficiencies of agricultural production in particular. In our global analysis, the agricultural production within one grid cell (5 arc-minute resolution) is considered as one uniform economic unit. The stochastic frontier production function represents the maximum attainable output for a given set of inputs. Hence, it describes the relationship between inputs and outputs. The frontier production function is thus “a regression that is fit with the recognition of the theoretical constraint that all actual productions lie below it” (Pesaran and Schmidt, 1999). In case of agricultural production the frontier function represents the highest observed yield for the specified inputs. Inefficiency of production causes the actual observations to lie below the frontier production function. The stochastic frontier accounts for statistical noise caused by data errors, data uncertainties, and incomplete specification of functions. Hence, observed deviations from the frontier production function are not necessarily caused by the inefficiency alone but may also be caused by statistical noise (Coelli et al., 2005).

The frontier production function to be estimated is a Cobb-Douglas function as proposed by Coelli et al. (2005). Cobb-Douglas functions are extensively used in agricultural production studies to explain returns to scale (Bravo-Ureta and Pinheiro, 1993; Bravo-Ureta and Evenson, 1994; Battese and Coelli, 1995; Reidsma et al., 2009a). If the output increases by the same proportional change in input then returns to scale are constant. If output increases by less than the proportional change in input the returns decrease. The main advantage of Cobb-Douglas functions is that returns to scale can be increasing, decreasing or constant, depending of the sum of its exponent terms. In agricultural production decreasing returns to scale are common. The Cobb-Douglas function is specified as following:

$$\ln(q_i) = \beta_I x_i + v_i - u_i \qquad \text{Equation 4.1}$$

where $\ln(q_i)$ is the logarithm of the production of the i-th grid cell (i = 1, 2,…,N), x_i is a (1 × k) vector of the logarithm of the production inputs associated with the i-th grid cell, β is a (k × 1) vector of unknown parameters to be estimated and v_i is a random (i.e., stochastic) error to account for statistical noise. Statistical noise is an inherit property of the data used in our study resulting from reporting errors and inconsistencies in reporting systems. The error can be positive or negative with a mean zero. The non-negative variable u_i represents inefficiency effects of production and is independent of v_i. Figure 4.1 illustrates the frontier production function.

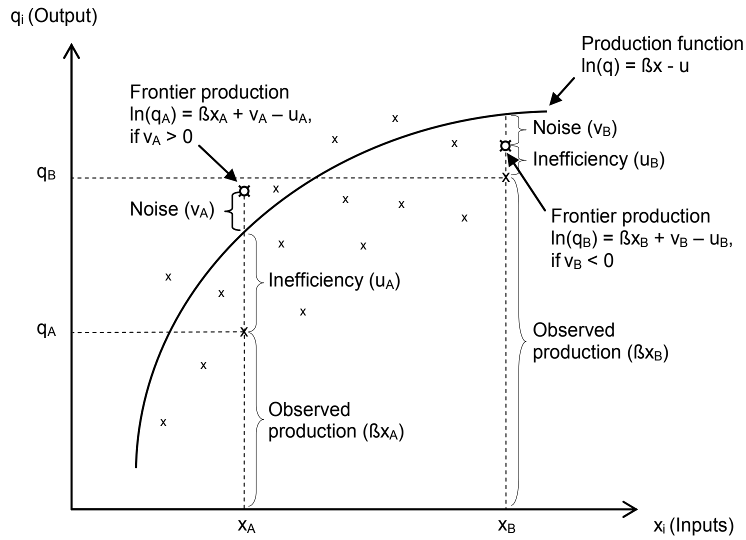

Figure 4.1: The stochastic Production Frontier (after Coelli et al., 2005). Observed productions are indicated with x while frontier productions are indicated with ¤. The frontier function is based on the highest observed outputs under the inputs accounting for random noise *(v_i)*. Further deviations of the observations are due to inefficiencies *(u_i)*. The frontier production *(q_i)* can lie above or below the frontier production function, depending on the noise effect *(v_i)*.

Stochastic frontier analyses are widely used for calculating efficiencies of firms and production systems. The most common measure of efficiency is the ratio of the observed output to the corresponding frontier output (Coelli et al., 2005):

$$E_i = \frac{q_i}{\exp(x'_i\, \beta + v_i)} = \frac{\exp(x'_i\, \beta + v_i - u_i)}{\exp(x'_i\, \beta + v_i)} = \exp(-u_i) \qquad \textbf{Equation 4.2}$$

where E_i is the efficiency in the *i*-th grid cell. The efficiency is an index without a unit of measurement. The observed output at the *i*-th grid cell is represented by q_i while $x'_i\beta$ is the frontier output. The efficiency E_i determines the output of the *i*-th grid cell relative to the output that could be produced if production would be fully efficient given the same input and production conditions. The efficiency ranges between zero (no efficiency) and one (fully efficient).

Kudaligama and Yanagida (2000) applied stochastic frontier production functions to study inter-country agricultural yield differences at the global scale. However, that study disregards spatial variability within countries, which can be very large. To our knowledge, our study presents the first application of a stochastic frontier function to grid cell-specific crop yield data at the global scale. At the national and regional scale a number of authors have applied frontier production functions to calculate both efficiencies of grain productions and frontier grain productions (Battese, 1992; Battese and Broca, 1997; Tian and Wan, 2000; Verburg et al., 2000). Each of these studies contribute significantly to the understanding of variation in grain yields and agricultural production efficiencies. However, most of these studies lack a comprehensive analysis and discussion of the spatial variations of the yield gap and production efficiencies within the region considered.

4.2.2 Global level estimation of frontier yields and efficiencies

We applied a stochastic frontier production function to calculate frontier yields, yield gaps, and efficiencies of wheat, maize, and rice production. Thereby, we integrated both biophysical and land management-related factors. In our analysis the actual grain yield is defined as observed grain yield expressed in tons per hectare. The frontier yield is indicative for the highest observed yield for the combination of conditions. Global data on actual grain yields were obtained from Monfreda et al. (2008). These datasets comprise information on harvested areas and actual yields of 175 crops in 2000 at a 5 arc-minute resolution and are based on a combination of national-, state-, and county-level census statistics as well as information on global cropland area (Ramankutty et al., 2008).

The vector of independent variables in the frontier production function contains several crop growth factors. Crop growth factors can be classified as *growth-defining, growth-limiting,* and *growth-reducing factors* (van Ittersum et al., 2003). According to van Ittersum et al. (2003) growth-defining factors determine the potential crop yield that can be attained for a certain crop type in a given physical environment. Photosynthetically Active Radiation (PAR), carbon dioxide (CO_2) concentration, temperature and crop characteristics are the major growth-defining factors. Growth-defining factors themselves cannot be managed but management adapts to these conditions, for example by choosing the most productive growing season. Growth-limiting factors consist of water and nutrients and determine water- and nutrient-limited production levels in a given physical environment. Availability of water and nutrients can be controlled through management to increase actual yields towards potential levels. Growth-reducing factors, such as pests, pollutants, and diseases reduce crop growth. Effective management is needed to protect crops against these growth-reducing factors. The interplay of growth-defining, growth-limiting, and growth-reducing factors determines the actual yield level.

The stochastic frontier production function was composed in such a way that the frontier grain yield is defined by growth-defining factors, precipitation and soil fertility constraints. Hence, frontier yields may be below potential yields because they consider growth-limiting factors for their calculation. Factors that determine the deviation from the frontier grain yield, and hence lead to the actual grain yield, are called inefficiency effects and are considered in the inefficiency function u_i. According to our definition this yield gap is caused by inefficient land management. The stochastic frontier production function to be estimated for each grain type:

$$\ln(q_i) = \beta_0 + \beta_1 \ln(temp_i) + \beta_2 \ln(precip_i) + \beta_3 \ln(par_i) + \beta_4 \ln(soil\_const_i) + v_i - u_i \qquad \text{Equation 4.3}$$

where q_i is the actual grain yield, specified per grain type. The most important crop growth-defining factors are PAR *(par_i)* and temperature. The relation between temperature and grain yield is not log-linear as it is implied by the Cobb-Douglas stochastic frontier model. Increasing temperature first leads to an optimum grain yield before the yield declines again. We therefore defined the variable $temp_i$ as the deviation from the optimal monthly mean temperature. The optimal monthly mean temperature is the mean monthly temperature at which the highest crop yields are observed according the observed actual crop yields. CO_2 concentration, another growth-defining factor, was not included in our production function because only slight CO_2 concentration differences exist between the Northern and Southern Hemisphere and local CO_2 concentrations show hardly any spatial variability. Precipitation *($precip_i$)* and soil fertility constraints *($soil\_const_i$)* represent growth-limiting factors, which can be controlled by management. Rather than using annual averages for each climatic variable, monthly mean temperature, precipitation, and PAR data were integrated over the grain type-specific growing period (Table 4.1). The growing period is defined as the period between sowing date and harvest date which differs between grain type and climatic conditions and thus location. Using growing period-specific climate data allows us to account for only those climate conditions which contribute significantly to grain development. A similar approach is also used in many crop modeling approaches (for examples see Kaufmann and Snell, 1997; Jones and Thornton, 2003; Parry et al., 2004; Stehfest et al., 2007). Empirical data on growing season were available for irrigated rice (Portmann et al., 2008), while we obtained grain-specific growing period information for wheat and maize from the LPJmL model (Bondeau et al., 2007). Cropping periods for rice are based on irrigated rice and the same growing period was applied for both irrigated and non-irrigated rice production areas because data on non-irrigated rice were not available. A full sensitivity analysis of the effect of cropping period choice was beyond the scope of this chapter. A description of all variables used is given in Table 4.1.

The influence of land management on the actual grain yield was considered in the inefficiency function u_i. Several regional and global studies have identified factors which determine land management and intensification (Tilman, 1999; Kerr and Cihlar, 2003; Keys and McConnell, 2005; Reidsma et al., 2007). Only a few of these factors are available as spatially explicit global datasets. Therefore, proxies of these factors for which global datasets are available were used instead as determinants of land management. The inefficiency function is specified as:

$$u_i = \delta_1(irrig_i) + \delta_2(slope_i) + \delta_3(agr\_pop_i) + \delta_4(access_i) + \delta_5(market_i) \quad \text{Equation 4.4}$$

Irrigation *($irrig_i$)* as a traditional management technique for improving actual grain yields was taken into account. Slope *($slope_i$)* might restrict actual grain yield because it hinders accessing land with machinery, leads to surface runoff of (irrigation) water, and supports soil erosion which limits soil fertility. Nevertheless, adverse slope conditions can, to a certain extent, be offset by effective management and were therefore considered in the inefficiency function. The importance of labor as determinant of agricultural production has been discussed and analyzed in several studies (Battese and Coelli, 1995; Mundlak et al., 1997; Hasnah et al., 2004; Keys and McConnell, 2005). A proper consideration of agricultural labor at the global scale remains, however, challenging with limited data availability as a major obstacle. For this reason we used non-urban population data as proxy for agricultural population and hence labor availability *(agr_pop_i)*. Market accessibility *($access_i$)* gives an indication of the attractiveness of regions for grain production in terms of the time- costs to reach the closest market. We considered the accessibility of the nearest markets, including large harbors, which are the door to distant markets as well. A proxy for the market influence *($market_i$)* was included in the inefficiency function as it is assumed that regions with stronger markets are better suited for investments in yield increases of agricultural production than regions with less strong markets. *$Market_i$* and *$access_i$* are at the same time proxies for the availability of fertilizers, pesticides and machinery.

Table 4.1: Variables used in the efficiency analysis.

Variable	Definition (measure)	Source
Actual yield		
Grain	Yield of wheat, maize and rice (scale)	(Monfreda et al., 2008) and SAGE (http://www.sage.wisc.edu/mapsdatamodels.html)
Frontier production function		
Temp	Deviation from optimal monthly mean temperature for grain-specific growing period (scale)	Average for 1950-2000 derived from Worldclim (www.worldclim.org) with growing period information from Portmann et al. (2008) and LPJmL (Bondeau et al., 2007)
Precip	Precipitation sum for grain-specific growing period (scale)	Average for 1950-2000 derived from Worldclim (www.worldclim.org) with growing period information from Portmann and Siebert (2008) and LPJmL (Bondeau et al., 2007)
Par	Photosynthetically Active Radiation (PAR) sum for grain-specific growing period (scale)	Computed as described by Haxeltine and Prentice (1996)
Soil_const	Soil fertility constraints (ordinal)	Global Agro-Ecological Zones – 2000 (http://www.iiasa.ac.at/Research/LUC/GAEZ)
Inefficiency function		
Irrig	Maximum monthly growing area per irrigated grain type (scale)	MIRCA 2000 (http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html)
Slope	Slope (ordinal)	Global Agro-Ecological Zones – 2000 (http://www.iiasa.ac.at/Research/LUC/GAEZ)
Agr_pop	Non-urban population density as ratio of population density (below 2500 persons per km^2) and agricultural area (scale)	(Ellis and Ramankutty, 2008)
Access	Market accessibility (scale)	Derived from UNEP major urban agglomerations dataset (http://geodata.grid.unep.ch) and the Global Maritime Ports Database (http://www.fao.org/geonetwork/srv/en/main.home)
Market	Market influence (index)	Purchasing Power Parity (PPP) per country derived from CIA factbook (https://www.cia.gov/library/publications/the-world-factbook) spatially distributed through an inverse relation with variable *access*

Fertilizer application, one of the most important management options to increase actual grain yields (Tilman et al., 2002; Alvarez and Grigera, 2005) could not be included in the inefficiency function due to lack of appropriate data. Globally consistent and comparable fertilizer application data are only available at the national scale. We obtained grain type-specific fertilizer application rates per country from the International Fertilizer Industry Association (IFA) (FAO, 2002a). A correlation analysis to identify the relationship between fertilizer application and efficiency of grain production was done with these data at the national level.

We computed a globally consistent grain yield frontier under the assumption of globally uniform relations with the growth-defining, growth-limiting, and growth-reducing factors. This consistency allows us to directly compare estimated frontier yields, efficiencies and yield gaps between grid cells across the globe. Only 5 arc-minute grid cells with a cropping area of at least 3% coverage of the particular grain type were considered in the analysis to prevent an overrepresentation of marginal cropping areas. From these grid cells a random sample of 10% with a minimum distance of two grid cells between each sampled grid cell was chosen to allow efficient estimations and reduce spatial autocorrelation, which may have been caused by the characteristics of the data that were derived from administrative units of varying size (Monfreda et al., 2008). We tested the robustness of this 10% sample to verify the appropriateness of the sample size. Maximum-likelihood estimates of the model parameters were estimated using the software FRONTIER 4.1 (Coelli, 1996).

4.2.3 Regional level estimation of frontier yields and efficiencies

The importance of the variables explaining the efficiencies is hypothesized to be different between world-regions. For example, the conclusion that slope is a determining factor for efficiencies of global wheat production does not rule out the possibility that in some world-regions slope does not influence efficiency of wheat production while other variables do. To uncover such differences, we conducted a second analysis at the scale of world-regions. World-regions consist of countries with strong cultural and economic similarities. We distinguish 26 world-regions for the regional analysis.

If frontier yields and efficiencies are calculated for each world-region individually inconsistencies may be introduced since some world-regions may not contain grid cells with actual yields close to the frontier yields. Such analysis can lead to an underestimation of the frontier yield. Efficiencies were therefore calculated at the global scale to retrieve globally comparable frontier yields. However, in this case efficiencies were calculated without synchronously estimating the inefficiency effects contrary to the global approach in Section 4.2.2. The applied stochastic frontier production function remains the same (Equation 4.3); however, the inefficiency effects are not synchronously estimated. In our regional analysis, forward stepwise regressions were applied to identify the statistically significant inefficiency effects (independent variables) and to determine their relative contribution to the overall efficiency of grain production (dependent variable) per world-region (Equation 4.5).

$$\ln(eff_i) = \beta_0 + \beta_1(irrig_i) + \beta_2(slope_i) + \beta_3(agr\_pop_i) + \beta_4(access_i) + \beta_5(market_i) \quad \text{Equation 4.5}$$

where eff_i is the efficiency in each grid cell. Again, efficiency in our study is defined as the actual yield in relation to the frontier yield. The percentage of grain area within a grid cell was used as weighting factor. The natural logarithm was calculated for the efficiency in order to account for non-linear relations. The variance inflation factor (VIF) was calculated to ensure independence amongst the variables. Variables with a VIF of 10 or higher were removed from the analysis.

4.3 Results

4.3.1 Global frontier yields and efficiencies

All coefficients in the stochastic frontier production function are significant at 0.05 level (Table 4.2). The deviation from optimal monthly mean temperature *(temp)* has a negative coefficient for all grain types, meaning that the frontier grain yield decreases with an increasing deviation from the optimal monthly mean temperature. The relationship is strong indicated by the large *t*-ratios (Table 4.2). *Precip* and *soil_const* also determine a significant share explaining the frontier production. The positive coefficients for *precip* for all three grain types indicate that with an increased precipitation sum the grain yield increases. The negative coefficient for *par* for all three grain types may be related to cloudiness which is closely related to precipitation. Another reason for the negative coefficient for *par* may be that the higher PAR (and consequently energy influx), the higher potential evapotranspiration, which causes water stress and might therefore decrease frontier grain yields. Furthermore, a relationship between the temperature sum over the growing period and *par* for all three grain types (Pearson correlation coefficient $r \geq 0.67$) is potentially causing multicollinearity. While frontier yields of maize and rice are negatively correlated to *soil_const*, a positive coefficient for *soil_const* for wheat is obtained. Highest actual wheat yields are found in countries with highly mechanized and capital intensive agriculture, such as Denmark and Germany. Soil fertility constraints in these countries can be reduced by an effective land management, especially fertilizer application. Hence, soil fertility constraints are only up to a certain level not an obstacle for wheat production in those countries. Because these countries supply a large share of global wheat production this may explain the positive coefficient for wheat. It is unlikely that there is a causal relation underlying this observation.

In the inefficiency function, a positive coefficient indicates that the respective variable has a negative influence on efficiency. *Irrig* and *market* have negative coefficients for all grain types. Hence, the absence of irrigation and a low market influence reduce efficiency. The coefficient for *slope* is positive for wheat and maize but negative for rice. Steeper slopes indicate lower efficiencies in wheat and maize production. The negative coefficient for rice may be explained by the large amount of global rice that is produced on terraces in sloped areas, especially in the core production regions in South-East Asia. The production on terraces is very intensive and may explain high actual yields and efficiencies. Furthermore, in many hilly regions rice is produced on the valley bottoms. Due to the limited spatial resolution of the analysis these locations are represented as sloping, leading to a possible negative association with inefficiency. The positive coefficients for *access* are all as expected. Hence, the more hours needed to reach the next city, the lower the efficiency of grain production. According to the theory of von Thuenen (1966), who concludes that crop production is only profitable within certain distances from a market, crop production becomes less productive and less efficient in more remote regions. Somewhat surprising results are achieved for *agr_pop*. While the coefficient for wheat is negative as expected it is positive for maize and rice. It can be argued that for many less developed countries the more labor is available the lower is the technology level and, therefore, the efficiency. This applies for many rice and maize growing countries as shown with our results. Furthermore, the percentage of agricultural population as part of the non-urban population tends to be smaller nearby urban agglomerations. In those regions agricultural activities provide often only a small contribution to the non-urban household income whereas off-farm activities are the primary income source, which tends to be associated with lower agricultural efficiencies (Verburg et al., 2000; Goodwin and Mishra, 2004; Paul and Nehring, 2005).

The correlations (Pearson coefficients) for fertilizer application and the grain production efficiency at country level are $r = 0.67$ for wheat, $r = 0.59$ for maize and $r = 0.27$ for rice. Countries with lower fertilizer application rates therefore achieve lower efficiencies in grain production than countries with higher fertilizer application rates.

Results of the obtained likelihood-ratio tests are shown in Table 4.2. The likelihood-ratio (LR) statistics for wheat (LR = 4307), maize (LR = 3695) and rice (LR = 1558) exceed the 1% critical values of 21.67 for 6 degrees of freedom and therefore indicate high statistical significance (Kodde and Palm, 1986). A Wald test was conducted to test the significance of all included variables. Results indicate that we can only explain about half of the efficiencies in wheat production (γ = 0.47). This means that the other half of the variation cannot be explained by inefficiency effects but rather by statistical noise. The γ-values for maize and rice are much higher: 0.91 for both. Hence, a major part of the error term is due to inefficiency rather than statistical noise. Reasons for the remarkable differences between the obtained γ-values are diverse. Statistical noise in our study is an inherent data property possibly introduced by data errors or data uncertainties. The large variation of sources and years of validity of the grain yield data and the different size of the administrative units that underlie these datasets are likely to cause high uncertainties. Input data are not validated and it can be expected that some of them are more accurate than others with large differences between regions. Statistical noise may also be caused by variances within the data. For example, variability of climate within a particular month may influence crop management but cannot be captured by mean monthly climate data. Furthermore, actual yields are likely to reflect large inter-annual variations due to climate variation which is not captured by the long-term average climate parameters used in this study. Uncertainties in cropping periods may also add to the statistical noise. Furthermore, we considered only a limited number of inefficiency effects to explain spatial variation in efficiencies.

The mean efficiencies for wheat, maize and rice are 0.637, 0.501 and 0.638, respectively (Table 4.2). Hence, the highest efficiencies at the global scale are obtained for production of wheat and rice, while maize production is the least efficient.

Frontier grain yields show a wide variation across the globe. Exemplary regions with high frontier yields are Northwest Europe, central USA, and parts of China, while central Asia, Mexico, and West Africa show low frontier yields for wheat, maize, and rice production respectively (Figure 4.2).

Figure 4.2 and 4.3 illustrate that some regions produce grain close to the estimated frontier yields while others show a large yield gap. These yield gaps are an indication for the potential to increase actual grain yields. The maximum yield gaps are 7.5 t/ha for wheat, 8.4 t/ha for maize and 6.4 t/ha for rice. If we express the global aggregated yield gap in total production (i.e., in tons) we can show that the yield gap equals 43%, 60%, and 47% of the actual global production of wheat, maize and rice, respectively.

Table 4.2: Coefficients for the parameters of the stochastic frontier production function at the global scale (significant at 0.05 level).

Variable	Parameter	Wheat coefficient*	Wheat *t*-ratio	Maize coefficient*	Maize *t*-ratio	Rice coefficient*	Rice *t*-ratio
Frontier production function							
Constant	β_0	0.98	9.2	3.05	18.3	10.08	22.7
Ln*(temp)*	β_1	-0.18	-31.8	-0.03	-19.8	-0.02	-12.4
Ln *(precip)*	β_2	0.17	22.6	0.07	9.9	0.05	11.7
Ln *(par)*	β_3	-0.17	-11.3	-0.24	-9.9	-0.42	-20.0
Ln *(soil_const)*	β_4	0.09	14.0	-0.21	-23.3	-0.11	-10.5
Inefficiency function							
Irrig	δ_1	<-0.01	-10.1	<-0.01	-28.7	<-0.01	-20.0
Slope	δ_2	0.17	53.4	0.20	35.9	-0.05	-5.2
Agr_pop	δ_3	<-0.01	-19.7	<0.01	10.7	<0.01	7.2
Access	δ_4	0.02	14.0	0.01	6.2	<0.01	5.3
Market	δ_5	<-0.01	-33.3	<-0.01	-54.8	<-0.01	-29.8
Variance parameters							
Sigma-squared	σ^2	0.26	79.0	0.82	41.7	0.80	37.4
Gamma	γ	0.47	48.1	0.91	166.3	0.91	134.4
Log-likelihood		-8411		-9350		-5356	
Likelihood ratio statistic (LR)		4307		3695		1558	
Mean efficiency		0.64		0.50		0.64	

* A positive coefficient in the frontier production function indicates that the respective variable has a positive influence on the frontier yield. A positive coefficient in the inefficiency function indicates that the respective variable has a negative influence on efficiency.

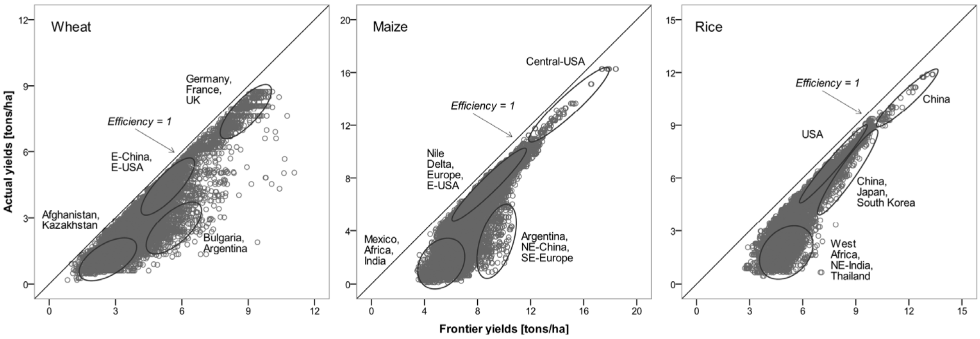

Figure 4.2: Actual and frontier yields for wheat, maize, and rice.

4.3.2 Regional determinants of efficiencies

We present and discuss only the most important results of the region-specific analysis of factors that explain efficiencies. Two world-regions per grain type, which are characterized by a different agricultural, cultural and economical background, were selected and are presented in Table 4.3. Results show that the individual contribution of determinants of efficiencies varies strongly between world-regions and grain types (Figure 4.4).

The results indicate that regional efficiencies of grain production can be explained by irrigation *(irrig)* in five of the six presented world-regions. The coefficients for *irrig* are all positive, but the individual contributions vary between world-regions. For example, in the Thailand region intensive irrigation is only applied in some rice growing regions, e.g., in the surroundings of Bangkok and in the Mekong Delta while rain-fed rice production mostly faces severe constraints in obtaining a highly efficient production. *Irrig* explains most of the variance in efficiency of rice production in the Thailand region. Market accessibility *(access)* can explain efficiencies of grain production in the USA, Southern Africa, Indonesia and the Thailand region. For all regions poor accessibility mean lower efficiency of grain production but the contribution of *access* differs between world-regions. For example, the USA is the world's main wheat exporter and *access* can explain most of the variability in wheat efficiency. In the more remote regions land prices are lower and inputs are therefore often substituted by land leading to lower efficiencies. China's wheat export is minor with less than 1% of its total production (FAOSTAT, 2009b) and within the densely populated wheat production areas generally little time is needed for reaching markets. *Access* can therefore not explain the variance in efficiency of Chinese wheat.

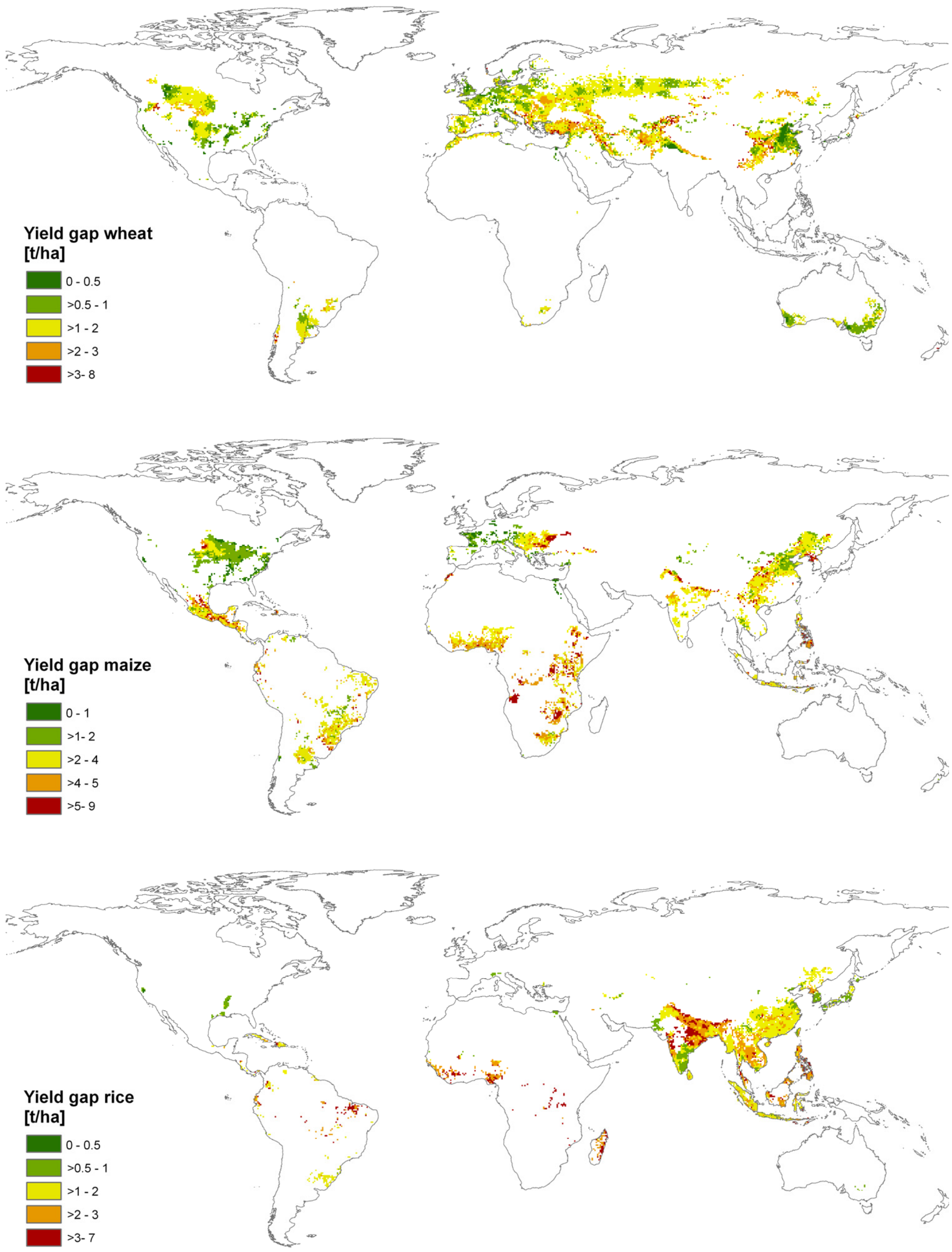

Figure 4.3: Global yield gap for wheat, maize and rice calculated as the difference between actual yield and estimated frontier yield.

Table 4.3: Multiple linear regression results for efficiencies of wheat, maize, and rice production for selected world-regions.

	Unstandardized Coefficients[a]		Standardized Coefficients[a]
	B	Std. Error	Beta
Wheat	USA (r^2 = 0.25)		
(Constant)	-2.2×10^{-1}	2.1×10^{-3}	
Irrig	8.2×10^{-5}	6.2×10^{-6}	2.8×10^{-1}
Slope	*	*	*
Agr_pop	1.0×10^{-4}	3.6×10^{-5}	6.0×10^{-2}
Access	-5.2×10^{-3}	3.3×10^{-4}	-3.5×10^{-1}
Market	*	*	*
Wheat	China (r^2 = 0.38)		
(Constant)	-1.9×10^{-1}	4.9×10^{-3}	
Irrig	1.2×10^{-5}	1.2×10^{-6}	2.2×10^{-1}
Slope	-1.0×10^{-1}	8.6×10^{-4}	-3.6×10^{-1}
Agr_pop	3.8×10^{-5}	8.0×10^{-6}	1.1×10^{-1}
Access	*	*	*
Market	8.9×10^{-6}	1.7×10^{-6}	1.1×10^{-1}
Maize	Mexico (r^2 = 0.10)		
(Constant)	-8.1×10^{-1}	5.0×10^{-1}	
Irrig	1.1×10^{-4}	2.5×10^{-4}	1.9×10^{-1}
Slope	2.0×10^{-2}	1.0×10^{-2}	9.0×10^{-2}
Agr_pop	2.3×10^{-4}	1.0×10^{-4}	1.0×10^{-1}
Access	*	*	*
Market	2.4×10^{-5}	6.1×10^{-6}	1.7×10^{-1}
Maize	Southern Africa[b] (r^2 = 0.22)		
(Constant)	-7.7×10^{-1}	4.0×10^{-2}	
Irrig	*	*	*
Slope	*	*	*
Agr_pop	-3.7×10^{-4}	1.8×10^{-4}	-7.0×10^{-2}
Access	-2.0×10^{-2}	4.0×10^{-3}	-1.6×10^{-1}
Market	8.6×10^{-5}	1.1×10^{-5}	3.4×10^{-1}
Rice	Thailand region[c] (r^2 = 0.21)		
(Constant)	-7.5×10^{-1}	2.0×10^{-2}	
Irrig	7.0×10^{-5}	4.6×10^{-6}	4.2×10^{-1}
Slope	2.0×10^{-2}	4.5×10^{-3}	1.2×10^{-1}
Agr_pop	2.6×10^{-4}	5.0×10^{-5}	1.4×10^{-1}
Access	-2.0×10^{-3}	6.6×10^{-4}	-9.0×10^{-2}
Market	*	*	*

Table 4.3: *continued*

		Unstandardized Coefficients[a]		Standardized Coefficients[a]
		B	Std. Error	Beta
Rice	Indonesia (r^2 = 0.28)			
(Constant)		-4.6×10^{-1}	2.0×10^{-1}	
Irrig		1.4×10^{-5}	3.4×10^{-6}	1.6×10^{-1}
Slope		1.0×10^{-1}	3.2×10^{-3}	1.1×10^{-1}
Agr_pop		6.2×10^{-5}	1.7×10^{-5}	1.6×10^{-1}
Access		-1.6×10^{-3}	3.8×10^{-4}	-1.6×10^{-1}
Market		5.5×10^{-5}	1.1×10^{-5}	2.3×10^{-1}

* Not significant at 0.05 level

[a] A positive coefficient indicates that the respective variable has a positive influence on efficiency.

[b] Includes South Africa, Lesotho, Mozambique, Zimbabwe, Tanzania, Zambia, Malawi, Angola, Namibia, Botswana, and Swaziland

[c] Includes Vietnam, Philippines, Cambodia, Burma, Laos, and Malaysia

production. Market influence *(market)*, as a proxy for land rent indicating the investments in machinery, pesticides and fertilizer, has a positive coefficient for most grain types and regions: especially for maize production. A large part of the variance in efficiency of maize production in Mexico and Southern African can be explained by the variation in market influence while it can neither explain efficiencies of wheat production in the USA nor efficiencies of rice production in the Thailand region. Agricultural population *(agr_pop)* as proxy for agricultural labor has a positive contribution to efficiencies of rice production in the Thailand region, Indonesia, and wheat production in the USA and China, while its contribution is negative for maize production in Southern Africa. For both Indonesia and the Thailand region these results can be traced back to the labor intensity of rice production with large number of people engaged in rice production and post-production activities including processing, storage, and transport. Also Chinese cereal production is well-known for being labor intensive. Farmers try to substitute capital and land with labor which explains the positive coefficient as also confirmed by Tian and Wan (2000). Slope explains most of the variability in efficiency of Chinese wheat production. Actual wheat yields in China are significantly higher in flat areas (yellow river valley) as these areas are easier to access and allow for better use of machinery. China's rapid urbanization has, however, forced wheat farmers to also produce in less productive, for example more hilly regions to meet the food demand (Chen, 2007; Xin et al., 2009). Slope coefficients are also positive for rice production in Indonesia and the Thailand region and for Mexico. Mexican maize is largely produced in the highlands of Mexico. However, slope adds less to the explanation of efficiency of maize production than most of the other inefficiency effects.

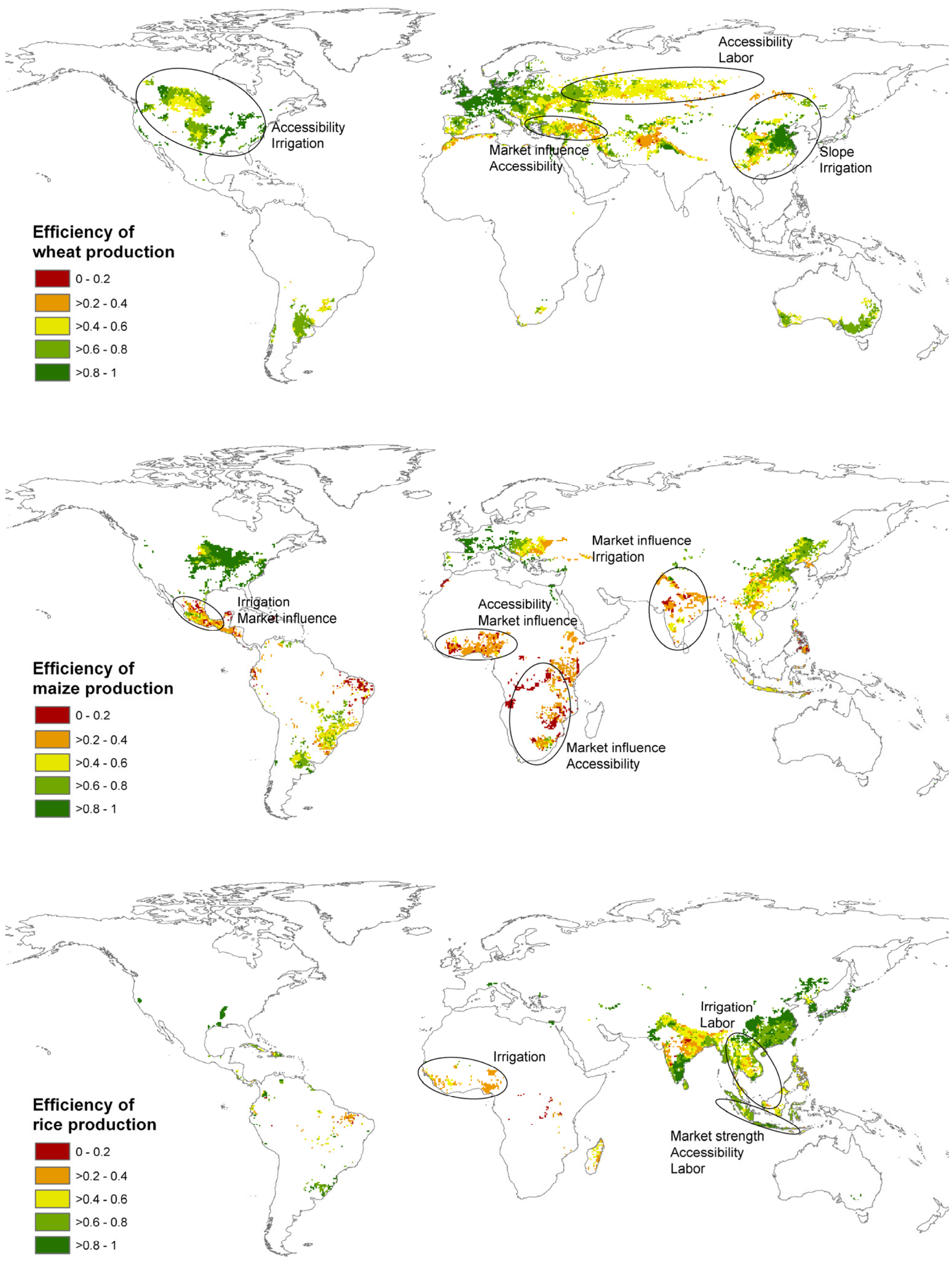

Figure 4.4: Efficiencies of wheat, maize and rice production with the most determining factors per world-region.

4.4 General discussion

4.4.1 Evaluation of data and methodology

Agricultural production efficiency, yield, and intensification are closely linked (de Wit, 1992; Matson et al., 1997; Cassman, 1999; Reidsma et al., 2009a). In this chapter, we have shown how to disentangle actual grain yields from production efficiencies by using stochastic frontier production functions. The strength of our approach lies in its integration of biophysical and land management-related determinants of grain yields. Kaufmann and Snell (1997) showed that climate variables alone account for only a minor part of the variation in US maize yield while socio-economic variables, such as farm size, technology, and loan rates, account for the main part of yield variation. This example underpins the necessity to include socio-economic variables when exploring crop yields. The selection of land management-related factors included as inefficiency effects in our analysis was, however, heavily restricted by data availability. Additional aspects related to agricultural production that may be considered are for example stimulation of alternative management options, applied technology, land ownership, farm size, and land degradation. All these factors may affect the yield gap but their consideration was beyond the scope of our study as consistent spatially explicit data are not available at the global scale.

The presented approach combines econometric methods with concepts applied in crop sciences. The Cobb-Douglas function implies a log-linear relation between dependent and independent variables. This may, however, be inappropriate to present the relation between yield, growth-defining, and growth-limiting factors as some of these factors may not have such a relationship. Yet, the data did not provide an indication that another functional form would be more appropriate.

A big advantage of the frontier production approach is the consistent use of one dataset of observed yields. Observed grain yield data were derived from different national censuses and partly show constant values for each grid cell belonging to the same administrative unit (Monfreda et al., 2008). We minimized this effect (that causes spatial autocorrelation of observations) by excluding all minor cropping areas from the analysis and using a sample with a minimum distance between the sampled grid cells. Alternatively, observed yields may be compared to simulated potential yields. However, only few model results of potential yields at the global scale are available. A simple comparison of published maps of potential yields originating from different models indicates large deviations between the simulated potential yields. The deviation between simulated potential yields is often larger than the yield gap itself, which makes a reliable yield gap analysis impossible based on these simulated yields (MNP, 2006; Bondeau et al., 2007).

4.4.2 Closing the yield gap

Potential yields were explored in many studies. One of the first studies carried out at the global scale was published by Buringh et al. (1975) who assessed maximum grain production per soil region. The authors calculated the highest total production levels for Asia and South America with up to 14,000 Mio tons/year but did not explore variability of grain yields within each soil region. In recent studies, Reidsma et al. (2009c) has simulated water-limited potential maize yields for Europe and observes a gradient from the North East of Europe to the South-West. Our frontier yields confirm this trend, although the gradient is weaker and the frontier yields tend to be higher than the model results. The same is observed for frontier wheat yields for the North China Plain which are tentative higher (up to 10 tons/ha) than potential wheat yields simulated by Wu et al. (2006) which do not exceed 8 tons/ha. Peng et al. (1999) have conducted several field level experiments and conclude potential rice yields of about the 10 tons/ha for the tropics. We can, however, not confirm such high frontier rice yields for the tropics, those we have only estimated for Central China where hybrid rice technology has been widely adopted (Cassman, 1999).

We define the process of closing the yield gap as intensification. To increase actual grain yields through intensification a catalyst is needed to initialize the intensification process. Lambin et al. (2001) have identified three trigger of agricultural intensification: (1) land scarcity, (2) investments in crops and livestock, and (3) intervention in state-, donor-, or non-governmental organization (NGO)-sponsored projects to further push development in a region or economic sector. For exploring potential temporal dynamics of intensification it is essential to know whether these triggers exist and how these interact with local constraints. The results of our analysis have confirmed that the factors explaining inefficiencies in production widely vary by region. Furthermore, factors explaining efficiencies are related to complex social, economic, and political processes. Taking this into account it is debatable to what extent the calculated yields gaps can and will be closed. Particularly developing and transition countries often lack capital investments, infrastructure, education, and effective agricultural policies and agricultural expansion is practiced instead to increase grain yield (Reardon et al., 1999; Swinnen and Gow, 1999; Coxhead et al., 2002).

The presented frontier yields illustrate what currently could be achieved while breeding improvements may lead to higher yielding varieties in the future. Several authors have discussed the role of technological development to further increase potential crop yields (Cassman, 1999; Evans and Fischer, 1999; Huang et al., 2002) but its specific contribution remains difficult to determine (Ewert et al., 2005).

Another aspect to be considered when exploring grain yields is the effect of climate change. Climate change is expected to have different impacts on agricultural yields in different parts of the world and for different crop types (Parry et al., 2004; Erda et al., 2005; Thornton et al., 2009; Wei et al., 2009). The presented methodology and results may be used for assessing the impact of climate change on actual and potential grain yields as well as for investigating possible adaptation strategies. A negative aspect often associated with intensification is environmental damage. Many studies have shown that agricultural intensification may lead to air and water pollution, loss of biodiversity, soil degradation and erosion (Harris and Kennedy, 1999; Donald et al., 2001; Foley et al., 2005) and more and more authors emphasize the need for a more efficient use of natural resources and ecological intensification (Cassman, 1999; Tilman, 1999).

4.5 Conclusions

In this study, we explored factors associated to grain production efficiencies and yield gaps of global grain production. We explained the spatial variation across the globe to explore the potential for intensification and the nature of the constraints given the current technological development. Results show that on average the present actual yields of wheat, maize, and rice are 64%, 50%, and 64% of their frontier yields, respectively. Based on these results it appears tempting to conclude a tremendous potential for intensification of global grain production. In fact, quantitative assessment of intensification potential remains challenging as intensification has multiple pathways and often goes parallel with agricultural expansion. Minimizing the yield gap requires understanding the nature and strength of region-specific constraints. From our results we can conclude that, while some factors can explain efficiencies of global grain production the same factors may not be relevant at the world-regional scale. Hence, the efficiency of grain production is the result of several processes operating at different spatial scales but the influence of each of these processes differs between the scales. From the comparison of our global results with the regional results we can conclude that these processes do not necessarily behave linearly across these scales.

Drawing conclusions from the global results about factors explaining grain production efficiencies at the regional scale would therefore be wrong. Hence, region-specific identified constraints need to be assessed separately to provide a basis for increasing actual grain yields. This chapter has provided a first global overview of the spatial distribution of the influence of some of these factors.

Chapter 5

Exploring global irrigation patterns: A multilevel modeling approach

Areas equipped for irrigation have almost doubled in the past 50 years across the globe and further expansions are expected in the future to meet a growing food demand. The Food and Agriculture Organization of the United Nations (FAO) projects for developing countries an expansion of the area equipped for irrigation by 40 million ha till 2030. Knowledge about the constraints for irrigation and spatially explicit information about the potential for irrigation expansion are, however, lacking at the global scale. The objective of our study is to explain the global pattern of irrigated cropland and to identify cropping regions where irrigation is likely to be expanded. Because drivers of irrigation operate at multiple spatial scales we accounted for biophysical determinants mainly at the grid cell level and for socio-economic and governance determinants primarily at the country level. To identify the variability of the determinants within and amongst these two spatial levels we applied a multilevel analysis. Results show that 56% of the global variance in irrigation occurs between countries while 44% of the variance occurs within countries. Our results suggest that it is necessary to consider biophysical, socio-economic and governance information for identifying cropland areas which are likely to be irrigated. Taking only biophysical information into account may lead to an overestimation of the likelihood for irrigation expansion in countries with low political stability and low economic strength. Under current conditions irrigation expansion is most likely in East China, North Africa, and parts of the Mediterranean region.

Based on: Neumann, K., Stehfest, E., Verburg, P.H., Siebert, S., Müller, C. and Veldkamp, T.: Exploring global irrigation patterns: A multilevel modeling approach. – Agricultural Systems (under review).

5.1 Introduction

The world's area equipped for irrigation has almost doubled in the past half a century. At present, 287 million ha land are equipped for irrigation (FAOSTAT, 2010), 24% of the total harvested cropland is under irrigation (Portmann et al., 2010) and more than 40% of the global cereal production is from irrigated land (Siebert and Döll, 2010). The contribution of irrigation to current and future food security has been discussed and analyzed in several studies (e.g., Becker and Johnson, 1999; Sauer et al., 2010). The global irrigation pattern, however, is very diverse, with more than two third of the total globally irrigated land located in Asia, and hardly any irrigation in Sub-Saharan Africa (Molden, 2007). Latitudinal distribution of irrigated area peaks between 20-45 degree North (Wisser et al., 2008). To achieve optimal crop growth, highest irrigation water requirements with more than 500 mm/yr are calculated for India, Pakistan (Indus basin), Uzbekistan, Iraq, Turkey, and Egypt, which almost triple in some regions when accounting for the irrigation water use efficiency (Döll and Siebert, 2002). Irrigation requirements are likely to increase in some cropping regions where precipitation is expected to decline in the future. If currently irrigated dates, rice, cotton, citrus and sugar cane were not irrigated, their production would decrease by up to 60% (Siebert and Döll, 2010) and many countries which expect serious water scarcity in the future (e.g., in the semi-arid regions of Asia, the Middle East, Sub-Saharan Africa), will see their food production from irrigated land threatened (Seckler et al., 1999; Zeitoun et al., 2010). Given their importance to provide global food demand, irrigated areas are expected to expand in the future. Economic growth and urbanization in many developing countries may lead to a diet shift from staples towards more vegetables and fruit, for example in China, which would require more irrigation (Molden, 2007). The area equipped for irrigation is expected to expand by 40 million ha till 2030 in developing countries (FAO, 2003). The implied annual growth rate of 0.6% is lower than the 1.9% achieved in the past four decades, which reflects the decrease of suitable areas and water resource availability in some countries, as well as growing investment costs for irrigation. Strongest expansion of irrigated areas is expected in the land-scarce regions in South Asia, East Asia and the Near East/ North Africa (FAO, 2003).

While a few attempts were made to map irrigated areas at the continental or global scale (Siebert et al., 2005; Siebert et al., 2006b; Portmann et al., 2008; Thenkabail et al., 2009; Wriedt et al., 2009; You et al., 2009), projections for expansion of irrigated areas are not mapped, and spatially explicit information about the potential for irrigation as well as the understanding of its drivers and constraints are lacking at the global scale. This may be traced back to limited data availability at the global scale. An earlier study has indicated large regional differences in irrigation across Europe, namely as a consequence of spatial and temporal variability in climate and water availability (Hartmann, 1979). But also political changes play a role for the development and maintenance of irrigation facilities as O'Hara and Hannan (1999) and Fraser and Stringer (2009) have shown for Turkmenistan and Romania, respectively. Such studies are, however, restricted to the regional and national scale. One attempt of identifying suitable areas for irrigation was done by Heistermann (2006). Based on the results of a Multi-Criteria-Analysis, the author simulated expansion of irrigated areas in Africa. At the regional scale Barreteau and Bousquet (2000) have developed a multi-agent model to assess the viability of irrigated agriculture in the Senegal River Valley based on access to credits for crop management, water distribution amongst famers, cropping periods, and farmers' organization.

These studies illustrate the importance of irrigation for agriculture and highlight regional differences. A globally consistent analysis of irrigation and its underlying location factors is, however, missing. The objective of our study is to explain the presence of global irrigated cropland and to identify cropping regions where irrigation is likely to be expanded. We took location factors at two different spatial levels into account: grid cells (5 arc-minutes) and countries. To identify the variability of the constraints within and amongst the two spatial levels we applied a multilevel analysis. While we considered biophysical aspects mainly at grid cell level we accounted for socio-economic and governance aspects primarily at country level. Based on the results areas are identified where irrigation is likely to be extended.

5.2 Data

5.2.1 Grid cell Data

We obtained spatially explicit information about harvested irrigated and harvested rainfed areas for the entire globe from the MIRCA2000 dataset (Portmann et al., 2010). The MIRCA2000 dataset indicates for each 5 arc-minute grid cell harvested areas of irrigated and rainfed crops referring to the year 2000. MIRCA2000 was developed by combining grid cell level data on cropland extent (Ramankutty et al., 2008), harvested crop area (Monfreda et al., 2008) and area equipped for irrigation (Siebert et al., 2006b) with census based statistics on irrigated and rainfed crop areas and cropping calendars collected from many different sources. The main improvement of MIRCA2000 compared to earlier products (Siebert et al., 2005; Siebert et al., 2006b) is that it presents areas actually used for irrigation instead of areas equipped for irrigation and that it explicitly considers multi-cropping practices. We used the MIRCA2000 map to calculate the fraction of irrigated cropland as the ratio of harvested irrigated cropland and harvested total cropland. We excluded marginal cropping areas with less than 0.1% cropland in total grid cell area from our analysis. To further limit data uncertainties, all areas with at least 10% irrigated cropland were classified as irrigated (irrigation = 1) and all areas with less than 10% irrigated cropland were considered as rainfed (irrigation = 0). By applying this 10% threshold, 24% of all grid cells included in our analysis are irrigated which coincides with the world's total harvested cropland under irrigation (Portmann et al., 2010). The resulting map of irrigated areas is shown in Figure 5.1. From this dataset we drew a random, balanced sample of 5% to allow efficient calculations and reduce bias in the estimation procedure as result of spatial autocorrelation.

Gridded data for independent variables to explain the locations of irrigation were obtained at a 5 arc-minute spatial resolution (Table 5.1). We applied climate data from the Climate Research Unit (CRU) to calculate river discharge using the dynamic vegetation model LPJmL (Mitchell and Jones, 2005; Bondeau et al., 2007). River discharge was simulated according to Rost et al. (2008) for the actual land use pattern.

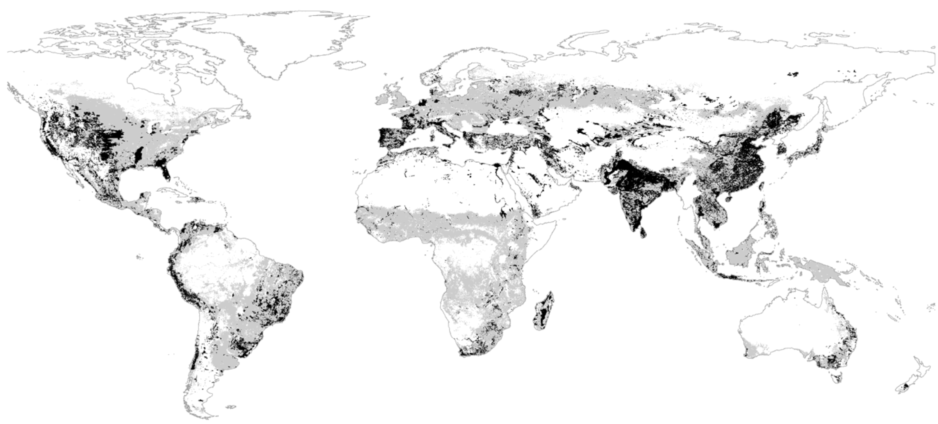

Figure 1: Irrigated cropland (black) and rainfed cropland (grey) as considered in this study.

For the hydrological and climate variables the average of monthly mean values for the period 1990-2005 was used. This 15 year period was chosen to account for the variability in the reference years of input data used to generate the global irrigation maps and to obtain representative hydrological information. We also included information on population density and market accessibility at the 5 arc-minute grid cell level.

Table 5.1: Descriptions and sources of data used in this study.

Variable name	Description [unit]	Data source
Variables at grid cell level (N=33619)		
Irrigation	1 if irrigation, 0 if rainfed	Based on (Portmann et al., 2010)
Slope	Slope [%]	Derived from Worldclim Altitude map (Worldclim, 2005)
Discharge	River discharge [mm/yr]	Calculated with LPJmL (Bondeau et al., 2007)
Humidity	Humidity, calculated as precipitation [mm]/ potential evapotranspiration (PET) [mm/yr] [index]	CRU TS 3.0 precipitation data (Climatic Research Unit, 2010), potential evapotranspiration calculated with LPJmL (Bondeau et al., 2007)
Evap	Evaporation [mm/yr]	Calculated with LPJmL (Bondeau et al., 2007)
ET	Evapotranspiration [mm/yr]	Calculated with LPJmL (Bondeau et al., 2007)
Access	Travel time to markets [hours]	Calculated based on UNEP major urban agglomerations dataset (UNEP, 2009), the Global Maritime Ports Database (GeoNetwork, 2009), and VMAP0 (MapAbility, 2009)
Population	Population density [persons/km^2]	(LandScan, 2000)
Variables at country level (N=139)		
Water	Natural total renewable water resources [m^3/yr/ha]	(AQUASTAT, 2010)
Political stability	Likelihood that the government will be destabilized [index]	(Worldbank, 2009)
Control of corruption	Control of corruption (the extent to which public power is exercised for private gain) [index]	(Worldbank, 2009)
Government effectiveness	Quality of public and civil service and the degree of its independence from political pressures [index]	(Worldbank, 2009)
GDP	Gross Domestic Product per capita [US$]	(Worldbank, 2009)
Democracy	Level of institutionalized democracy [index]	(Marshall and Jaggers, 2009)
Autocracy	Level of autocracy [index]	(Marshall and Jaggers, 2009)

5.2.2 Country data

Additional socio-economic and political aspects were considered at the country level. We obtained governance information from the Worldbank (2009) and the Polity IV Project (Marshall and Jaggers, 2009) for the year 2000, or if not available for a year close to 2000, for all countries. Indicators that we considered are control of corruption, government effectiveness, political stability, GDP per capita, as well as level of democracy and autocracy (Table 5.1). These indicators show, however, strong correlations potentially causing multicollinearity in the multilevel analysis. To reduce redundancies in the data and to obtain independent variables we applied a factor analysis with principal component extraction and varimax rotation. The country-specific factor scores, which are the scores of each country on each factor, were then used in the multilevel analysis. The factor analysis resulted in two factors which explain most of the variance. Both factors together explain 87.7% of the total variance, with factor 1 contributing 69.1% and factor 2 contributing 18.7%. The factor communalities (Table 5.2) show that between 78% and 95% of the variance occurring in each variable is accounted for. The high values let conclude that the extracted factors represent the variables well. The rotated component matrix in Table 5.2 presents the factor loadings for each of the variables. The results show that "control of corruption", "government effectiveness", "GDP", and "political stability" are highly correlated with the first factor. "Autocracy" and "democracy" are highly correlated with the second factor. The results suggest that factor 1 can be interpreted as a factor comprising mainly aspects of governmental performance and we therefore labeled it 'gov_performance'. Factor 2 essentially expresses the level of autocracy and democracy and is therefore called 'gov_type'. We furthermore included the amount of natural total renewable water resources as an independent variable at the country level.

Table 5.2: Characteristics of the obtained factors.

		Rotated component matrix	
Variables	Factor communalities	Factor 1 (gov_performance)	Factor 2 (gov_type)
Control of corruption	.934	.946	.200
Government effectiveness	.902	.907	.280
GDP	.790	.869	.189
Political stability	.779	.861	.193
Autocracy	.951	-.088	-.971
Democracy	.907	.494	.814

5.3 Methodology

5.3.1 Multilevel analysis

The importance of multi-scale approaches in land use studies has been emphasized by several authors (Kok and Veldkamp, 2001; Veldkamp et al., 2001a; Evans and Kelley, 2004; Verburg et al., 2008). Multilevel analysis (Snijders and Bosker, 1999) is particularly suited for addressing different spatial scales in hierarchically structured data. Hierarchically structured data are for example land use decisions, which are governed by policy implementation at municipality level, which again are conform to national scale policy incentives. It is not recommended to analyze such hierarchically structured data, or nested data, by common ordinary least squares analysis as these produce misleading regression results (Snijders and Bosker, 1999; Bickel, 2007). Instead, hierarchical data are preferably analyzed by accounting for statistical within-group and between-group relationships within a single analysis. A 'group' is an aggregated unit (e.g., country) and is referred to as a level two (or higher) unit while at the lowest hierarchical level units are called 'individuals' (e.g., municipalities). In our study the individuals are represented by the grid cells and the groups by countries. Multilevel models represent each of these levels by its own sub-model which represents relationships amongst variables of the respective level but also specifies how variables at this level influence relationships occurring at other levels. In this way any number of levels can be analyzed (Raudenbush and Bryk, 2002). Although multilevel models have been mostly used in disciplines such as educational research they have in recent years become more popular in analysis of environmental issues and land use in particular (Polsky and Easterling, 2001; Pan and Bilsborrow, 2005; Overmars and Verburg, 2006; Vance and Iovanna, 2006; Gray et al., 2008; Reidsma et al., 2009b).

Multilevel analyses are explained in detail by Snijders and Bosker (1999) and Raudenbush and Bryk (2002). In the following we refer to one important tool for multilevel analysis: the hierarchical linear model. The hierarchical linear model is a more advanced type of regression model which particularly addresses the structure of multilevel data. It can represent random variability within and between groups by applying random coefficients, i.e., applying a random intercept or both a random intercept and a random slope. The hierarchical linear model can furthermore account for random differences within and between groups, which are called random effects. In contrast to the conventional multiple regression model, which contains one error term, the hierarchical linear model contains at least one error term per level. The base model for multilevel models is a model without random effects, which is a conventional multiple regression model (Snijders and Bosker, 1999). As with all regression models its objective is to explain one dependent variable by a set of explanatory variables, so-called independent variables. As the hierarchical linear model explains a process or situation at the most detailed level the dependent variable must be a variable at level one (Snijders and Bosker, 1999). The core of multilevel modeling is therefore that the dependent variable Y has both a group and an individual element. The same applies to the other level one variables X which may also contain a group element. The mean of X in one group may differ from its mean in another group and hence, X may have a positive between-groups variance (Snijders and Bosker, 1999).

5.3.2 Specifying the multilevel models

The model to be estimated is a logistic model because the dependent variable is Boolean (presence of irrigation is true or false). We distinguish between two levels, the grid cell level (level one) and the country level (level two). Variables at the grid cell level may explain part of the grid cell level variability of irrigation. Grid cell variables may in addition explain part of the country level variability of irrigation, if the respective variable (e.g., humidity) is in some countries significantly higher or lower than its mean. Variables at country level may explain differences in irrigation between countries. Equation 5.1 shows a simple two-level model containing one independent variable at each level.

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \gamma_{0j} + \gamma_1 x_{ij} + \gamma_2 z_j$$ **Equation 5.1**

with the probability for presence of irrigation p_{ij}. The independent variable x refers to the grid cell level and independent variable z refers to the country level. Grid cell level effects are marked with the index $_i$ while all country level effects have the index $_j$. The regression coefficients to be estimated are γ_n. Equation 5.1 implies that the grid cell-dependent residuals are assumed to be mutually independent with a mean of zero. To account for between-country variability country-dependent intercepts are included in the model as indicated by γ_{0j}. Hence, the probability, in our study for the presence of irrigation, does not only depend on the grid cell variabilities but also on the countries (Snijders and Bosker, 1999).

The country-dependent intercept γ_{0j} can be split into an average intercept γ_{00} and the country-dependent deviation U_{0j}.

$$\gamma_{0j} = \gamma_{00} + U_{0j}$$ Equation 5.2

U_{0j} are the unexplained group effects, so-called group residuals, which control for the effects of variable *x*. U_{0j} are mutually independent and with zero mean. In our study U_{0j} represents the country-specific deviation of the probability to find irrigation (assuming all other conditions equal). If we exchange the relevant part of Equation 5.1 with Equation 5.2 and exclude all explanatory variables *x* and *z* we obtain the simplest case of the hierarchical model, the so-called unconditional or empty model (Equation 5.3).

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \gamma_{00} + U_{0j}$$ Equation 5.3

The unconditional model (model 0) only contains random effects. As it analyzes which part of the total variance results from between and within level components, it is a good starting point for multilevel analysis. With this model we can estimate whether the variance at the country level is significant. For partitioning the total variance in the variance that is due to the country level the intra-class correlation coefficient (ρ_I) is used (Snijders and Bosker, 1999). In our study ρ_I represents the proportion of the total variation between countries.

Model 1 includes all independent biophysical grid cell variables (*slope*, *discharge*, *humidity*, *evap* and *ET*; Table 5.1) to explain the variance at grid cell level (Equation 5.4). Because linear hierarchical model require normality *slope* and *discharge* were log-transformed. All other variables show normally distributed values.

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \gamma_{00} + \gamma_1 \ln(slope_{ij}) + \gamma_2 \ln(discharge_{ij}) + \gamma_3(aridity_{ij}) + \gamma_4(evap_{ij}) + \gamma_5(ET_{ij}) + U_{0j}$$

Equation 5.4

Model 2 (Equation 5.5) includes in addition to these variables the socio-economic grid cell variables (*access* and *population*) as well as all country level variables (*water, gov_performance* and *gov_type*; Table 5.1). A log-transformation was necessary for *access, population* and *water* to achieve normally distributed variables.

$$\log\left(\frac{p_{ij}}{1-p_{ij}}\right) = \gamma_{00} + \gamma_1 \ln(slope_{ij}) + \gamma_2 \ln(discharge_{ij}) + \gamma_3 (aridity_{ij}) + \gamma_4 (evap_{ij}) + \gamma_5 (ET_{ij}) + \gamma_6 \ln(access_{ij}) + \gamma_7 \ln(population_{ij}) + \gamma_8 \ln(water_j) + \gamma_9 (gov\_performance_j) + \gamma_{10} (gov\_type_j) + U_{0j}$$

Equation 5.5

All independent variables were centered prior the multilevel analysis to control for correlations amongst random components and to stabilize the model. Centering options are discussed and recommended by several authors (Kreft and de Leeuw, 2002; Paccagnella, 2006; Bickel, 2007). We centered the grid cell level variables around their respective country means. The country level variables were grand-mean centered, i.e., they were centered around the overall mean (Raudenbush and Bryk, 2002). We used the HLM6 software for estimating the different models. All parameters were estimated using the restricted maximum likelihood (RML) method and the penalized quasi-likelihood (PQL) approach (Raudenbush and Bryk, 2002). The calculated regression coefficients can be interpreted in the same way as regression coefficients obtained from ordinary logistic regression.

To evaluate the goodness-of-fit of all models we applied a Relative Operating Characteristic (ROC) analysis. The ROC measure indicates how well the estimated models explain the dependent variable. While an ROC value of 0.5 indicates a pure random model an ROC value equal to 1 is considered as a perfect fit (Swets, 1988; Pontius and Schneider, 2001).

To assess whether the multilevel models perform better than an ordinary least square analysis we applied a binary logistic regression to all grid cell variables. All grid cells of the global 5% sample were included in the regression analysis. We did not include the country level variables since they are not grid cell-specific (Equation 5.6).

$$\log\left(\frac{p_i}{1-p_i}\right) = \beta_0 + \beta_1 \ln(slope_i) + \beta_2 \ln(discharge_i) + \beta_3 (aridity_i) + \beta_4 (evap_i) + \beta_5 (ET_i) + \beta_6 \ln(access_i) + \beta_7 \ln(population_i)$$

Equation 5.6

The regression coefficients to be estimated are β_n. Like for the multilevel analysis, Relative Operating Characteristic (ROC) analysis was applied to assess the goodness-of-fit.

5.4 Results

The unconditional model (model 0) has a highly significant variance component. This means there is a significant variability amongst countries in terms of irrigation. The intra-class correlation coefficient ρ_I is 0.56 indicating that 56% of the variance occurs between countries while 44% of the variance occurs within countries. Table 5.3 presents the estimation results of model 1, model 2, and the binary logistic regression analysis. Model 1 shows that humidity and river discharge significantly explain the variability at grid cell level. Hence, the probability for irrigation is higher under arid conditions and if river water resources are available. Slope, evaporation and evapotranspiration have no significant influence on the probability of irrigation. The intra-class correlation coefficient ρ_I is comparable to the unconditional model indicating that these variables cannot explain the variance at the country level as identified by the unconditional model. The results of model 2 show that irrigation is significantly correlated with population density and market accessibility. The variables *gov_performance* and *gov_type* also make a significant contribution to the model at national level. Higher levels of democracy negatively influence the likelihood for irrigation while at the same time the likelihood increases in economically strong and politically stable countries (i.e., countries with higher government performance). Availability of renewable water resources per country cannot explain variability of irrigation at country level. Results of the binary logistic regression analysis indicate that all grid cell level variables contribute to the explanation of the global variability of irrigation. The Wald test (Table 5.3) shows that population density explains most of the global irrigation pattern. Population density alone explains 63.0% of the variability of irrigation while all independent variables together explain only slightly more (65.8% of the total variability).

The ROC value indicates for all three multilevel models a good model fit, which does not much increase from model 0 (ROC = 0.786) through model 2 (ROC = 0.812). This indicates that in spite of the significant contribution of the variables they only have a relative small effect on the overall variance. The model fit of the binary regression analysis is with 0.724 below the model fits of the three multilevel models.

Table 5.3: Coefficients obtained from the multilevel analyses and binary logistic regression.

Variable name	Model 1 Unstand. coefficient	Model 1 *t*-ratio	Model 2 Unstand. coefficient	Model 2 *t*-ratio	Binary logistic regression Unstand. coefficient	Binary logistic regression Wald test
Fixed effects						
Grid cell level (level one)						
Intercept	-0.566**	-3.2	-0.570**	-3.2	0.542***	119.3
Ln*(slope)*	-0.018	-0.3	0.009	0.2	0.136***	248.7
Ln*(discharge)*	0.150***	5.3	0.133***	5.3	0.078***	94.6
Humidity	-1.211***	-5.4	-1.039**	-2.6	-0.347***	88.6
Evap	0.002	1.7	<0.001	0.6	0.003***	221.0
ET	<-0.001	-0.1	-0.001	-1.7	-0.002***	470.8
Ln*(access)*			-0.319***	-4.3	-0.382***	467.9
Ln*(population)*			0.278***	3.4	0.241***	1467.8
Country level (level two)						
Ln*(water)*			-0.006	<-0.1		
Gov_performance			0.409*	2.2		
Gov_type			-0.434**	-2.7		
Random effects (level two)						
var(U_{0j})	4.153***		4.131***		-	
ρ_I	0.558		0.557		-	
Model fit						
ROC	0.806		0.812		0.724	

*** significant at 0.001 level, ** significant at 0.01 level, * significant at 0.05 level

Figure 5.2 and 5.3 show how likely current cropland is irrigated based on respectively model 1 and model 2. The likelihoods for irrigation are high in most arid areas, such as North Africa, Arabian Peninsula, India, Central Asia, Sub-Saharan Africa, South Africa and West America. Many humid countries, for example in Northern Europe and South East Asia, have low probabilities for irrigation. If accounting for socio-economic and governance constraints increases the likelihood for irrigation in countries with a general better government performance (e.g., in France, Germany, USA, Japan, parts of China, Australia) (Figure 5.3). The opposite trend is observed for some countries which are characterized by lower political and economic stability, with a decrease in likelihood for irrigation when also accounting for political factors in model 2, compared to model 1 (e.g., in Bolivia, Central American countries, Nigeria, Zambia, Angola, Ukraine). Hence, unfavorable socio-economic and political conditions are a barrier for irrigated agriculture in some countries.

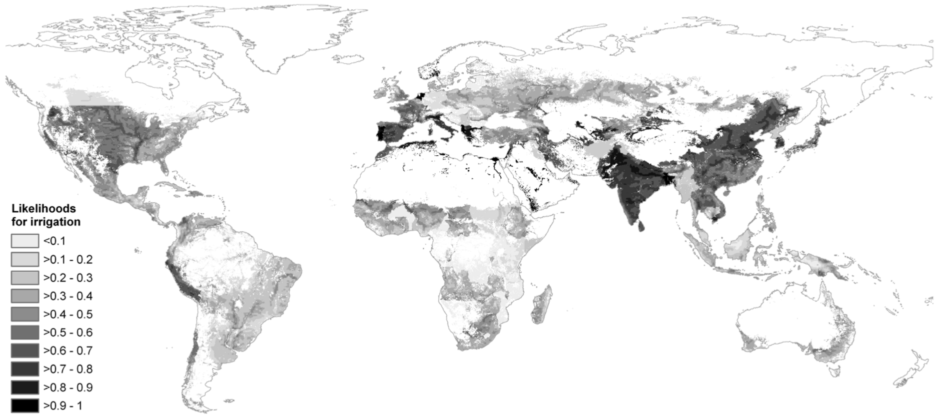

Figure 5.2: Likelihood for irrigation of current cropland considering biophysical information only (model 1).

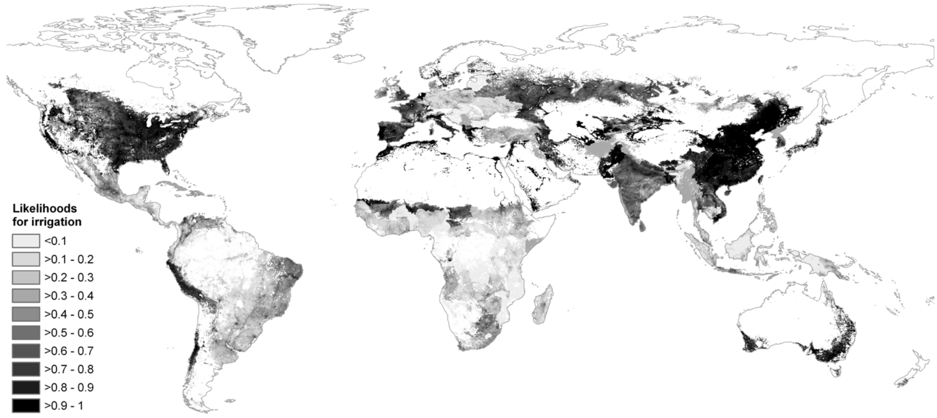

Figure 5.3: Likelihood for irrigation of current cropland considering biophysical, socio-economic and governance information (model 2).

Differences between model 1 and model 2 are not only remarkable between countries but also within countries. Figure 5.3 shows that probabilities for irrigation in model 2 are higher than in model 1 for many metropolitan areas with high population densities and better market accessibility representing the capital investment needed for establishing irrigation (e.g., in California, East USA, around Lake Victoria, Java, East China). In the USA and East China likelihoods for irrigation are dominated by the occurrence of river discharge in model 1. In model 2, the contribution of the socio-economic and political factors significantly changes the regional pattern of irrigation likelihoods.

5.5 Discussion

The study has shown how a multilevel analysis can be applied for the spatial analysis of land use management, such as irrigation, accounting for processes operating at different spatial scales. In this section we first discuss the methodological issues related to this analysis followed by a discussion of the findings.

5.5.1 Data and methodology

Water availability and climate are important drivers of irrigation and we therefore considered river discharge, evaporation, evapotranspiration and humidity at the grid cell level. These variables may, however, vary within a year and between years. For example, temporal seasonality of precipitation within a particular year likely influences the farmer's decision to irrigate in a certain season, which is difficult to capture by the averaged monthly mean data. Furthermore, in many cropping regions irrigation facilities are installed to anticipate periods of uncertain precipitation and to minimize the risk of crop yield losses in exceptionally dry periods. Often these irrigation facilities are used every other year only and their presence cannot be explained by long-term average climate data as used in this study, which potentially causes statistical noise.

Another hydrological aspect to be considered when explaining the global distribution of irrigated areas is the accessibility of groundwater because for several countries groundwater is the most important source of irrigation water. Groundwater has been extracted for irrigation for many years in the USA, India, Pakistan, China, Mexico, Yemen and many other countries (Shah et al., 2000; Shah et al., 2006). The accessibility of groundwater is therefore not only important for explaining the current pattern of irrigated areas but also for identifying potential areas for irrigation. Global datasets with the spatial extent and characteristics of aquifers are, however, not available. The World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) has mapped groundwater sources of the world but the spatial resolution is too coarse for our purposes and no information about accessibility of the water resources is provided (http://www.whymap.org/). We could therefore not explicitly account for aquifers as explaining factor for irrigated cropland.

The most detailed units of analysis are 5 arc-minute grid cells. This resolution was chosen because irrigation data as well as a number of socio-economic variables are available at this resolution. The hydrological data are, however, only available at 0.5 degree resolution. We applied the 0.5 degree data to the 5 arc-minute resolution which may introduce some bias. Yet, we did not include the 0.5 degree resolution as an extra level as it is rather a spatial scale for representing the data and not a distinct spatial level. Neither did we resample the irrigation data to 0.5 degree in order to not loose too many spatial details. This consideration leads to the issue of data quality. The irrigation data are based on a large variation of sources from different years which most likely causes uncertainties. Independent variables were collected from different sources and since they are not validated it can be expected that their accuracies differ. Statistical noise is therefore an inherit property of the data used in our study.

Land management decisions are often made at the household level and it may be tested whether conditions at the household level are also important for explaining the overall pattern of irrigated cropland. At this level information on (additional) income sources, ethnicity, land ownership, water rights and access to funding may be accounted for. Several authors have considered the household level in multilevel analysis of land use studies (Pan and Bilsborrow, 2005; Overmars and Verburg, 2006; Vance and Iovanna, 2006). Considering the global context of this study such aspects could not be included given the lack of consistent data at the global scale. We consider irrigation therefore as a function of local biophysical, socio-economic, and political constraints rather than as a land management technique applied at household level.

5.5.2 Evaluation of results

Figure 5.2 and 5.3 show a remarkable difference in probabilities for irrigation between model 1 and model 2. While the first model only accounts for biophysical information the latter model accounts for biophysical, socio-economic and governance information. The results of the multilevel analysis show that accounting for multiple levels is important for analyzing global irrigation pattern. The considered variables at national level explain, however, only little of the variation in irrigation between countries. We consider two main reasons for this.

To some degree this may be explained by recent political changes. Irrigation systems were often established decades ago when economic and political conditions may have been different from today. Hence, the current global irrigated pattern is inherited from earlier circumstances, which makes it difficult to explain it with current political and economic information. Heavy investments in irrigation systems in Central Asia, carried by the former Soviet government as important part of its agricultural development policy, resulted in an expansion of irrigated areas during the Soviet period (Saiko and Zonn, 2000). For example, irrigation is still largely applied in the former Soviet Republic Uzbekistan, while the political and economic conditions have changed drastically in the meantime. The different time reference of the construction of irrigation and the independent variables impede a complete explanation of the current situation. The same applies of course for the grid cell level constraints, such as market accessibility and population density. However, many of the grid cell level variables are assumed to be less dynamic over time.

A second explanation for the limited influence of the country level variables is the large size of a number of countries. For large countries such as the USA, Brazil or China the use of country average governance data may be less appropriate. Significant differences in GDP per capita between different regions of China have been revealed by Akita (2003). To capture such regional disparities an intermediate level, for example the province level, may be needed. Globally consistent and complete data at such level is, however, not available.

Results of the binary logistic regression analysis show that all independent grid cell variables contribute to the explanation of the presence of irrigated cropland. This is in contrast to the results of the multilevel analyses which conclude that slope, evaporation, evapotranspiration and national water resources do not significantly contribute to the explanation of the irrigated cropland pattern. Moreover, the individual contribution of the significant independent variables differs between the two applied methodologies. In multilevel analysis variables at the grid cell level can explain variability within and variability between countries. While certain grid cell variables may largely vary across the globe they may, however, vary less within countries because some countries may capture some of the biophysical effects due to their geographic location. This may result in non-significant variables in the multilevel analysis. It may furthermore explain the little increase of the ROC value through the three multilevel models.

The predicted probabilities for the presence of irrigation may also indicate areas where expansion of irrigation is likely. Therefore a map of probability areas that are currently not irrigated was made based on the results of model 2 (Figure 5.4). This map shows cropping regions where irrigation is likely to be applied if demand for irrigation increases and biophysical, socio-economic and governance conditions do not change. Under these circumstances expansion is most likely in the neighborhood of irrigated areas, for example in East China, North Africa, and parts of the Mediterranean region, as well close to urban areas, for example in the East USA. The identified regions of high likelihoods for irrigation expansion largely coincide with potential areas for irrigation identified by FAO (2003). An exception is South-East Asia (Indonesia, Papa New Guinea, Malaysia, Philippines) for which we have identified low probabilities for extending irrigation given the high humidity in this region. The calculated probabilities do not only indicate rainfed grid cells where irrigation may be introduced but also irrigated grid cells where the percentage of irrigation may be increased. Only 12% of all grid cells classified as irrigated cropland are fully irrigated while the majority of grid cells include at least some rainfed areas. Hence, potential for irrigation expansion may also exist within currently irrigated regions. Information on areas with high probabilities for irrigation expansion is crucial for any model application on spatial-temporal dynamics of food production. These maps can be used to explain possible locations of agricultural intensification (Neumann et al., 2010; Chapter 4). Climate change will influence precipitation, evapotranspiration, snow pack, groundwater recharge, and other factors of water resources and water demand. This, in turn, will affect both the demand for irrigation and the availability of irrigation water (Döll, 2002; Izaurralde et al., 2003; Rosenzweig et al., 2004). Hence, to further investigate potential areas for irrigation expansion future scenarios of climate change are recommended to be used to account for changes in irrigation water requirements. Rosegrant et al. (2009) argue that irrigation will remain the world's largest user of fresh water till 2050, although its share is projected to decline compared to domestic and industrial water uses. While our results show possible locations for irrigation expansion under current constraints, possible emerging water scarcity should be taken into account when modeling future expansion of irrigated areas. The results of our study also indicate that political developments may influence investments in irrigation systems. For example, the recent land reforms in Zimbabwe led to the fail of agriculture and a loss of nearly all irrigation systems throughout the country (Moss and Patrick, 2006) and the collapse of the communism in Eastern Europe caused a drastic decline in the extent of irrigated areas (Theesfeld, 2004; Fraser and Stringer, 2009). Contrariwise, the collapse of the communism did not lead to a comparable decline of irrigated cropland in Uzbekistan since irrigated cotton and rice production have a strong tradition and are still supported by the Uzbek government.

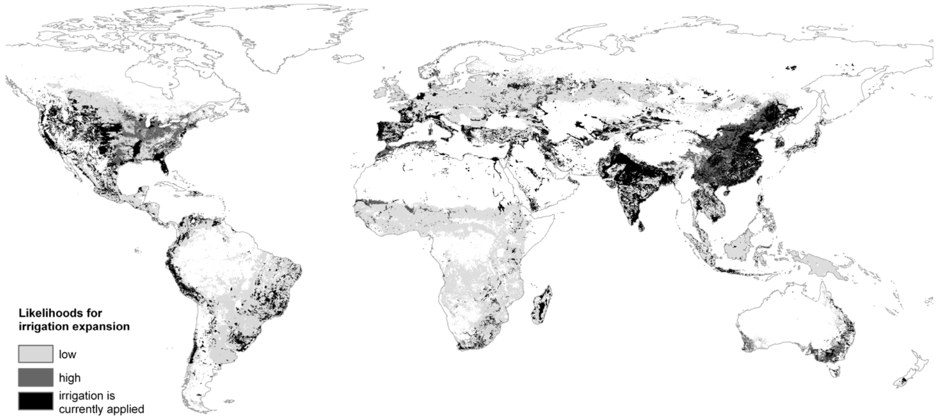

Figure 5.4: Potential areas for irrigation expansion.

5.6 Conclusions

The results of this study have confirmed the multilevel structure of the determinants of irrigation by accounting for grid cell and country level variables. Our results suggest that it is necessary to consider biophysical, socio-economic and governance information for identifying location factors of irrigation. Taking only biophysical information into account may lead to an overestimation of the likelihood for irrigation in countries with low political stability and low economic strength. The current study is a first step of addressing irrigated land more explicitly in global models of land use change and food production based on empirical analysis.

Chapter 6

Synthesis

6.1 Explaining agricultural intensity at the European and global scale

6.1.1 Introduction

During the past half a century, world population more than doubled from approximately 3 billion in 1960 to 6.6 billion in 2008 (Worldbank, 2010). To accommodate the growing food demand global food production has strongly increased. Since 1960 global cereal production has almost tripled and today, more than 2.5 billion tons are harvested per year (FAOSTAT, 2010). In the same period, production quantities from cattle has approximately doubled (beef meat and milk) and chicken meat production increased tenfold. The increase in food production is mainly a consequence of increased crop and livestock productivity, resulting from improved breeding, increased livestock stocking densities, and larger use of fertilizer, water and pesticides (Tilman et al., 2002). Agricultural intensification could largely avert a shortfall in food supply till 2000 (Cassman, 1999). However, since 2000 the number of undernourished people increased to 1 billion which is largely the result of a growing world population, increasing scarcity of agricultural resources, and the economic slowdown following the food crisis in 2006-08 (FAO, 2009a). Considering the population growth, a diet shift towards more meat in numerous developing countries, competition for land from biofuel cultivation as well as land scarcity in many cropping regions, agricultural intensification is expected to also play an important role for achieving food security in the future (Matson et al., 1997; Ruttan, 2002; Balmford et al., 2005).

The debate about growing food demand, food security and environmental consequences of food production draws more and more attention in both the scientific community and society. Agricultural land management and agricultural land use intensity have been extensively studied at the farm scale and regional scale (Shriar, 2000; Maertens et al., 2006; Pascual and Barbier, 2006; Tittonell et al., 2009). However, at the global and continental scale (spatially-explicit) information on agricultural land management practices and land use intensities is scarcely available (GLP, 2005). Many methodologies that are developed for farm scale research cannot be applied at the global scale (given the underlying assumptions and data requirements) and upscaling farm scale information to the global scale is problematic since drivers and processes of land management often do not behave linearly. Hence, to explain agricultural land management and land use intensity at the global scale new methodologies need to be developed and implemented as shown in this thesis. In this chapter the findings of this thesis are used to discuss perspectives for continental and global land use intensity research. The new insights are used to discuss development support options for policies that specifically target the issues of food supply, environmental protection, and climate change mitigation at different spatial scales. This chapter finishes with some suggestions for modeling agricultural intensification at the continental and global scale.

6.1.2 Methodological conclusions

The main objective of this thesis was to explore spatial diversity in agricultural land management and land use intensity, including livestock, efficiency of crop production, and irrigation, across the globe. To meet this objective a variety of quantitative methodologies was developed and applied. A portfolio of different methodologies, originating from different scientific fields, was used. This was done to deal with the characteristics of the land use system and to account for differences in data structure. The applied methodologies can be classified into expert-based and empirical. While expert-based approaches use assumptions based on case study evidence and system understanding, empirical approaches test hypotheses by using observed or experimental data. Empirical approaches used in this thesis include commonly applied methods (regression analyses), originate from social sciences (multilevel analysis) and econometrics (frontier production function) (Snijders and Bosker, 1999; Coelli et al., 2005). In this section the main methodological conclusions derived from the individual chapters are discussed.

Chapter 2 combines an expert-based and an empirical approach to identify location factors of five different livestock types in Europe. Both expert-based allocation rules and multiple linear regressions results were used to downscale livestock data from NUTS regions to grid cells. The purpose of using the two different approaches was to study the robustness of the methodology. From the validation results it can be concluded that both the expert-based and empirical approach are equally suited for predicting the locations and concentrations of herbivores (dairy cattle, beef cattle, and sheep). Monogastrics (pigs and poultry) can be better predicted by accounting for socio-economic factors in addition to biophysical factors as it was done in the empirical approach. Generalizing this, it can be concluded that downscaling efforts for continental and global non-grazing livestock distributions perform best when based on empirical findings obtained from biophysical and socio-economic information.

Chapter 3 integrates results of Chapter 2 in a dynamic multi-scale modeling framework. The objective of the developed modeling approach was to explore spatial and temporal dynamics of livestock distribution by integrating a broad range of processes and factors related to livestock farming, for example economic development and climate change. Continental land intensity modeling studies can most effectively be carried out by integrating empirical findings with expert knowledge. Because empirical approaches are not necessarily causal, adding expert knowledge on processes ensures a certain level of causality which is needed for extrapolating the relations in a dynamic modeling context. By doing this, general land use (intensity) trends can be simulated as shown in Chapter 3.

One issue that is frequently addressed in discussions about how agricultural land management and intensification can be improved in a sustainable manner is the efficiency of agricultural production (Matson et al., 1997; Cassman et al., 2002; Tilman et al., 2002; Rosegrant et al., 2009). Econometrics provides a wide range of tools for efficiency analyses, for example stochastic frontier production functions. In this thesis a stochastic frontier production function was chosen for a consistent analysis of the yield gap in current global grain production using observed grain yield data (Chapter 4). Alternatively, potential grain yields may be simulated with crop models. However, a comparison of observed grain yields with simulated grain yields bears several disadvantages, mainly due to possible data inconsistencies (Chapter 4). Furthermore, simulated potential grain yields do not indicate how realistic they are. Lobell et al. (2009) discuss whether average grain yields can actually exceed the eighty percent of their potential yields, which is the economic optimum production level in many major cropping systems. Because farmers aim for maximizing profit instead of grain yield the suitability of potential yields can, and has been debated (see Veldkamp et al., 1996). Global yield gap studies should account for the feasibility of reaching certain crop yields to not overestimate potential yield gains. The frontier production function is therefore a suitable methodology since it allows calculating the yield gap based on maximum attainable yields and, hence accounts for realistic crop yields.

Land use is the result of several processes operating at different spatial scales. One approach that is particularly suited for addressing different spatial scales in hierarchically structured data is multilevel analysis. Multilevel analysis accounts for within-level and between-level relations within a single analysis and therefore does not require aggregation or disaggregation of the variables to the level of analysis. A multilevel analysis was applied to explain the presence of global irrigated cropland using variables at two different spatial levels: grid cells and countries (Chapter 5). This methodology was chosen because drivers of irrigation are assumed to operate at different spatial scales and much irrigation related data are hierarchically structured. Biophysical constraints of irrigation, such as climate and water availability, are location dependent (i.e., grid cell-specific) while political constraints, for example economic strength and governance aspects, may influence irrigation at the country level. From the results it can be concluded that countries are an important level for explaining global irrigation: 56% of the total variance in irrigation occurs between countries while 44% of the variance occurs within countries. This observation underpins the important role of countries as unit of analysis in land use pattern analyses, which has also been confirmed by Kok and Veldkamp (2001). Generalizing this, it can be concluded that the country level is important for global analysis of intensively managed land use systems.

The expert-rules downscaling approach (livestock; Chapter 2), the frontier production function (crop yields; Chapter 4), and the multilevel analysis (irrigation; Chapter 5) were consistently applied across the globe. Hence, the same assumptions and statistical relationships were applied to all grid cells. A different approach was used for the empirical downscaling approach of livestock for which country-specific relationships between individual livestock types and their location factors were identified (Chapter 2). Such analysis supports a better understanding of differences between countries and information on country-specific location factors may be used to facilitate the development of national spatial environmental planning instruments. However, the functions and individual drivers (e.g., regression coefficients) cannot be exchanged between countries. Globally consistent approaches support a better understanding of causalities at the global scale. For example, the efficiency of resource use in crop production is consistently calculated globally and hence, the obtained frontier yields and derived yield gaps can be compared between countries or any other scale of detail (Chapter 4). Such a globally applied approach gives, however, no indication for country-specific inefficiency effects and their magnitude of influence. Whether to apply a globally consistent or a country- or region-specific approach (within a global framework) depends on the objective of the study.

6.1.3 Conclusions about agricultural land management and land use intensity

Despite the methodological focus of the thesis three main observations on agricultural land management intensity were made. These observations address characteristics of the land, path dependencies of land use (management) as well as spatial scale issues and are discussed in this section.

The first observation addresses the basis of agricultural land use: the land. Results of this thesis show that agricultural land management and land use intensity depend only to a certain degree on the biophysical characteristics of the location. A similar result was found for Central American countries by Veldkamp et al. (2001b). Chapter 2, 4, and 5 illustrate that livestock farming, efficiency of crop production, and irrigation can only to some degree be explained by climate and land related information, such as land cover, slope, grassland productivity, or temperature. Socio-economic and political factors, for example population density, labor availability, and market accessibility also explain the spatial variability of agricultural land management and land use intensity. This is especially obvious for monogastrics for which the empirical downscaling approach, considering socio-economic variables in addition to the land related variables, is generally better suited than the expert-based approach which only accounts for land related and climate information (Chapter 2). However, the availability of socio-economic variables is limited and results (especially for poultry) lead to the conclusion that other factors, for example farming traditions, religions, farm sizes, specialization trends, regional and local politics, subsidies, and attractiveness of other sector employment may be even more influential. A similar observation was made for crop production and irrigation (Chapter 4 and 5), as well as in earlier land use pattern studies (de Koning et al., 1998; Long et al., 2007). Efficiencies of crop production depend on land management and socio-economics; and irrigation is largely constrained by local climatic and hydrological conditions but political and socio-economic aspects influence irrigation as well. Although the observations made in this thesis are specific for irrigation, livestock farming, and grain production, it can be concluded that agricultural land management and land use intensity in general cannot solely be explained by biophysical characteristics of the environment. Agricultural land management and land use intensity studies should therefore account for socio-economic and political constraints in addition to the biophysical conditions. Because consistent spatially explicit data are scarce at the global scale their development and improvement should be prioritized on the research agenda. Preferably such data should be collected a global level and not based or modeled from other existing global data sources as often done.

The issue of data availability leads to the second observation which addresses the explanatory power of the conducted studies. Results of Chapter 2, 4, and 5 reveal that land use intensity and agricultural land management cannot fully be explained by the explanatory variables included in the analysis. This is indicated by either a low coefficients of determination (Chapter 2), a low gamma value (Chapter 4), or a low ROC value (Chapter 5). Reasons for this are limited availability and quality of data (poor data quality leads to more random noise yielding poor relationships) describing current conditions and drivers of agricultural land management and land use intensity (see the above discussion in this section). Another, probably similarly important, reason is the path dependency of land use and land management which explains some of the current livestock distribution and irrigation pattern. Livestock farming and irrigation of arable land often have a strong path dependency as they go along with long-term investments (irrigation equipment, machinery, farming infrastructure etc.). Analyzing the current state of agricultural land management gives therefore only some information on what has triggered intensification in the past. But the space time analogy assumption does imply that current pattern can give insight in future patterns. Results of this thesis suggest accounting for both historic developments and current conditions when explaining the contemporary pattern of agricultural land management and land use intensity. A few spatially explicit datasets on historic development of global land use and population have been available since a few years (Ramankutty and Foley, 1999; Goldewijk, 2001; Goldewijk, 2005) which are currently being supplemented by mapping efforts of historic development of urban areas and anthropogenic biomes (Ellis et al., in press; Goldewijk et al., in press). However, these datasets are largely based on modeling results, e.g., downscaling national information to grid cells based on several assumptions, which limits their applicability as independent datasets.

The third major observation refers to the spatial scale issue. Results of Chapter 4 let conclude that factors explaining differences in grain production efficiencies at the global scale are not necessarily equally important at the world-regional or national scale. Knowledge about factors explaining differences in land use and land management at one scale cannot linearly be applied to another scale. Moreover, drivers and constraints of agricultural land management are only appropriately considered in land use analyses if they are addressed at the correct scale. For example, international agricultural policies like the CAP or other national regulations are most appropriately addressed at the national scale. Hence, at the scale they were developed and implemented for. On the other hand, ecosystem properties such as climate, hydrology, and soil characteristics are most likely better addressed at the local or regional scale, which should be determined by a scale sensitivity analysis. Aggregation of local scale variables to administrative units may introduce biases, especially if the variables show a significant variability within such an administrative unit. To avoid such bias different spatial scales should be considered as an inherent characteristic of land use systems (Chapter 3 and 5).

6.2 Perspectives for land use intensity research in land change science

6.2.1 Current constraints for continental and global land use intensity studies

Land use change has been extensively studied addressing issues like the location of change, moment of change, type of change, and drivers of change (e.g., Wear and Bolstad, 1998; Lambin et al., 2003; Verburg et al., 2004; Overmars and Verburg, 2005; Lambin and Geist, 2006; Long et al., 2007). Despite enormous scientific and technological progress in the recent years these questions are, however, still difficult to answer for several regions across the globe. This is either because reliable information about the extent and location of land use change does not exist or causal relationships between land use change and its drivers are not fully understood. Exploring possible future changes of land use remains an even larger challenge as many driving processes cannot be foreseen. If we narrow the perspective to agricultural land management and land use intensity the knowledge gap is even larger. Information on agricultural land management and land use intensity at the continental and global scale is scarce. Only recently first global datasets of land management aspects were generated (Siebert et al., 2005; Portmann et al., 2010; Potter et al., in press) which is in contrast to the better availability of biophysical data (USGS, 1996; Worldclim, 2005; Climatic Research Unit, 2010). Moreover, different theories exist which address land use intensification differently. While the Malthusian theory considers expansion of the land area under cultivation if population grows (Malthus, 1960) Boserup argues that land, if it becomes scarce due to population growth, is more intensively used (Boserup, 1965). In fact, agricultural intensification often goes together with agricultural expansion at the land frontier (e.g., Maertens et al., 2006; Morton et al., 2006; Galford et al., 2008). Moreover, in many regions where agricultural practices are characterized by modernization and rationalization agricultural intensification takes place in the most favorable areas while land abandonment occurs elsewhere (MacDonald et al., 2000; Strijker, 2005). Drawing conclusions about possible intensification processes is therefore difficult.

Although information on agricultural management and land use intensity is available for many farms or regions this information is not comparable across the globe because data were often obtained from different sources, for different moments, or different methods and processing techniques were applied. Furthermore, upscaling land management characteristics from farms to regions is challenging because agricultural land management practices are often specific for a farm or region and are influenced by a plentitude of factors (Tengberg et al., 1998; Tittonell et al., 2005; Beyene et al., 2006). Upscaling drivers and processes of land management is similarly challenging because they often behave non-linearly across scales (Easterling, 1997). Linear upscaling approaches will most likely not suffice and non-linear or hierarchical upscaling procedures may be required. Moreover, upscaling farm level information to an aggregated level inevitably implies a loss of information on the diversity of land management practices.

One way to collect additional data is the use of remote sensing. Remote sensing techniques are frequently used in land change studies for detecting land cover characteristics by measuring their spectral radiance. However, the detection of certain land use types, land use management pattern, or different intensities of land use is hardly possible. Yet, some encouraging studies have shown the potential of remote sensing data to derive land management related information by using multi-spectral analysis, such as grazing intensities (Kawamura et al., 2005), degree of land degradation (Hunt et al., 2003; Archer, 2004), parcel size (Kuemmerle et al., 2009), and hydrological information being valuable for irrigation management (Bastiaanssen et al., 2000). So far such studies are, however, restricted to the regional scale. Moreover, remote sensing techniques are only able to detect surface characteristics with a distinct spectral response pattern (e.g., vegetation type, moisture, altitude). The palette of detectable determinants of agricultural land management is therefore largely restricted to biophysical factors. Results of this thesis show that agricultural land use and land management are, however, influenced by both biophysical and socio-economic factors. Socio-economic data can best be derived from (agricultural) census data, which are available for most countries at national and sub-national level. Agricultural census data include management information, such as irrigation, fertilizer application, manure management, mechanization, specialization, which cannot be collected through remote sensing. Several agricultural land use studies have combined and harmonized remote sensing data with census data to benefit from both data sources (Frolking et al., 2002; Kerr and Cihlar, 2003; Ramankutty et al., 2008).

Quality and support of remote sensing data and census data differ, however, and data are often only limitedly comparable (between time and space) due to differences in data acquisition, classification systems, and reporting methods. To overcome such limitations, strategies for harmonization and standardization need to be developed and implemented. In the recent years several international efforts have been made aiming at assisting ongoing and upcoming mapping initiatives to foster consistent and comparable ways for creating land cover maps (Jansen and Gregorio, 2002; GCOS, 2004; Herold et al., 2006). However, analogous efforts for land use data are missing since international consensus on the definition and classification of land use has not yet been reached (Jansen, 2006). Future data generation therefore has to go together with the development and enhancement of standardization methods for remote sensing data and census data.

Data quality is a fundamental restriction for consistent land use intensity assessments at the continental and global scale. But improving data availability alone does not lead to a better understanding of the land management processes. Based on available data relationships between agricultural land management and its drivers and constraints need to be analyzed and causal relations can be used for theory building.

6.2.2 Methodologies for land use intensity research at the continental and global scale

One approach for identifying the human impact on the biosphere is the Human appropriation of net primary production (HANPP) (Haberl et al., 2007). HANPP indicates the difference between the amount of NPP that would be available in an ecosystem without human activities and the amount of NPP that actually remains in the ecosystem. HANPP can therefore be used as an indicator for land use intensity, i.e., how much of the land and its production is used, which is not restricted to agriculture.

One method that is particularly suited for representing the complex interplay of several agricultural land use related aspects is the development of farming system descriptions. Farming systems are typically characterized by the type of agricultural production at the farm but also farm management aspects are often an inherent characteristic. Farming systems have been defined and analyzed in many studies, although most of them are linked to the regional scale (Morris and Winter, 1999; Devendra and Thomas, 2002; Poudel et al., 2002; van de Steeg et al., 2010). Because consistent and comparable farm level information is not available at the global scale the development of a reliable, spatially explicit and globally applicable farming system description is hampered. At the global scale Ellis and Ramankutty (2008) have identified and mapped land use systems that go beyond the agricultural sector using information on land cover, land use, and population density. The obtained 18 anthropogenic biomes illustrate the human–ecosystem interactions across the terrestrial biosphere. Agricultural land management has been considered by including information on irrigated areas but other aspects of input intensity (e.g., fertilizer application, machinery use) or output intensity (livestock or crop productivity) were not considered. Results of this thesis support the elaboration of (agricultural) land use system descriptions. Livestock densities (Chapter 2) may either represent an agricultural land use type or can be used as a proxy for land use intensities while yield gap information may contribute to the system definition as a measure of production efficiencies (Chapter 4). Together with available information on additional land use types, crop types, cropping periods, remoteness, (agricultural) population and land management (e.g., irrigation, fertilizer application), agricultural land use systems may be defined at the continental and global scale.

The allocation of agricultural resources is frequently analyzed using econometric approaches. Econometric approaches assess input demand (e.g., fertilizer, labor, machinery) and output supply (e.g., production) at the household level to represent the behavior of a population of farmers. Such analyses are usually conducted at the regional scale and only a few studies were implemented at the country scale (Antle and Capalbo, 2001; Pender et al., 2004; Stoorvogel et al., 2004; Benin et al., 2005). At the continental scale, limited data availability and the increased complexity of environmental and economic feedbacks often hampers the implementation of econometric approaches. Chapter 4 illustrates that an econometric approach can be applied spatially explicitly at the global scale without explicitly considering the household level. Results show that inefficient land management causes the present average actual grain yields being below two thirds of their frontier yields. Hence, improving the efficiency of agricultural land management could increase food production up to 50% of the current production levels. This approach was applied at the global scale but can be applied at any other spatial scales of agricultural production. This thesis furthermore suggests alternative methods to identify how resource availability, for example productive grassland and natural water resources, influence land management and land use intensity at the European and global scale (Chapter 2, 3, and 5).

Households play a crucial role in many regional land management studies. This is because land management decisions are often made at the household level (Vosti and Witcover, 1996; Swinton, 2002; Tittonell et al., 2005). At the household level farmers decide what to produce, whether to irrigate, fertilize, mow or plough the land and if so, to what degree. The farmer's decision is influenced by many factors. Climate, soil properties, and environmental legislations for example largely determine the ability of a farmer to manage the land in a certain manner. Other factors, such as alternative income sources, farmer's age, and land ownership influence the farmer's willingness for using and managing the land in a particular way (Siebert et al., 2006a; Valbuena et al., 2008). To model agricultural intensification it is therefore often argued that decision making processes of the individuals need to be accounted for. Modeling decision making processes at the global scale faces, however, many challenges. An adequate representation of land use management drivers including socioeconomic, environmental, and political factors interacting across multiple spatial and temporal scales is one of the main challenges. Furthermore, decision making processes need to be simplified (although they do not necessarily need to be reduced to one level) to reach model transparency, error reduction, and proper parameterization of complex relationships. However, such a generalization hampers a sound representation of the globally diverse decision makers and their dynamics, regardless their large contribution to land use and land management change (Verbeeten et al., 2007). According to Lambin et al. (2000) integrated assessment models may have the largest potential for simulating agricultural intensification. Integrated assessment models summarize the complexity of decision making in a few simple model rules and hence, treat intensification processes in a simplistic manner. Chapter 2, 4, and 5 identify clear relationships between livestock densities, crop production, irrigated cropland and their respective explanatory variables, which shows such simplification is possible. However, the remaining variances indicate that simplification may also reduce the level of explanation. Figure 6.1 gives an overview of different land management-related processes that should be considered in land use intensity research. The figure shows at which spatial scales these processes occur and which model types are commonly used to address them.

6.3 Policy development support

Land use type and land use management data are essential for estimating greenhouse gas (GHG) emissions and reporting them to the commission of the Intergovernmental Panel on Climate Change (IPCC). At present, countries report their changes in land use and land use management as well as the consequent land use emissions to the commission individually, making best use of their available national or regional data. However, using different data sources and applying different land use classification systems result in globally inconsistent GHG emission estimates. For example, estimating emissions from livestock requires annual population numbers and population characteristics such as feed intake (IPCC, 2006). Definitions of livestock categories and subcategories may, however, vary between countries, which potentially leads to inconsistent livestock emission estimates. Consistent and detailed information

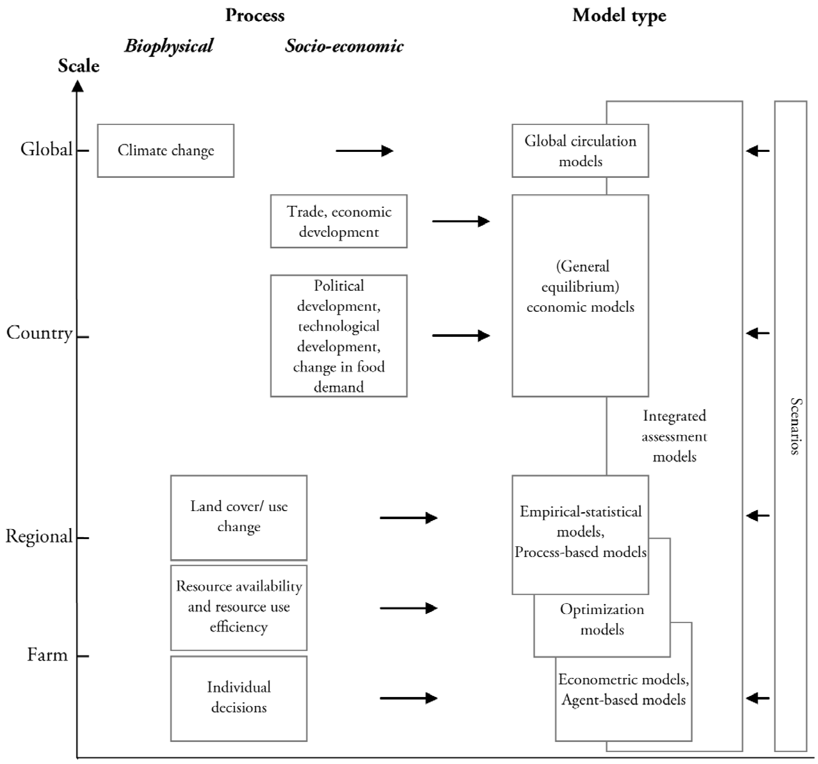

Figure 6.1: Scale-dependent processes to be accounted for in land management research and exemplary model types to address these processes.

on livestock type-specific populations at the continental or global scale (Chapter 2) could ease IPCC practice if they supplement or replace national data sources for livestock emission inventories. The same applies for all other land use types and land use management practices.

Global emissions of agricultural methane (CH_4) and nitrous oxide (N_2O) have increased by nearly 17% since 1990 and today, agriculture accounts for 10-12% of total global anthropogenic emissions of GHGs (Smith et al., 2007). Numerous politicians and scholars argue that agriculture needs to be part of any new mitigation mechanisms under post-Kyoto agreements to reduce GHG emissions while providing food security. To contribute to the development of policy-relevant decision support systems for international policy approaches, information about agricultural land use and land management are crucial. A variety of mitigation options exist that particularly address land management. These options include improved management of crops and grazing land, restoration of organic soils, and improved water, rice, livestock and manure management (Paustian et al., 2000; Smith et al., 2000; Cai et al., 2003b; Weiske et al., 2006). Yet, it is argued that only little progress has been made in their implementation at the global scale which can only be enhanced by policy and economic incentives, such as promoting global sharing of new technologies (Smith et al., 2007).

A number of policies have been implemented for the member states of the European Union targeting both environment and food production. Environmental policies aim for protecting water (e.g. Water Framework Directive and Nitrate Directive), threatened habitats and species (Habitats Directive and High Nature Value Farmland), or soil (the proposed Soil Framework Directive) while the European Common Agricultural Policy (CAP) supports famers income and the implementation of environmentally beneficial farming methods. For assessing the effectiveness or need for such continental policies detailed data on land management and land intensity are required which are, however, limited. For example, European wide nutrient losses from livestock manure were modeled at NUTS level by Oenema et al. (2007) to discuss environmental policies that regulate the use of animal manure. However, the variability of livestock within these regions may vary substantially (Chapter 2 and 3), which may reduce the applicability of the regional policies. By integrating dynamic high resolution livestock density information (Chapter 3) with dynamic information on livestock management (e.g., housing systems, manure storage systems), land cover and soil characteristics, the impact of different policies on future nitrogen (N) and GHG emissions can be assessed at high spatial resolution.

At the global scale, effective policies are lacking or non-existent in many agricultural production regions. Such lack often caused non-sustainable agricultural land management and hence a threat for food production. Examples are found across the globe, for example near the Aral Sea (Cai et al., 2003), in many drylands (Geist and Lambin, 2004) and along the Nile Delta (Kotb et al., 2000). Policies are, however, not only required to combat environmental damage but also to boost sustainable agricultural production in many regions. The yields gaps identified in Chapter 4 indicate regions of inefficient grain production where policies may be implemented to increase food crop production. For example, efficiency of Chinese wheat production is mainly influenced by the variability of slope; the steeper the slope the lower is the efficiency of wheat production (Chapter 4). By managing adverse slope conditions the wheat productivity can be increased. In this example, agricultural policies may target at supporting the farmer to purchase certain machinery to manage steeper slopes. Besides, alternative land management techniques may be stimulated to avoid soil erosion and runoff of precipitation and irrigation water to increase grain and consequently food production.

6.4 Modeling global agricultural intensification: An outlook

From the discussions above some suggestions are derived what to consider for modeling agricultural intensification at the continental and global scale. Three main issues were identified and addressed: data requirements, model requirements and policy impact assessment.

- Data requirements:
  - Consistent time-series on biophysical and socio-economic conditions are essential to identify different pathways of agricultural intensification in the past. These pathways, in turn, may be considered for the development of scenarios of alternative intensification trajectories in the future. However, currently available data do not allow for identifying historical agricultural intensification pathways across the globe.
  - Information on biophysical conditions, socio-economic conditions and land management practices should be equally considered when modeling agricultural intensification.
  - To characterize intensity of agricultural management in an overall manner rather than characterizing one single management aspect, an overall intensity

index may be developed and applied. An overall intensity index can aggregate several aspects of land management (e.g., irrigation, rotations, mechanization) as shown for Europe and Canada by Herzog et al. (2006) and Kerr and Cihlar (2003), respectively.

- Model requirements:
  - Approaches for modeling agricultural land management and land use intensity should consider countries as unit of analysis to account for political and governance aspects but also for certain socio-economic characteristics at that level.
  - Agricultural intensification is probably best modeled if simultaneously accounting for agricultural expansion and land abandonment. This requires to explicitly addressing the feedbacks between these processes. Because the interplay of these three processes is not yet fully understood further research on this topic is required.
  - Constraints and drivers of agricultural production need to be addressed at the appropriate spatial scales which can be achieved by integrating models operating at different spatial scales (e.g., a nested model). At the detailed scale intensification processes can be simulated that would be too computationally intensive if applied globally (e.g., agricultural intensification and expansion).
- Policy impact assessment:
  - Future research should elaborate on approaches that explore policy impacts both within the region of policy implementation (e.g., influence of the CAP on European land use (intensity)) and outside (e.g., influence of the CAP on non-European land use (intensity)).

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Summary

In the previous decades agricultural intensification led to strong increases in agricultural production in both developed and developing countries. Given the world's growing population together with a diet shift towards more meat in many developing countries as well as the land scarcity in many cropping regions, agricultural intensification is expected to remain crucial for accommodating growing food demand. Agricultural intensification can have different forms, which are determined by different types of agricultural land management. Agricultural land management, in turn, may be specified by the interplay of production mix, production techniques, mechanical technology, water management, labor, or other capital investments. Agricultural land management and land use intensity differ across the globe but their constraints and drivers are limitedly understood at the continental and global scale. The main objective of this thesis is to explore spatial diversity in agricultural land management and land use intensity and to explain their variability across the globe. To meet this objective a variety of quantitative methods were developed and applied at different spatial scales. The thesis targets three important aspects of agricultural land management and land use intensity: livestock farming, efficiency of grain production, and irrigation. The research was conducted at the European and global scale.

At the European scale, an explanatory analysis was done to determine the spatial distribution of five different livestock types. Location factors for the occurrence of dairy cattle, beef cattle, and sheep (herbivores), as well as pigs and poultry (monogastrics) were explored to produce a detailed spatial distribution map of livestock densities. Both an expert-based and an empirical approach were applied to disaggregate consistent and harmonized EU-wide regional statistics to 1km grid cells. It was found that both the expert-based and empirical approach are equally suited to modeling herbivores, while in general, the spatial distribution of monogastrics could be better modeled by applying the empirical approach. In contrast to the expert-based approach the empirical approach considers socio-economic factors which explain the distribution of monogastrics to some degree.

Results obtained from this study were used to explore spatial and temporal dynamics of the livestock types. A multi-scale modeling approach was developed to simulate

changes in livestock densities between 2000 and 2030. A broad range of driving factors for livestock farming, operating at different spatial scales, was integrated. Amongst others these driving factors include global trade, economic development, climate, regional carrying capacities of the land and environmental policies. An allocation model was developed to spatially distribute the scenario-specific livestock numbers at the landscape scale according to the scenario assumptions. Results indicate for most of the old European Union (EU) member countries a decrease in almost all livestock types, which is particularly remarkable for herbivores. In the new EU member countries sheep, goats and pigs are expected to decline while beef cattle and poultry are expected to grow. Livestock densities are expected to increase both within and outside current livestock hotspot regions in the absence of environmental legislations.

At the global scale, efficiencies of grain production and irrigation of cropland were analyzed. First, actual grain yields were disentangled from production efficiencies to explore if and where grain productivity could be increased without increasing management inputs. A stochastic frontier function is explicitly suited for such purpose and was applied to explore the efficiency, maximum attainable yield, and yield gap of global wheat, maize, and rice production. It is shown that the actual grain yield in some regions is already approximating its maximum possible yields while other regions show large yield gaps and therefore tentative larger potential for intensification.

One of the factors that turned out to explain global variance in grain production efficiencies was explicitly addressed in a separate study: irrigation. Irrigation is as an important aspect of agricultural intensity and determinants for irrigation were identified. Because drivers of irrigation operate at multiple spatial scales we accounted for biophysical determinants, for example slope, humidity, and river discharge, mainly at the grid cell level. Socio-economic and governance determinants, for example Gross Domestic Product (GDP), government effectiveness, and political stability, were primarily addressed at the country level. To identify the variability of the determinants within and amongst these two spatial levels we applied a multilevel analysis. Multilevel analysis is particularly suited for addressing different spatial scales in hierarchically structured data. Results show there is a significant clustering of countries in terms of irrigation. The results suggest that in most countries the interplay of biophysical, socio-economic and governance factors influence the likelihood for cropland to be irrigated.

In this thesis three main observations on agricultural land management and land use intensity were made. First, agricultural land management and land use intensity

depend only to a certain degree on characteristics of the land itself. Socio-economic and political factors, for example population density, market accessibility, and political stability explain the spatial variability of agricultural land management and land use intensity as well. Second, land use and land use management often have a strong path dependency as they go along with long-term investments (for example, irrigation equipment, machinery, farming infrastructure). The current agricultural land management can therefore only to some degree explain what has triggered intensification in the past. Third, factors explaining differences in agricultural land management at one scale may be differently important at another scale. Hence, their influence cannot be assumed to behave linearly across scales. Identifying drivers of land management change should therefore always be done at the spatial scale of interest.

The thesis concludes with a discussion of identified perspectives for continental and global scale land use intensity research. Different methodologies for land use intensity research and its potential for the development of environmental and agricultural policies are discussed. The synthesis finalizes with some suggestions for modeling agricultural land management and land use intensity at the continental and global scale.

Samenvatting

In de afgelopen decennia heeft de intensivering van de landbouw geleid tot een sterke stijging van de landbouwproductie in zowel ontwikkelde landen als ontwikkelingslanden. Naar verwachting zal de wereldbevolking de komende decennia blijven groeien. Ter gelijkertijd wordt voorspeld dat in veel ontwikkelingslanden een verschuiving naar een dieet met toenemende vleesconsumptie zal plaatsvinden en dat in veel akkerbouwregio's het land schaars blijft. Daarom zal intensivering van de landbouw naar verwachting cruciaal blijven om aan de stijgende vraag naar voedsel te voldoen. Intensivering van de landbouw kan op verschillende manieren bereikt worden door verschillende soorten agrarisch landbeheer. Dit agrarische landbeheer, op zijn beurt, kan nader worden gedefinieerd als het samenspel van productie-mix, productietechnieken, mechanisatietechnologie, waterbeheer, arbeidskosten of andere investeringen. Het beheer van landbouwgrond en de intensiteit van het landgebruik verschillen over de hele wereld, maar hun beperkingen en hun sturende factoren zijn slechts gedeeltelijk begrepen op continentale en mondiale schaal. Het belangrijkste doel van dit proefschrift is om de mondiale ruimtelijke verscheidenheid in het beheer van landbouwgronden en de intensiteit van het landgebruik te verkennen en te verklaren. Om aan deze doelstelling te voldoen werden diverse kwantitatieve methodes ontwikkeld en toegepast op verschillende ruimtelijke schaalniveaus. Het proefschrift richt zich op drie belangrijke aspecten van het management van landbouwgrond en landgebruikintensiteit: de veeteelt, de efficiëntie van graanproductie en als laatste irrigatie. Het onderzoek werd uitgevoerd op de Europese en mondiale schaal.

Op de Europese schaal is een analyse gedaan om de ruimtelijke verdeling van vijf verschillende soorten dieren te verklaren. Locatiefactoren voor de aanwezigheid van melkvee, vleesvee en schapen (herbivoren), alsmede varkens en pluimvee (monogastrische dieren) werden onderzocht en gebruikt om de ruimtelijke verdeling van de veedichtheid te karteren. Zowel een aanpak gebaseerd op expertkennis als een empirische benadering werden toegepast om consistente en geharmoniseerde EU-brede regionale statistieken tot een resolutie van 1 km te desaggregeren. De aanpak gebaseerd op expertkennis en de empirische benadering bleken even geschikt te zijn voor het modelleren van herbivoren, terwijl in het algemeen de ruimtelijke verdeling van monogastrische dieren beter kon worden gemodelleerd met de empirische benadering. In tegenstelling tot de expertkennis benadering neemt de empirische benadering ook sociaal-economische factoren in beschouwing, die de verdeling van monogastrische dieren tot op zekere hoogte verklaren.

De resultaten van deze eerste studie werden gebruikt om de ruimtelijke en temporele dynamiek van verschillende soorten vee te verkennen onder verschillende toekomstscenario's. Hiervoor werd een model ontwikkeld waarmee op verschillende schaalniveaus veranderingen in de veedichtheid tussen 2000 en 2030 zijn gesimuleerd. In het model wordt een breed scala van sturende factoren voor de veehouderij op deze verschillende ruimtelijke schalen geïntegreerd, waaronder de wereldwijde handel, economische ontwikkeling, klimaat, de regionale draagkracht van het land en milieubeleid. Een allocatiemodel verdeelt vervolgens de scenario-specifieke aantallen vee op de landschapsschaal volgens scenario-specifieke aannames. In de meeste van de oude lidstaten van de Europese Unie (EU) worden afnames geconstateerd van bijna alle soorten vee, waarbij de daling vooral opmerkelijk groot is voor de herbivoren. In de nieuwe EU-landen zullen de aantallen schapen, geiten en varkens naar verwachting ook afnemen, terwijl de aantallen runderen en pluimvee zullen toenemen. In scenario's waarbij milieuwetgeving ontbreekt, nemen de veedichtheden naar verwachting zowel binnen als buiten de huidige concentratiegebieden van veeteelt toe.

Vervolgens werd op de mondiale schaal de efficiëntie van graanproductie en de irrigatie van akkerland geanalyseerd. De bijdrage van de productie-efficiëntie aan de graanopbrengsten werd bepaald om te onderzoeken of en waar de graanproductiviteit zou kunnen worden verhoogd. Een stochastische frontier functie is uitermate geschikt voor dit doel en werd toegepast om de efficiëntie, de maximaal haalbare opbrengst en het verschil tussen de maximaal haalbare en de daadwerkelijke opbrengst van de mondiale tarwe-, maïs- en rijstproductie te bepalen. De resultaten laten zien dat in sommige regio's de daadwerkelijke graanopbrengst de maximaal haalbare opbrengst al benadert, terwijl andere regio's grote opbrengstverschillen laten zien en daarmee ook een groter potentieel voor intensivering.

Een van de factoren die de mondiale variatie in de efficiëntie van graanproductie verklaart, kwam aan de orde in een aparte studie naar irrigatie. Irrigatie is een belangrijk aspect van de landbouwintensiteit en daarom werden de sturende factoren voor irrigatie geïdentificeerd. Omdat deze op verschillende ruimtelijke schalen opereren, zijn de biofysische determinanten, zoals bijvoorbeeld helling, luchtvochtigheid en rivierafvoer te integreren op het niveau van de gridcellen. Socio-economische determinanten zoals bijvoorbeeld het Bruto Binnenlands Product (BBP), maar ook de bestuurlijke kwaliteit van de overheid en de politieke stabiliteit werden voornamelijk geïntegreerd op het landelijke niveau. De variabiliteit van de sturende factoren binnen en tussen deze twee ruimtelijke niveaus is geïdentificeerd met een multilevel analyse. Een multilevel analyse is bijzonder geschikt voor het onderzoeken van verschillende ruimtelijke schaalniveaus in hiërarchisch gestructureerde data. De resultaten laten een significante clustering van landen op het gebied van irrigatie zien. De resultaten suggereren hoe het samenspel van biofysische, sociaal-economische en bestuurlijke factoren de waarschijnlijkheid dat akkerland wordt geïrrigeerd, beïnvloedt.

In dit proefschrift worden drie belangrijke opmerkingen over het beheer van landbouwgrond en de intensiteit van het landgebruik gemaakt. Ten eerste, het beheer van landbouwgrond en de intensiteit van het landgebruik hangen slechts beperkt van de biofysische kenmerken van het land af. Sociaal-economische en politieke factoren, zoals de bevolkingsdichtheid, de toegang tot de markt en politieke stabiliteit verklaren mede de ruimtelijke variabiliteit van het beheer van landbouwgrond en de gebruiksintensiteit. In de tweede plaats hebben landgebruik en landbeheer vaak een sterke padafhankelijkheid omdat ze regelmatig samengaan met langetermijninvesteringen (in bijvoorbeeld irrigatie-apparatuur, machines en agrarische infrastructuur). Het huidige beheer van landbouwgrond kan dus alleen maar tot op zekere hoogte verklaren wat de intensivering in het verleden aanstuurde. In de derde plaats kunnen de factoren die verschillen in het beheer van landbouwgrond op de ene schaal verklaren, een ander effect hebben op een andere schaal. Hun invloed over de verschillende schalen heen kan daarom niet als lineair worden verondersteld. Het identificeren van de sturende factoren van veranderingen in landbeheer moet daarom altijd worden gedaan op de daarvoor meest geschikte ruimtelijke schaal.

Het proefschrift sluit af met een bespreking van de geïdentificeerde perspectieven voor het onderzoek op continentale en mondiale schaal naar landgebruikintensiteit. Verschillende methodologieën voor het onderzoek naar de intensiteit van landgebruik en hun potentieel voor de ontwikkeling van milieu- en landbouwbeleid worden besproken. De synthese rondt af met enkele suggesties voor het modelleren van landbouwgrondbeheer en landgebruikintensiteit op de continentale en mondiale schaal.

Acknowledgement

The four years of my PhD was an intense and continuous period of learning. I learned about working independently, but also as part of a group. I learned about identifying and solving problems, making realistic plans, writing papers, and defending my ideas and results. I took a main step in becoming a scientist. For sure, I would not have succeeded doing this on my own. Many persons – colleagues, co-authors, friends and family – have supported me whom I would like to thank here. The list is long and invariably I may have missed some names. Thanks to all of those who have contributed to this thesis and my growth as a person.

First of all I'd like to express my gratitude to my promoters Tom Veldkamp and Peter Verburg. Peter, you have been a great support for the last four years. You were always the first to share my ups and downs in academia. You helped me to find my way in the scientific jungle without getting lost or eaten. Tom, thanks for giving me all the freedom to search my own path and your trust in me to choose the right one. You helped me to put my research in a broader perspective without losing my focus. A further word of thanks goes to my committee members Frank Ewert, Wolfgang Cramer, Lex Bouwman and Martin Herold. Thank you for taking up this task. Next, Elke Stehfest deserves special thanks. Although not an official supervisor, you were always critically supportive of my research. Your sharp comments and your different perspective on many global land use aspects were invaluable. I enjoyed very much working together with you and hope continuing so in the future. Tom Kram, thanks for the stimulating discussions on integrated modeling we had from time to time, I'm looking forward to our upcoming tasks. Thanks as well to all my other colleagues from PBL whom always made me feel welcome there. I was sometimes a bit invisible but this was only due to a lack of time.

A big word of thanks goes to all my colleagues from Land Dynamics (LAD) who supported me in several ways in the last four years. My officemates Mathijs and Derek – thanks for sharing ideas, cookies, joy, but also the inevitable setbacks. You guys have set the bar high; it will be difficult to find appropriate successors. Derek, thank you as well for editing my English whenever needed. Wieteke and Diego, our lively exchange of experiences with GIS, statistics, writing papers, handling supervisors and life in general is something I'll certainly miss. Thanks for the four years we spent together and all the things we shared. Aurelien, the two of us were the 'global people' at LAD and I wish we sometimes had a bit more time for brainstorming together, but both our schedules were tight. Thanks in any case for your GIS help! Henny and Mieke, thanks for helping me with all kind of administrative issues, you are a treasure! A great all-round support at LAD, especially in the recent months, was Jetse – thanks for this! Special thanks go to Frans and Nynke who translated the summary into Dutch and to the large group of PhD students for the little briefings on agriculture, land use and scientific methods; as well as, for the countless enjoyable breaks we had.

Lenny and Hester, it was good to have you around. Together we started as "IMAGE-PhDs" and kept exploring the (IMAGE-) world together. Good luck for you both with finishing your PhD! Christoph, we started working together at the time you were still with PBL and kept on collaborating ever since. Whenever you promised me data or feedback on our papers – you delivered on time. Thanks for this! I'd furthermore like to thank my colleagues from Alterra. Berien Elbersen, thanks for the good collaboration on the livestock research. Igor Staritsky, what would I have done without you!? Your patience in helping with data processing in the beginning of my PhD was invaluable, thanks for this. Anne van Doorn, Han Naeff, and Marta Pérez Soba - thanks for sharing your livestock data with me, and Wim de Vries, thanks for the good collaboration and the inspiring discussions we had in Nitroeurope.

Many, many friends took care that I stayed grounded and when I lost my footing, they knew how to bring me back to earth. Although I cannot name them all here I'd like to thank some of them especially. Daniela, Anne, Lydia, Carol, Markus, thanks for listening so often and coming over to Wageningen from time to time to show me that the real world is not spinning around my PhD. Cathelijne, thanks for introducing me to the Dutch culture and language, I hope our paths will keep crossing in the future. Thanks to my friends in Dresden whom I have seen much less than I wished in the past four years. Alexander thank you so much for the book cover – you did a great job! And there is of course Frans, mein Holländer, whom I owe a lot, if not the most. Thanks for listening, reading, discussing and encouraging me again and again, but particularly in the last months. Thanks for being there for me - as friend and colleague - whenever I needed you. We have been a good team and I know we always will be.

Und zum Schluss noch ein Dankeswort an meine Eltern. Meine Entscheidung nach Holland zu gehen war für Euch nicht unbedingt einfach. Nichts desto trotz habt Ihr mich immer in meinem Vorhaben unterstützt und dafür will ich Euch von Herzen danken.

About the author

Curriculum Vitae

Kathleen Neumann was born on November 18, 1977 in Dresden, Germany. After finishing secondary school in 1996 she studied Geography at the Technical University of Dresden. In 1998/1999 she took half a year of Geography at the Salzburg University, Austria. There she gained her first experience in working with remote sensing data and GIS, which turned out to be the start of her fascination for pixels. During her entire study Kathleen did several internships, amongst others at the International Institute for Geo-Information Science and Earth Observation (ITC) in Enschede, the Netherlands. For her Master thesis Kathleen was with the Leibniz Institute of Ecological and Regional Development (IÖR) in Dresden where she studied land use and land cover changes in the 19th and 20th century in the Dresden region. After her graduation in 2003 Kathleen became a researcher at the Friedrich-Schiller University in Jena, Germany in the Global Observation for Forest and Land Cover Dynamics (GOFC-GOLD) Project Office. In April 2006 Kathleen started her PhD at the Land Dynamics group at Wageningen University in collaboration with the Netherlands Environmental Assessment Agency (PBL), Bilthoven. She finished her PhD in April 2010. Since August 2010 Kathleen has been working as researcher at the PBL where she studies global impacts of European environmental policies.

List of peer-reviewed publications

Neumann, K., Stehfest, E., Verburg, P.H., Siebert, S., Müller, C. and Veldkamp, T.: Explaining the global irrigation pattern: A multilevel modeling approach. – Submitted to Agricultural Systems.

Neumann, K., Verburg, P.H., Elbersen, B.S., Stehfest, E. and Woltjer, G.: Multi-scale scenarios of spatial-temporal dynamics in the European livestock sector. – Submitted to Agriculture, Ecosystems & Environment.

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PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (4.2 ECTS)

- Literature research on land use change, spatial dynamics, modelling and livestock intensity (2006)

Writing of Project Proposal (5.6 ECTS)

- Modeling the spatial dynamics in European land use (the proposal was entirely written by the PhD student) (2006)

Laboratory Training and Working Visits (0.6 ECTS)

- Informing about on going research activities and exploration of opportunities for collaboration; Institute of Crop Science and Resource Conservation (INRES), Bonn University (2009)

Post-Graduate Courses (5.6 ECTS)

- Land science course (South Africa); PE&RC (2006)
- Modeling land use-decision making, 3rd young scholar's network; AIMES (2007)
- Multivariate analysis; PE&RC (2008)

Deficiency, Refresh, Brush-up Courses (1.4 ECTS)

- Basic statistics; PE&RC (2006)

Competence Strengthening / Skills Courses (2.7 ECTS)

- PhD Competence assessment; PE&RC (2006)
- C Programming; University Eindhoven (2007
- Techniques for writing and presenting a scientific paper; WGS (2007)

Discussion Groups / Local Seminars and Other Scientific Meetings (14.1 ECTS)

- Statistics, maths and modelling in Production Ecology and Resource Conservation (2006-10)
- Spatial methods (2006-10)
- Presentations and discussion of my research (progress) at the biannual IMAGE workshops (2006-10)
- NITROEUROP Project meetings (3x) (2008-09)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (0.9 ECTS)

- "The Scientific Agenda: Who pulls the string? "; PE&RC day (2006)
- "Expect the unexpected"; PE&RC day (2008)
- "Intelligent communication: On the origin of communication"; PE&RC day (2009)

International Symposia, Workshops and Conferences (8.7ECTS)

- FLUD Conference; Utrecht (2007)
- Nitro-Europe General Assembly & Open Science Conference; Gent (2008)
- Land Use Dynamics Conference; Berlin (2008)
- Impacts of Global Change on Tropical Ecosystems – cross-cutting the Abiotic, Biotic and Human Spheres Conference; Marburg (2009)

Courses in Which the PhD Candidate Has Worked as a Teacher

- Assistance in the MSc-course "Global Change"; LAD; 10 days (2008)

The research presented in this thesis was financed by the Dutch National Research Programme Climate Changes Spatial Planning (KvR BSIK) within the project IC2 "Integrated analysis of emission reduction over regions, sectors, sources and greenhouse gases" and was granted endorsement by the Global Land Project (GLP).