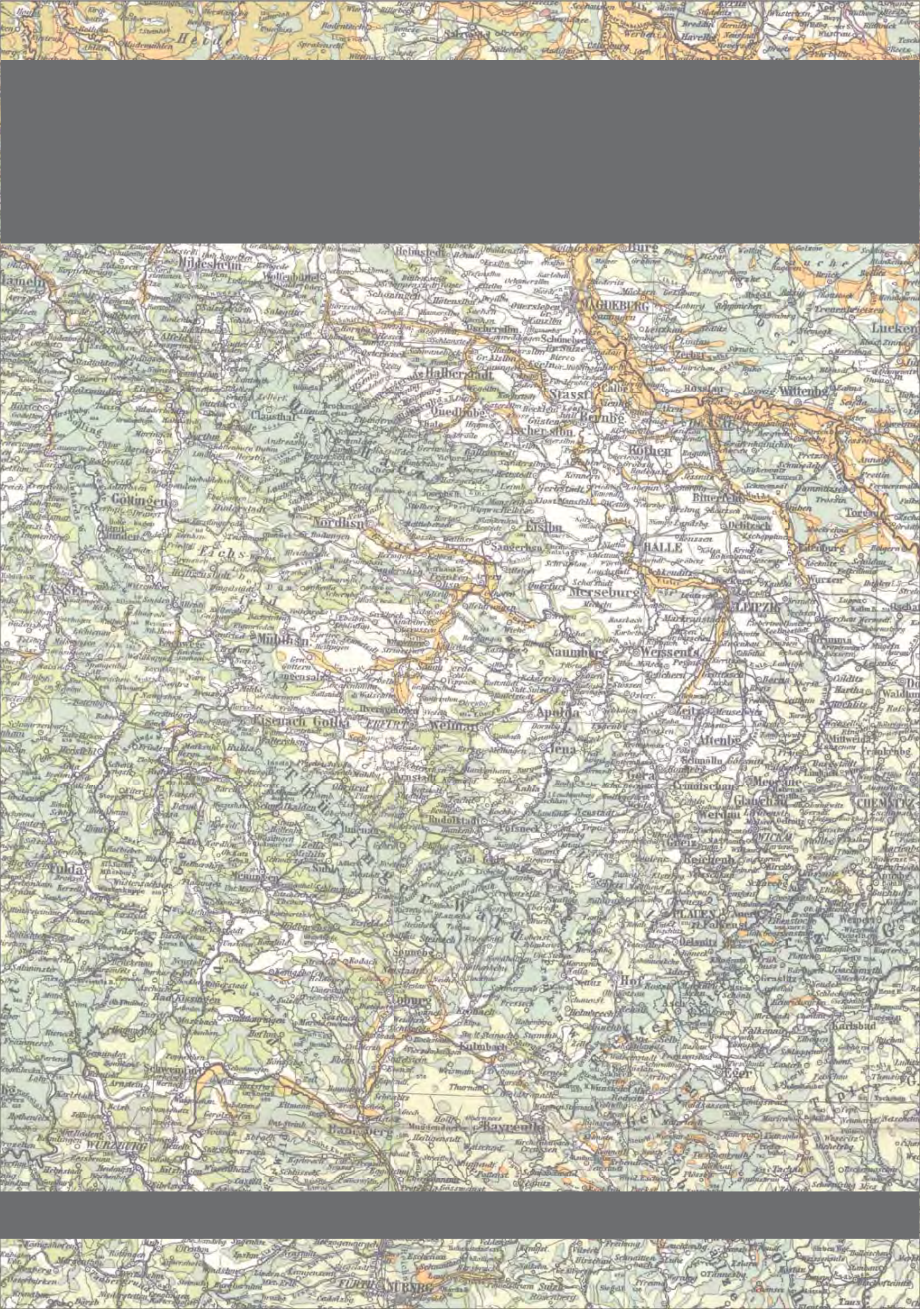
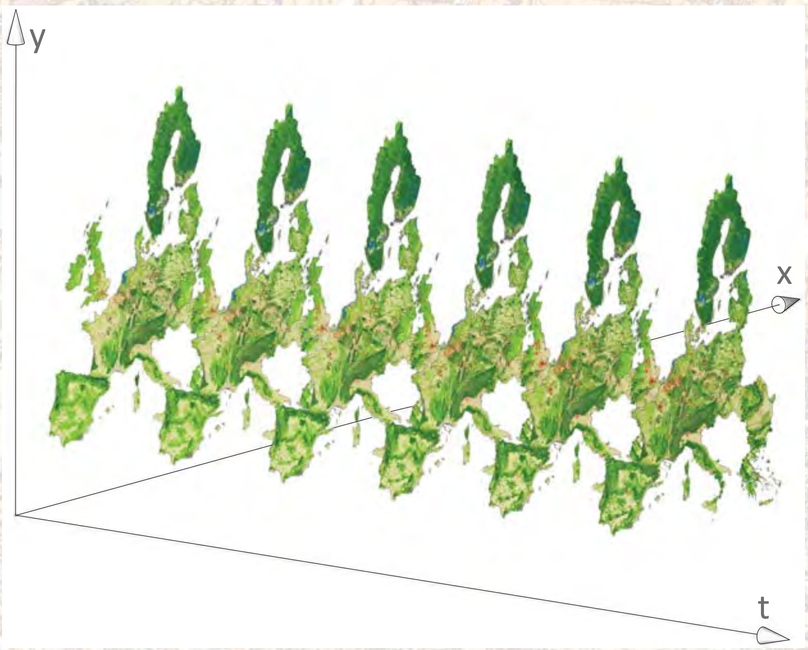


A reconstruction of historic land cover/use change

Richard Fuchs 2015

A data-driven reconstruction of historic land cover/use change of Europe for the period 1900 to 2010



Richard Fuchs

A data-driven reconstruction of historic land cover/use change of Europe for the period 1900 to 2010

Richard Fuchs

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A data-driven reconstruction of historic land cover/use change of Europe for the period 1900 to 2010

Richard Fuchs

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Dedicated to my little family Steffi and Louis. I love you.

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1. Introduction

"…Every mammal on this planet instinctively develops a natural equilibrium with the surrounding environment but you humans do not. You move to an area and you multiply and multiply until every natural resource is consumed and the only way you can survive is to spread to another area. There is another organism on this planet that follows the same pattern. Do you know what it is? A virus. …"

Agent Smith
The Matrix (1999)

1.1 Land change dynamics as consequence of increased population

The population in Europe almost has doubled within just a little more than 100 years, from ca. 288 million people in 1900 (EU27 plus Switzerland) (Lahmeyer, 2006) to roughly 503 million inhabitants (European Commission, 2014). This rapid growth in population and the related need for food, fibre, water, and shelter (Foley *et al.*, 2005) has led to a tremendous reorganization of the European land cover (biophysical cover on the earth's surface) and its use (arrangements, activities and inputs people undertake in a certain land cover to produce, change or maintain it) (DiGrigorio and Jansen, 2000). Land change dynamics of the last century in Europe were stimulated by multiple changes in political systems, political crises or shocks, warfare, several land reforms and enhancing technological, institutional and economic drivers of land change (Jepsen *et al.*, 2015).

Two striking examples for this increased demand in natural products as a result of increased population in Europe were the development of the Haber-Bosch Process (artificial nitrogen fixation) and the massive afforestation programs after the Second World War. In the shadow of both World Wars, the Haber-Bosch process was developed not only to produce explosives for warfare but also synthetic fertilizers (Encyclopaedia Britannica, 2014). To overcome the famine after the Second World War, synthetic fertilization experienced a sudden boom in the agricultural sector leading to a consecutive intensification of croplands and the green revolution in Europe (Jepsen *et al.*, 2015). While Europe in the 50's still had to fear a famine, its agriculture sector generated an agricultural surplus in later decades due to synthetic fertilizers of the Haber-Bosch process (Alma, 1993).

At the same time, shortly after the end of the Second World War, Europe suffered a timber shortage due to non-sustainable forest management and overexploitation. As a consequence most countries in Europe started massive afforestation programs to fight the timber shortage. In the 50's the timber supply was regarded essential to sustain economic growth. Since 1950 Europe has increased its forest areas constantly until today (Gold *et al.*, 2006).

However, the population and the related need of area for cropland, grassland and forest are not homogeneously distributed over Europe. The natural characteristics (e.g. precipitation, soil type, relief, sunshine hours, temperature, etc.) and the socio-economic activities (e.g. two world wars and the following famine, different economic and political systems) have led to different regional change trajectories of landscapes, land cover and its use. Altogether this makes Europe's landscapes divers with often a long cultural history.

1.2 Historic land reconstructions in climate change research

Land cover/use changes have far-reaching consequences for many ecosystem processes which directly or indirectly drive the climate on continental and global scale (Brovkin *et al.*, 2004, 2013; Ciais *et al.*, 2011; Don *et al.*, 2011; Guo and Gifford, 2002; Houghton *et al.*, 2012; Poeplau *et al.*, 2011; Schulze *et al.*, 2010; Zaehle *et al.*, 2013). Often land changes go along with changes in albedo, transpiration, water balance and surface roughness (Foley *et al.*, 2005; Kalnay and Cai, 2003; Pielke *et al.*, 2011).

Anthropogenic nutrient inputs to the biosphere from fertilizers and atmospheric pollutants now exceed natural sources and have widespread effects on water quality and coastal and freshwater ecosystems (Bennett *et al.*, 2001; Foley *et al.*, 2005; Matson, 1997). Land cover/use change may cause a net decline in biodiversity through the loss, modification, and fragmentation of habitats, degradation of soil and water, and overexploitation of native species (Pimm and Raven, 2000).

Associated biogeochemical effects, in particular direct emissions of CO_2 from land conversion (e.g. from forest to grassland or cropland) affect atmospheric gas composition, alter carbon stocks in soils and vegetation (IPCC, 2013) and hence climate (Brovkin *et al.*, 2004; Ciais *et al.*, 2011; Foley *et al.*, 2011; France *et al.*, 2013; Houghton and Hackler, 2001; Olofsson and Hickler, 2008; Pielke *et al.*, 2002, 2011; Pongratz *et al.*, 2009; Schulze *et al.*, 2010; Stocker *et al.*, 2014; van der Werf *et al.*, 2009).

Certain land changes lead to rapid changes in carbon pools (e.g. deforestation), but legacy effects, which are delayed carbon/greenhouse gas (GHG) emission or sequestration, can occur from slow decomposition of dead biomass, soils, and forest products and the longer-term uptake of carbon in re-/afforested areas, respectively (Houghton *et al.*, 2012; Le Quéré *et al.*, 2009). This time lag of GHG fluxes requires to consider present and past land use change dynamics. To assess GHG fluxes of present and past land use change dynamics model-based reconstructions of historic land cover/use are needed as data input (Arora and Boer, 2010; Kato *et al.*, 2011; van Minnen *et al.*, 2009; Poulter *et al.*, 2010; Shevliakova *et al.*, 2009; Stocker *et al.*, 2011; Strassmann *et al.*, 2008; Yang *et al.*, 2010; Zaehle and Dalmonech, 2011).

In that respect the dynamics of historic land changes play an essential role for GHG emission and sequestration fluxes. However, historic land cover/use data are fragmented, hard to obtain (copyright, secrecy statuses, accessibility, language barriers), difficult to harmonize and to compare. Statistical datasets are mainly numbers on an administrative level and are therefore not distinct enough. On the other hand, aerial photos and national maps are limited in their spatial extent. Furthermore, all data sources are limited in their temporal extent and difficult to compare due to different class legends, semantic meanings and definitions of land cover/use. Nonetheless, all these mapping and statistical techniques are commonly being used since the mid of the 19th century. For Europe a vast amount of land cover/use data have been produced since then.

This lack of available data for reconstructions leads to limitations in historic land change assessments, especially on large scales. Many continental to global historic land cover/use reconstructions provide only limited detail in change dynamics, have a rather coarse spatial resolution (0.5 degrees to 0.05 degrees) and reconstruct only a few land cover/use classes. Furthermore, most of them consider only the net area difference between two time steps (net changes) instead of accounting for all area gains and losses (gross changes), which leads to serious underestimation of the amount of area that has been changed in the past (Houghton *et al.*, 2012; Intergovernmental Panel on Climate Change (IPCC), 2013). Nonetheless, for GHG and climate assessments gross land change information, that captures the land change dynamics, and a high spatial, temporal and thematic resolution are crucial. They are also important for biogeochemical process understanding (Houghton *et al.*, 2012a; IPCC, 2013; Stocker *et al.*, 2014; Wilkenskjeld *et al.*, 2014).

The amount of area changes determines the dynamics of carbon fluxes and the land conversion types determine on which carbon stocks the land changes have to be allocated. However, studies about the impact of gross and net land change accounting methods on the carbon balance are still lacking (IPCC, 2013). But also the spatial, temporal and thematic detail are essential for estimating carbon fluxes, since they provide valuable information about regional differences in land distribution, land transitions and pathways of changes and thus have a direct impact on the legacy effects of carbon fluxes. Due to the limitation of large scale historic reconstructions, current research lacks detailed histories of carbon fluxes with a high spatial detail that are able to account for path dependency.

Several methods exist to account for the temporal legacies of land cover/use change emissions, such as bookkeeping approaches (Houghton, 1999; Houghton *et al.*, 1983, 2012; Houghton and Hackler, 2001), biophysical models (Brovkin *et al.*, 2004; Pongratz *et al.*, 2009; Stendel *et al.*, 2005; Stocker *et al.*, 2014; Strassmann *et al.*, 2008; Zaehle *et al.*, 2013) or climate models (Davin *et al.*, 2007; Feddema *et al.*, 2005; Pielke *et al.*, 2002, 2011; Plattner *et al.*, 2008; Stendel *et al.*, 2005). These methods again rely on historic land cover/use change data as input over long time spans. The recent monitoring systems of the satellite era provide valuable information on land cover/use changes (Achard *et al.*, 2004; DeFries *et al.*, 2002; Van Der Werf *et al.*, 2010). However, satellite archives, such as from the Landsat satellite, reach only back to the early 70’s. For legacy effects, longer time frames of observations are needed. Historic land cover/use maps of former nations/empires and military mapping surveys as well as statistical information from old encyclopaedias or national land use records can potentially fill this data gap. Up to now only little use of such historic data has been made due to the difficult implementation in historic reconstructions.

Although initial large-scale estimates on the consequences of historic land cover/use change on the climate and CO_2 concentration can be made, climate models and greenhouse gas assessments are limited by available data on historic land cover/use and are therefore uncertain (Gaillard *et al.*, 2010; Klein Goldewijk and Verburg, 2013; Pielke *et al.*, 2011).

Consistent historic land change data are needed, besides quantifications of fossil fuel emissions, to quantify the influence of human activity on the carbon balance. Estimating the influence of human activity was one of the key issues of the Kyoto Protocol (article 3.4) (UNFCCC, 1998).

1.3 Current methods for historic land cover/use change estimations

The estimation and reconstruction of European historical land change on a continental scale is dominated by two different approaches. The national/regional level approach consolidates country level reconstruction methods for national purposes. These country level studies usually have a set of land cover/use maps that are compared for different time steps to determine the land change. The second approach focuses on global historic land cover/use reconstructions, which were often developed specifically for the climate change modelling community. These global reconstructions have to be modelled, since they span wider areas and longer time spans than national or regional studies. The results of global land cover/use change models have been widely applied in international biogeochemical and environmental assessments, such as in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2013). However, both historic land reconstruction methods have specific limitations.

National or regional studies (Bicik *et al.*, 2001; Carni *et al.*, 1998; Van Eetvelde and Antrop, 2009; Gutiérrez and Grau, 2014; Leite *et al.*, 2012; Mander and Kuuba, 2004; Mueller *et al.*, 2009; Nanni and Grau, 2014; Orczewska, 2009) are limited in their spatial extent and may not always be representative for larger regions (Table 1.1). Methods used in these studies mostly rely on data that were often exclusively available for the investigated region. Furthermore, the studies are often not compatible or comparable in terms of definitions of land categories. This makes it difficult to merge different regional studies to one consistent continental ‘picture’.

Global reconstructions of historic land cover/use provide valuable estimates of land cover/use for a certain historic period, but lack detailed insights into the dynamic changes in land cover/use that may have taken place over time. Due to the spatial coverage, global studies, like the ones listed in Table 1.1, are too coarse (~ 8 km - 50 km per pixel) to characterize change patterns at scales where land changes actually take place. All these reconstruction studies rely on land cover/use databases that are based on country level statistics, population statistics, and model assumptions, due to a lack of available historic datasets for long time periods. Therefore, global reconstructions have to make strong assumptions to fill data gaps and identify subnational patterns of land cover/use.

Studies on a continental scale like for Europe (e.g. Kaplan *et al.*, 2009, 2012) have the objective to avoid these limitations. These studies differ quite a lot in temporal scale and extent. Some only capture the last few decades, while others go back to the Middle-Ages or even further back in time. Depending on the time scale they often treat several decades as one time step. An overview of geographically explicit studies of historical land cover and their use is given in Table 1.1.

1.4 Potential of available land cover/use data for historic reconstructions

Unlike other regions Europe produced a vast amount of various land cover/use data (e.g. old military maps, encyclopaedias, topographic maps, national and intergovernmental statistics, remote sensing products, etc.) throughout the last centuries. Recently, many of these data became available due to copyright expiration, e.g. for historic land cover/use maps (Schlueter, 1952, 1953, 1958) and encyclopaedias with statistical information (Bibliographisches Institut, 1909; Chisholm and Phillips, 1911). The ending of secrecy statuses for historic military maps eases accessibility, e.g. for soviet military topographic maps (Vlasenko, 2008) or maps of the Central Intelligence Agency (CIA) (University of Texas Libraries, 2014). Many mapping communities have started to collect and share historic land cover data (e.g. Rumsey, 2014). National cartographic institutes and cadastres increasingly adhere to transparency, open data policy and data sharing with society (Bundesamt fuer Kartografie und Geodaesie, 2014; Centro National de Information Geografica, 2013; Eötvös University Department of Cartography and Geoinformatics, 2013; Geoportail, 2013a, 2013b; Koningklijke Bibliotheek van België, 2014; Mapster, 2014; National Libary of Scotland, 2013; University of Stockholm, 2013a, 2013b).

New and increased availability of data offer several opportunities for the study of historic land cover/use changes in Europe, if major constraints can be overcome (e.g. harmonization of data format and class definitions, local languages, changing country border throughout history). Other than in national or regional studies the available data at continental scale can be harmonised to one large ‘picture’, allowing to study land cover/use changes at larger scales and cross-country. Compared to global reconstruction approaches, for continental approaches it is easier to benefit from more input data for the same area. The increased amount of input data would help to decrease the uncertainty in the reconstruction (Gaillard *et al.*, 2010; Klein Goldewijk and Verburg, 2013; Pielke *et al.*, 2011). At the European scale available data allow to reconstruct land changes at a higher spatial resolution and with more thematic detail than available from global reconstructions for the same area. Furthermore, the dynamics of land changes can be evaluated with higher quality.

Table 1.1: Examples of geographically explicit studies of historical land cover/use at different spatial and temporal scales (extended after Klein Goldewijk and Ramankutty, 2004).

Authors	**Spatial characteristics**	**Temporal characteristics**
Local/National level		
White and Mladenoff (1994)	Northern Wisconsin, WI, USA	1860s, 1931, 1989
Bicik (1995)	Czech Republic	1845, 1948, 1990
Bork *et al.* (1998)	Germany	7th century-present
Cousins (2001)	South East Sweden	17th, 18th century, 1946, 1980
Crumley (2000)	Burgundy (France)	Iron Age-present
Himiyama (1992)	Japan	1850, 1900, 1980
Larsson and Frisk (2000)	Sweden	ca. 1700-present
Manies and Mladenoff (2000)	Sylvania Wilderness Area, MI, USA	pre-settlement
Odgaard and Rasmussen (2000)	Denmark	past two millennia
Petit and Lambin (2002)	Belgium Ardennes	1700-present
Bicik *et al.* (2001)	Czech Republic	1850-2000
Carni *et al.* (1998)	Slovenia	1770-1990
Gutiérrez and Grau (2014)	North West Argentina	1972-2010
Nanni and Grau (2014)	North West Argentina	1986-2006
Continental level		
Darby (1956)	Central Europe	900, 1900
Maizel *et al.* (1998)	Conterminous United States, country data	1850-1990
Richards and Flint (1994)	South East Asia	1880, 1920, 1950, 1970, 1980
Kaplan *et al.* (2009)	Continental Europe	1000 BC – 1850
Global level		
Richards (1990)	10 regions of the world	1700, 1850, 1920, 1950, 1980
Ramankutty and Foley (1999) (updated version)	5 min. resolution	1700-2007
Klein Goldewijk *et al.* (2010, 2011)	5 min. resolution	10.000 B.C.-2.000 A.D.
Kaplan *et al.* (2012)	0.5 degree	1500-2000
Pongratz *et al.* (2008)	0.5 degree	1000-2000
Hurtt *et al.* (2006)	0.5 degree	1700-2000

1.5 Objectives

This thesis aims to reconstruct historic European land cover/use and its changes for the period from 1900 to 2010 using more detail in terms of land cover/use classes and a higher spatial resolution as compared to previous studies. The main objective of this thesis is to explore new reconstruction methods that improve the spatial and temporal detail and reduce the uncertainty in the estimates at continental level by better using available data sources. The use of available historic data sets as input data for the reconstruction is evaluated.

It is hypothesized that this objective can be achieved by providing a full representation of gross land changes at continental scale in order to capture all major land change processes and their dynamics for Europe throughout the last century. The thesis also explores and discusses implications of those change dynamics on environmental and biogeochemical research, such as climate change research.

Therefore, this thesis investigates the following research questions:

A. Does the combination of different data sources, more detailed modelling techniques and the focus on land change dynamics allow the creation of an accurate, high resolution historic land change reconstruction for Europe covering the period 1900 to 2010?
B. How can local/regional knowledge, like statistics from encyclopaedias and old topographic maps, be used in large scale reconstructions?
C. To what extent do historic land cover/use reconstructions underestimate land cover/use changes in Europe for the 1900–2010 period by accounting for net changes only and how does that affect the European carbon fluxes?

1.6 Outline

This thesis consists of four main chapters, each addressing one or more of the research questions presented in section 1.5.

Chapter 2 addresses research question A and investigates the combination of different data sources, more detailed modelling techniques and the integration of land conversion types to create accurate, high resolution historic land change data for Europe suited for the needs of GHG and climate assessments.

Chapter 3 addresses research questions A and B by analysing how historic statistics of encyclopaedias and old topographic maps can improve the accuracy and representation of land cover/use and its changes in historic reconstructions.

Chapter 4 addresses research question A and C by exploring to what extent historic land cover/use reconstructions underestimate land cover/use changes in Europe for the 1900–2010 period by accounting for net changes only.

Chapter 5 addresses research question C by investigating to what extent historic gross land changes lead to differences in continental carbon flux estimations compared to net land changes.

This thesis is concluded by Chapter 6, where the findings for each research question are presented and discussed with respect to the core objective. Chapter 6 ends with an outlook and suggestions for further research.

2. A high-resolution and harmonized model approach for reconstructing and analysing historic land changes in Europe

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"History is not nostalgia, it is a lesson for the future"

François Hollande
Elysée-Palace, 8th May (2015)

Abstract

Human-induced land use changes are nowadays the second largest contributor to atmospheric carbon dioxide after fossil fuel combustion. Existing historic land change reconstructions on the European scale do not sufficiently meet the requirements of greenhouse gas (GHG) and climate assessments, due to insufficient spatial and thematic detail and the consideration of various land change types. This paper investigates if the combination of different data sources, more detailed modelling techniques and the integration of land conversion types allow us to create accurate, high resolution historic land change data for Europe suited for the needs of GHG and climate assessments. We validated our reconstruction with historic aerial photographs from 1950 and 1990 for 73 sample sites across Europe and compared it with other land reconstructions like Klein Goldewijk *et al.* (2010, 2011), Ramankutty and Foley (1999), Pongratz *et al.* (2008) and Hurtt *et al.* (2006). The results indicate that almost 700,000 km² (15.5%) of land cover in Europe has changed over the period 1950 to 2010, an area similar to France. In Southern Europe the relative amount was almost 3.5% higher than average (19%). Based on the results the specific types of conversion, hot-spots of change and their relation to political decisions and socio-economic transitions were studied. The analysis indicates that the main drivers of land change over the studied period were urbanization, the reforestation program after the timber shortage since the Second World War, the fall of the Iron Curtain, the Common Agricultural Policy and accompanying afforestation actions of the EU. Compared to existing land cover reconstructions, the new method considers the harmonization of different datasets by achieving a high spatial resolution and regional detail with a full coverage of different land categories. These characteristics allow the data to be used to support and improve ongoing GHG inventories and climate research.

2.1 Introduction

Human induced land use changes (e.g. from deforestation) are nowadays the second largest contributor to atmospheric carbon dioxide after fossil fuel combustion (van der Werf *et al.*, 2009). For earlier decades (before 1960) the contribution of land change emissions to total emissions was even higher because of lower fossil fuel emissions (Brovkin *et al.*, 2004; Houghton and Hackler, 2001; House and Prentice, 2002; Prentice *et al.*, 2001). However, a large uncertainty in those assessments is present due to the varying anthropogenic and natural land change processes going on in parallel (Houghton *et al.*, 2012). A main shortcoming in making an assessment of the consequences of land cover change for climate and greenhouse gas (GHG) balances is the lack of spatially explicit and thematically complete historic high resolution land cover change data and its conversion types that feed into these models. This historic information on land cover is needed for GHG assessments, since every current land cover type contains also the legacy of previous land cover types, such as soil carbon from residues (Houghton *et al.*, 2012; Poeplau *et al.*, 2011). The consideration of this information may have a huge effect on the GHG estimation (Poeplau *et al.*, 2011). Moreover, the information is needed for GHG models to deal with parameters like vegetation structure. Unless better base observations are available the accuracy of GHG assessments will remain limited when based on uncertain data and methodologies (Ciais *et al.*, 2011; Schulze *et al.*, 2010). High resolution and validated long term consistent time series of land changes and its conversion types are fundamental to appropriately address potential error sources in GHG modelling, like scaling issues, management practices (e.g. tillage, N-fertilizer) or information on the legacy of soil organic carbon after land conversion (Ciais *et al.*, 2011; Gaillard *et al.*, 2010; Poeplau *et al.*, 2011; Schulp and Verburg, 2009; Schulze *et al.*, 2010).

In recent years, large progress in the gathering of historic land change data and reconstructions has been made by several authors both at global and at continental scales. This includes work of Klein Goldewijk *et al.* (2010, 2011), Ramankutty and Foley (1999), Pongratz *et al.* (2008), Hurtt *et al.* (2006), Olofsson and Hickler (2008) and Kaplan *et al.* (2009) (Table 2.1). Most of these are made for long time spans (several centuries to millennia) at broad geographic scales with limited spatial detail and not accounting for regional differences in land transition processes. For assessments at the continental scale the current data have limitations regarding the spatial, temporal, and thematic resolutions for the periods they cover (Gaillard *et al.*, 2010). The spatial resolution of existing data sets is not high enough to study land change patterns at continental and regional scale. The time steps of existing land data sets are often not consistent. This inconsistency makes it difficult to analyse on-going processes like reforestation or cropland abandonment continuously over several decades. Moreover, existing land reconstructions focus primarily on just a few classes (e.g. cropland, pastures, population). None of the data sets offers a full land balance. This lack is problematic since certain change patterns cannot be fully observed. Although land categories like settlements, inland water and other land comprise only a small proportion of the full land cover (ca. 8-10%) it is important to consider these classes in a land balance, as they are accounted otherwise to classes like forests, cropland or grassland. By not considering a full land balance previous land reconstructions ignore competing land categories (since only 100% of the land area is available) and land conversion types (e.g. from cropland to settlement). For Europe these shortcomings appear in the same way. Since the EU-reporting is on an advanced level for GHG emissions, there is a growing demand for high-resolution, harmonized and spatially explicit land change products, to improve our understanding of the amount and extent of human induced land change processes (global and regional) (Ciais *et al.*, 2011; Gaillard *et al.*, 2010; Schulze *et al.*, 2010).

At the same time, more detailed historic land use reconstructions based on real data (such as historic maps and remote sensing) have been gathered for local case studies or small regions (e.g. Antrop 1993; Čarni *et al.* 1998; Bicik *et al.* 2001; Petit and Lambin 2002; Van Eetvelde and Antrop 2004, 2009; Kuemmerle *et al.* 2006; Orczewska 2009). Such studies are able to describe land conversion patterns at a fine spatial, temporal and thematic detail and on the level where human-induced change processes take place.

Table 2.1: Examples of geographically explicit studies of historical land cover/use, suitable for a European-wide assessment

Author/Dataset	**Spatial Coverage**	**Temporal Coverage**	**Thematic Coverage**	**Spatial resolution**
Kaplan *et al.* (2009)	Pan-European	BC 1000 to 1850	Forests	5 arc minutes
Ramankutty and Foley (1999)	Global	AD 1700 to present	Cropland Pastures	0.5 degree fractions & 5 arc minutes fractions
Pongratz *et al.* (2008)	Global	AD 800 to present	UMD classes (w/o Settlements)	0.5 degree
Olofsson and Hickler (2008)	Global	BC 4000 to present	Permanent agriculture Non-permanent agriculture	0.5 degree
Klein Goldewijk *et al.* (2010, 2011)	Global	AD 1700 to present	Cropland Pastures	0.5 degree for classes 5 arc minutes for fractions
Hurtt *et al.* (2006)	Global	AD 1700 to present	Cropland Pastures	0.5 degree

However, they are difficult to compare and combine with each other, especially cross border. On a continental level their synergistic use will remain limited, due to a lack of an accepted and commonly used reporting scheme for land use classes, including standardized definitions and harmonization levels but also as a result of their limited spatial coverage and focus on regions that are often known for large historic changes.

Many land transitions in Europe have taken place affecting the land use pattern due to changes in farming or management systems (e.g. fallow land, abandoned, reactivated and reforested land). These changes follow fine scale variability in environmental conditions, socio-ecological factors, such as demographic change, accessibility and cultural factors (Kuemmerle *et al.*, 2009; Mander and Kuuba, 2004; Pinto-Correia and Vos, 2004; Prishchepov *et al.*, 2012). Thus, they require high resolution data sets to observe and study these local heterogeneous processes. These changes may have large consequences for GHG emissions and climate variables (e.g. albedo) together with European specific determinants that are crucial (e.g. management practices) (Houghton *et al.*, 2012).

Based on the shortcomings of current land cover reconstructions and the needs of GHG and climate assessments, the objective of this study is to investigate if the combination of different and new data sources, detailed region specific modelling techniques and the consideration of multiple land cover types allows us to reconstruct historic land change for Europe at a high spatial resolution for the period 1950-2010. Thereby, we will focus on allocating existing harmonized land cover change data (see section 2.2.2.1) rather than modelling these changes based mainly on assumptions for change processes. Validation with independent data and comparison with comparable land cover reconstructions is used to evaluate the research objective.

After presenting the methods employed to reconstruct historic land changes, this paper will analyse the regional land change hotspots over the 1950-2010 period and its major conversion types at the continental scale. The results will be compared with existing global scale historic land change databases of Klein Goldewijk *et al.* (2010, 2011), Ramankutty and Foley (1999), Pongratz *et al.* (2008) and Hurtt *et al.* (2006), henceforth referred to as Goldewijk, Ramankutty, Pongratz and Hurtt, respectively. Finally, the validation and performance assessment with independent historic high-resolution data (aerial photographs from 1950 and 1990) will outline uncertainties in our allocation of land cover and its changes on a pixel level.

2.2 Data and methods

2.2.1 Overview of the method

This study uses a *land change quantity and land change allocation* approach. The approach simulates land conversions on the basis of land change pressures, resulting from area statistics on country level for each land category (*land change quantity*), and allocates this information based on data that are able to indicate pixels of this land category where these changes are likely to happen (*land change allocation*). The preparation of the *land change quantity* data is explained in section 2.2.2, the pre-processing of data for the *land change allocation* procedure in section 2.2.3. The processing steps and the usage of the two data stacks are described in section 2.2.4. To validate the performance of our approach, the results were compared with high-resolution aerial photos (1950 and 1990) obtained for regional case studies. This is presented in section 2.2.5. The resulting data set of this investigation is called *HIstoric Land Dynamics Assessment* (HILDA).

2.2.2 Harmonization and aggregation of data sources – land change quantity

2.2.2.1 Data sets and preparation

Focus of this work will be on EU-27 plus Switzerland, since the data for these countries are quite good, even on regional scales (spatially, thematically and temporally). For this study the following land cover data sets with national level time series were used for all EU-27 states plus Switzerland: CORINE for 1990, 2000 and 2006 (EEA 2012); GlobCorine for 2005 and 2009 (ESA 2011); UMD land cover classification (reference year 1991) (Hansen *et al.*, 1998, 2000); Eurostat from 1974 to 2007 (European Commission, 2012); FAO-STAT from 1961 to 2008 (FAO 2012); FAO-FRA for 1946, 1953, 1958, 1963, 1976, 1985, 1990, 1992, 2000, 2005 and 2010 (FAO 2012b); population statistics by Lahmeyer from 1950 to 2010 (Lahmeyer, 2006).

While remote sensing products could provide spatially explicit land cover and use information and its changes, it temporally covers only a relatively small proportion of the investigated time frame (1990s – 2010 vs. 1950 – 2010). Some statistics instead span longer terms and some even the complete period. However, they are often just available as aggregated numbers on country scale and lack the information on spatial allocation within these administrative boundaries (Verburg *et al.*, 2011).

For recent years (from 1990 onwards) the data availability and quality (temporal, spatial and thematic) is appropriate to cover major land changes in Europe. Remote sensing data can be used for the spatial allocation of land cover classes and for cross-calibration of temporal land change trends with spatially coarse national statistics. Thus, the period 1990-2010 is used to inter-calibrate the existing data sources and extrapolate the change trends using the less detailed data for the historical periods back to 1950.

The various data do not necessarily follow the same nomenclature and class definitions have to be harmonized and aggregated to make them comparable. Besides the detailed analysis of existing legends (Herold and DiGregorio, 2012), the main idea was to aggregate to broad land categories in order to avoid definitional conflicts. In line with GHG accounting and climate modelling requirements five suitable land categories were defined for the modelling:

- Settlements (incl. green urban areas),
- Cropland (incl. orchards and agro-forestry),
- Grassland (incl. natural grassland, wetlands, pasture and Mediterranean shrub vegetation),
- Forest (incl. transitional shrub and woodland, tree nurseries, reforested areas for forestry purposes) and
- Other Land (incl. glaciers, sparsely vegetated areas, beaches and water bodies).

These classes and their definitions cover 100% of the land area in Europe and are based on the Intergovernmental Panel on Climate Change (IPCC) categories (IPCC 2003). However, due to the lack of sufficient land information for the last 60 years of the wetland category, it was integrated in the grassland category.

The Land Cover Classification System (LCCS) (DiGrigorio and Jansen, 2000) was used to harmonize all existing data sets on the five IPCC classes. An overview of the class accounting and parameter description by LCCS is given in Appendix A (see supplemental material in the online publication). The advantage of this procedure is an objective class accounting using describable and comparable class features, instead of subjective appraisals.

2.2.2.2 Data adjustment and analysis of land change trends

The finest scale for a cross-comparison along the data sets was the country scale, so all harmonized data were brought on that level for the analysis of land change trends. Spatially explicit data were geo-referenced on an equal area projection (Lambert Equal Area) to compare areas. Despite the harmonization process, the data sources could still differ in the overall amount of land cover area per class, e.g. due to the relatively coarse spatial resolution of GlobCorine (300 m) and UMD (1 km) or due to the fixed thematic boundary of some statistical classes. It was also recognized that in the Forest Resource Assessment (FRA) reports for Mediterranean countries like Spain, shrublands were accounted in some years to forests and in other years to cropland and grassland. In these cases other data sets, for example FAOSTAT, could be used instead.

The FAO-FRA data set provides cropland and grassland back to 1946. In comparison with FAO-STAT data (back to 1961), where these two classes are separated, area relations of these two classes and their relative trends over time could be calculated for each country. This allowed the separation of the FAO-FRA cropland and grassland class before 1961.

Since settlement data were not separately reported in the statistics data (mainly included in settlement and others- FAO or other land and settlements - FRA), population data and CORINE of the year 2000 was used to calculate the occupied settlement area per person in m^2. This factor for each individual country could then be applied for all years of population data to estimate the area changes in settlements. Although we see this assumption as very simple and pragmatic, it turned out to be best practices compared to the otherwise required effort and its impact on the final results. Examples of 25% change in population density showed that most of the countries were only affected by less than 1.5 % of area change (Appendix D - see supplemental material in the online publication). By the use of the processed settlemen*t* areas, the other land class component could be extracted as residual.

For all countries and its land categories, outliers were sorted out and gaps with missing data were filled. An overview of the used method per country, per class and per year is given in Appendix B (see supplemental material in the online publication). Available data, which could be used for this study, were inter- and extrapolated by the use of approximation functions that were able to describe the land change trends over the whole period. The chosen polynomial order for each class per country is also given in Appendix B (see supplemental material in the online publication).

Due to the heterogeneous data sources, the sum of all harmonized land categories may lead to varying total areas per country over time. These differences occur, if the land categories are subject to high variances in area along the used data sets at one time step. For the investigated land categories the variances were highest for grassland and lowest for settlements and forest. Reasons for these variances might be remaining inhomogeneity of class definitions and inaccuracies in classification of the products itself. To correct for discrepancies between the total area per country and the sum of all land categories, the one with the highest variance, in this case grasslands, was used to match the sum of all land categories with the total area per country. This step introduced a bias in the grassland estimates. However, the bias is very small (ca. 1%) as compared to the overall uncertainty in the grassland category. By tuning the final reconstruction results to reported national quantities, all errors identified are basically location errors. The spatial allocation of land classes is validated using aerial photographs (see section 2.2.5).

2.2.3 Spatial distribution procedure – land change allocation

A simple allocation procedure was implemented to distribute the land areas within the administrative boundary to 1 km² pixels based on probability maps for each land category (Fig. 2.1). Probability maps represent the spatially explicit likelihood of a dominating land cover. The probability maps are derived through an empirical analysis of the relations between observed land use patterns in the year 2000 and a range of supposed explanatory factors conducted by Verburg *et al.* (2006) and Verburg and Overmars (2009) for the purpose of parameterizing a forward looking land change model. Land use patterns in 2000 reflect the effect of a longer history of land change in response to biogeophysical and socio-economic conditions. As explanatory factors Verburg and Overmars (2009) used biogeophysical factors with parameters like soil properties, precipitation, sunshine hours, altitude, slope, and socio-economic factors involving accessibility to settlements based on settlement size and population density. Logistic regressions were estimated for all land cover types and countries separately, allowing different variables to explain different land cover types across the different countries. Then, the probability of finding the land cover type under the prevailing conditions was calculated for all locations on a 1 km grid. The resulting probability maps are visualized in Figure 2.1. Other Land was not processed since it is treated differently in the approach than the other classes (see section 2.2.4).

Although the influence of some of the allocation factors on the probability maps may vary in time (e.g. population density and accessibility), most of the allocations remain stable over longer time periods (e.g. climate, terrain, soil factors). The impact of varying factors on the final data set was considered low and quantified in section 2.2.2.2. Since this approach focusses mainly on input from land change data, many otherwise used allocation factors, such as management (e.g. major mechanization trends, strong increase in chemical fertilizers use, drastic decrease in labour force, different EU accession dates, etc.) are incorporated in the land demand part (so the statistics). For example, mechanization and increase of fertilizer use in agriculture led to less demand in cropland area due to higher yields. This decrease in demand can already be seen in almost every European cropland statistic, of which this approach makes use.

2.2.4 Model structure and processing

The approach processes the data in decadal time steps for each country separately. Each time step can be separated into a pre-processing phase (Fig. 2.2, upper box), a class-processing phase (Fig. 2.2, middle box) and post-processing phase (Fig. 2.2, lower box).

In the pre-processing phase it is decided which land cover map (LCM) has to be chosen. This is dependent on the time step that needs to be processed. If these time steps are 2010 or 1990 the baseline map of the year 2000 is used, otherwise the LCM of the previous time step is used.

For land allocation in the class-processing phase the model follows a process hierarchy. The land categories are ranked by its socio-economic value, so that settlements are calculated first, croplands second, forest third, and grasslands at last. Forest was ranked third, because its area was almost constantly increasing since 1950 according to land change quantity data (LCQ). This implies an increasing aggregated area to be allocated. On the other hand, grassland was calculated last, since it was mainly decreasing according to the LCQ data, implying a lower aggregated area to be allocated for that land. Furthermore, grassland contains pastures and natural grasslands (peatlands, highlands, etc.), so that the socio-economic value was assumed to be lower than for the other land categories.

The approach treats the other land class, which mainly consists of water, glaciers, bare soils and sandy areas, like beaches, desserts and dunes as static, and therefore it was masked from the data set. Since other land areas are small, influences from climate, tides and the meandering of rivers, were considered to be low at this spatial resolution.

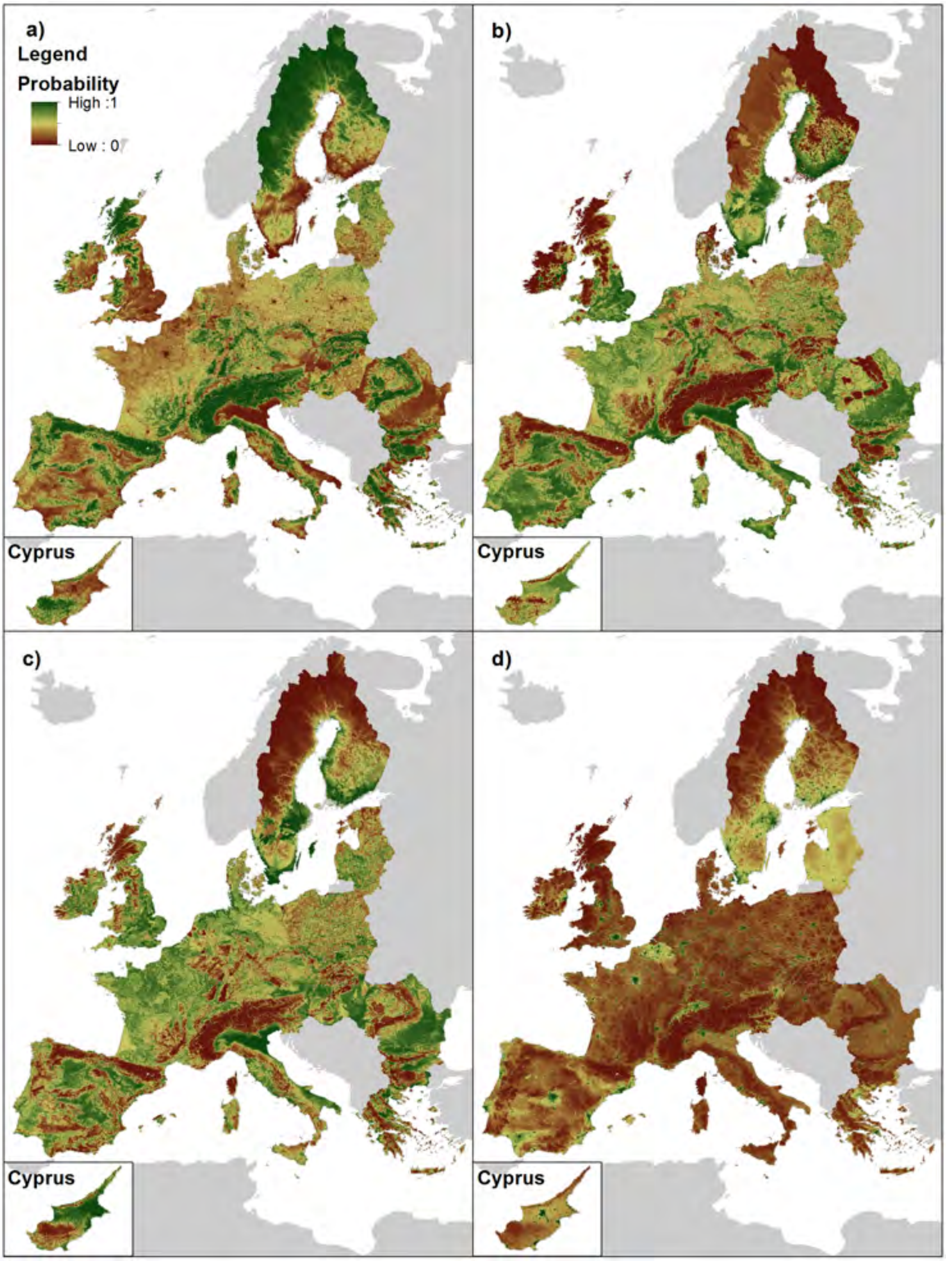

Figure 2.1: Probability maps for each land cover class (forest (a), cropland (b), grassland (c), settlement (d)) calculated based on regression analysis conducted by (Verburg and Overmars, 2009). High probability values are in green, low probability values are in red. The “Other land” class has no probability map, because it is treated differently.

If a class is selected for processing the next time step, the model requests information from the LCQ database on increase or decrease of the class area (Fig. 2.2, left vertical box). Every class that is increasing its area from one time step to another uses the probability map of its own class for all areas where this class can potentially grow (including unclassified areas). The selected areas are then converted into the according class (Fig. 2.2, middle box). Should the class decrease, the model masks the relevant class instead of all other classes, and picks the lowest values in the appropriate Probability Map (PM) equal to the LCQ area for that class. The area is then converted into unclassified area, which can be incorporated in other increasing classes later on as part of their increase mask (Fig. 2.2, middle box). Since the sum of all increasing and decreasing classes is zero at the end of one time step, all unclassified areas are assigned to a class. All new class areas are merged (including other land) to a new time step in the post-processing phase if all classes have been processed (Fig. 2.2 lower box).

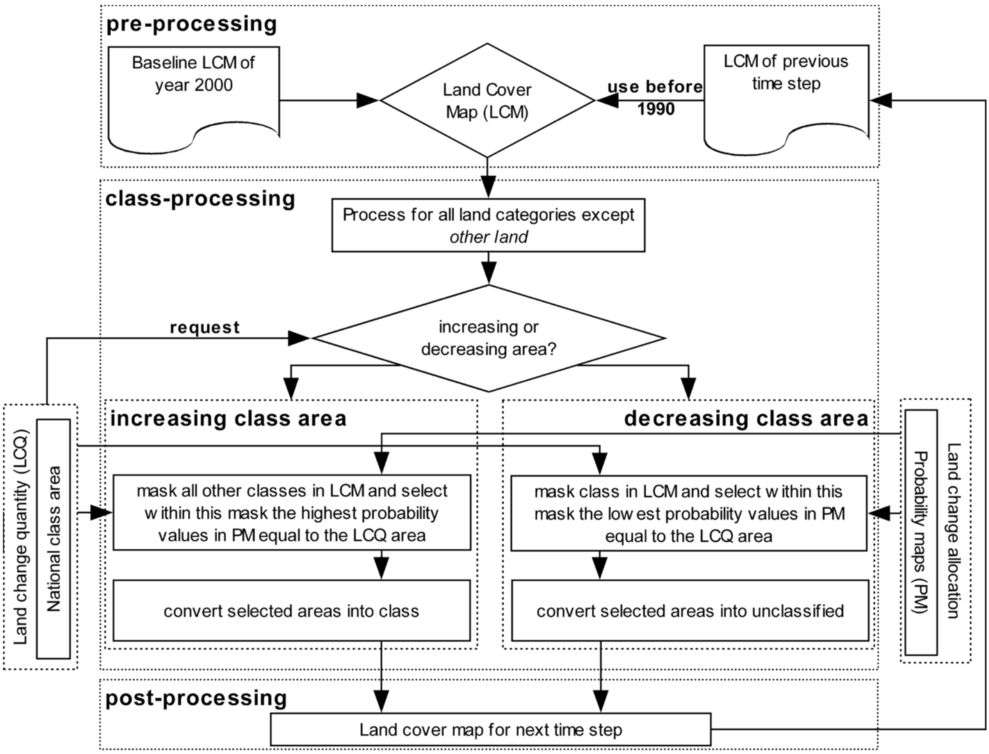

Figure 2.2: Exemplary workflow of the model approach for one country.

2.2.5 Comparative assessment and validation

In order to check the performance, the approach was compared with other land change reconstructions available for this scale. Four relevant global models were chosen: Goldewijk, Ramankutty, Pongratz and Hurtt. Their spatial, temporal and thematic features are shown in Table 2.1. Our approach comprises pastures and natural grasslands as result of the harmonization process to the IPCC land category. That implied that the comparative assessment between these reconstructions and ours was only possible for cropland. On the one hand the comparison was performed in a spatially explicit way to point out the differences of detail due to the resolution and to show similarities and discrepancies of regional hotspot patterns. On the other hand a time-series was elaborated for four European regions (Northern Europe, Eastern Europe, Southern Europe and Western Europe) to show differences of the total class area per region among the investigated land reconstructions. Finally, to evaluate the performances and accuracies of all approaches with ours, the results were cross-validated with already classified high-resolution aerial photographs for the years 1950 and 1990 in 73 different locations (validation site ca. 30 km by 30 km) distributed across Europe (Fig. 2.3). The study sites cover 17 different countries of five bio-geographical zones (Boreal, Atlantic, Continental, Alpine and Mediterranean) with an area of 59.297 km², which is about 1.5 % of the total surface area of Europe. This validation material was obtained from Gerard *et al.* (2010).

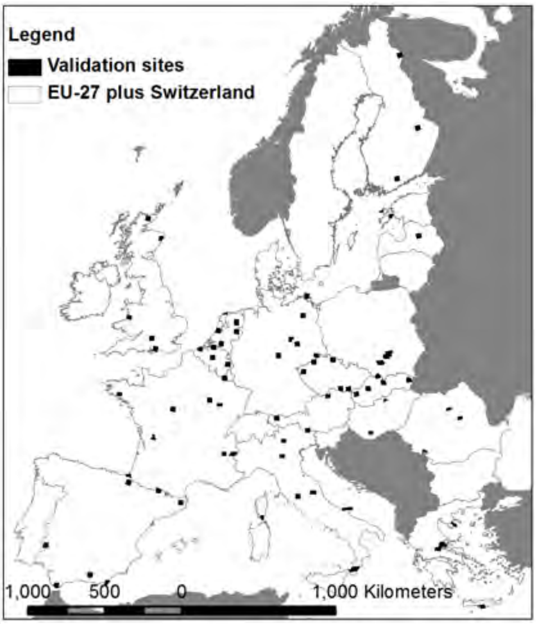

Figure 2.3: Overview of validation sites for this study.

It was possible to use the same class aggregation scheme for the five IPCC classes (LCCS) and for the CORINE product, since they use the same nomenclature and definitions. For this study the results were compared for 1950 and for 1990. Unfortunately, the data for 2000 were not available for all validation sites.

2.3 Results

2.3.1 Land use reconstructions

The result was analysed for the period 1950-2010 (Fig. 2.4) and is separately displayed for the years 2010, 1990, 1970 and 1950. The five IPCC classes and a water mask (sub class of other land) are shown for all EU-27 states plus Switzerland.

For the whole period it can be observed that forest increased the most since 1950 by 314177 km² (+25.35% or 0.42% per year) as well as settlements with 35818 km² (+24.54% or 0.41% per year). On the other hand cropland decreased by 278922 km² (-18.73% or 0.31% per year) and grassland (pastures and natural grassland) by 73283 km² (-5.63% or 0.09% per year).

The growing population of Europe within the last 60 yr (+122 M) has led to the development of settlement agglomerations across the entire study area, especially in the population belt, known as the *blue banana* (Brunet, 1989).

Forests in Sweden increased their coverage by almost 20% within 60 years compared to 1950, mainly occurring between the lake Vänarn and Stockholm. In Finland the same patterns occur, although more heterogeneously, for the coastal region reaching from Saint Petersburg in Russia to the upper Gulf of Bothnia.

The Baltic States underwent a notable land transformation. The loss of cropland and the increase in forests and grassland can be determined as the main drivers for that region.

For the Mediterranean countries it can be concluded that the coastal areas of Italy, Spain and southern Portugal experienced a considerable drop of cropland by simultaneous conversions into mainly grasslands and to a minor extent into forests. Especially the regions of Alentejo in Portugal and Tuscany in Italy are affected by these changes.

The forest for France increased from 109540 km² (1950) to 159540 km² (2010) by 50000 km², mainly occurring in the Provence and around Paris, which implies an increase of 45.64% within the last 60 years. The same conversion type occurred also in Poland, more or less spread over the whole country, reaching a forest increase of +35.14% between 1950 and 2010. In Romania, while forests stayed almost constant, the main driver was the drop in cropland in the Transylvanian and Moldavian regions, resulting in increasing grassland areas.

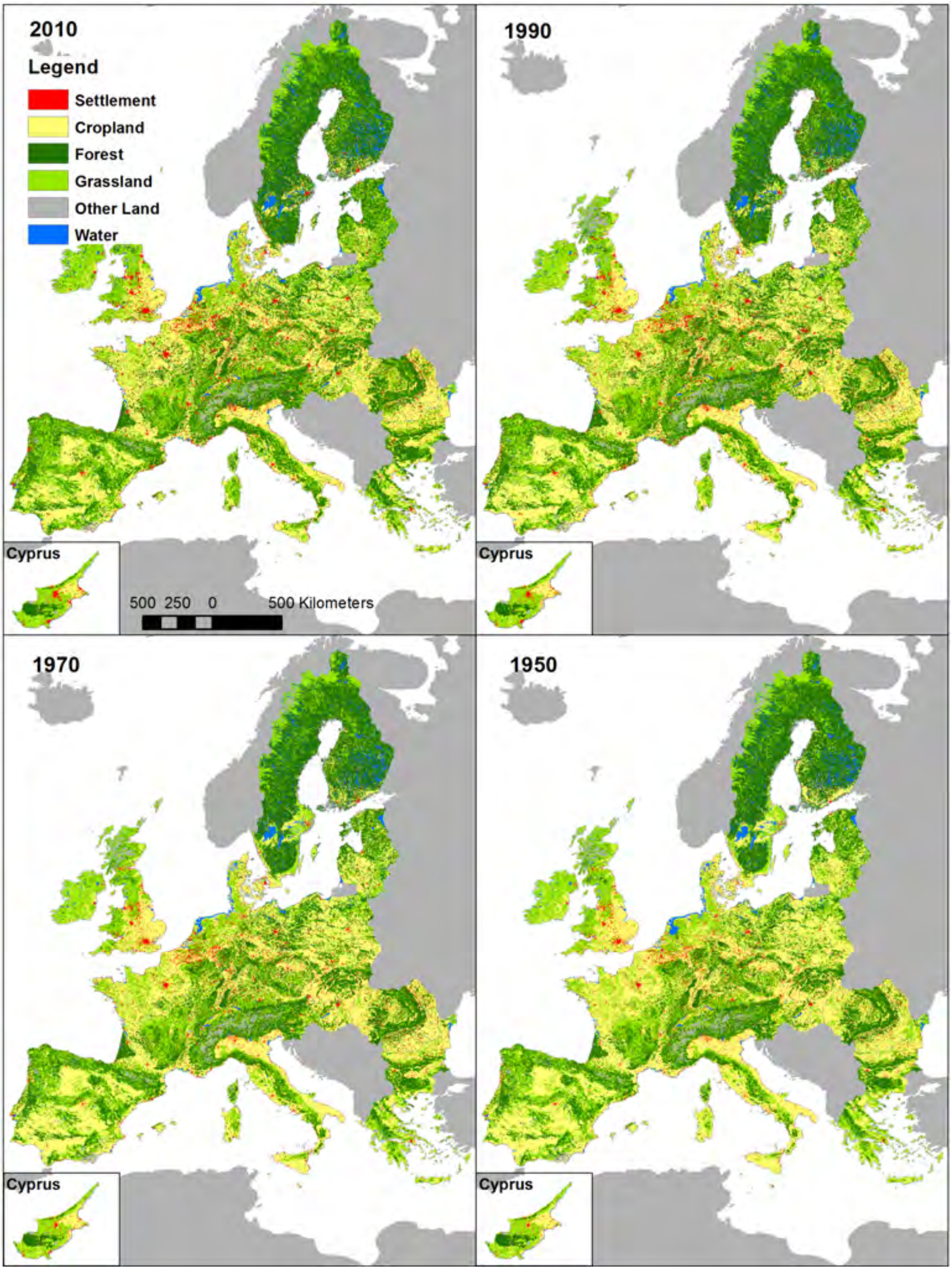

Figure 2.4: Reconstruction results for four time steps: 2010, 1990, 1970 and 1950 and five classes (settlement, cropland, forest, grassland and other land; water mask is part of the other land class) for EU27 + Switzerland.

Accumulating the land changes between every single time step, a hotspot map can be generated for the whole period (Fig. 2.5). The hotspot map allowed focusing just on the modelled land changes instead of on the coverage, in order to analyse the spatial hotspot patterns and agglomerations of multiple land changes per pixel. This way hot spots are highlighted and clustered for visualization. Moreover, it shows areas of multiple land changes that took mainly place in France, Scandinavia, the Baltic States, Czech Republic, Austria, Italy and Portugal. This could be used to calculate the overall land changes for the entire study area with varying regional amounts of land changes. Therefore, the study area was separated into four major regions: Northern Europe, Eastern Europe, Southern Europe and Western Europe (see Fig. 2.5 and Table 2.2).

For the investigated period the area of affected land by land changes could be calculated as 601154 km², which is 13.79% of the total area of all EU27 states plus Switzerland (Table 2.2). If the amount of all land changes is considered (including multiple land changes) an area of 674684 km² has changed, which is 15.47% of the EU-27 plus Switzerland region. This implies that every year 0.26% of the entire 4.36 M km² is converted, an area similar to Northern Ireland (Fig. 2.5). While the amount of changes of Northern and Eastern Europe follows the total average of land changes, Western Europe was roughly 2% below average. Contrary, Southern Europe was roughly 3.5% above average.

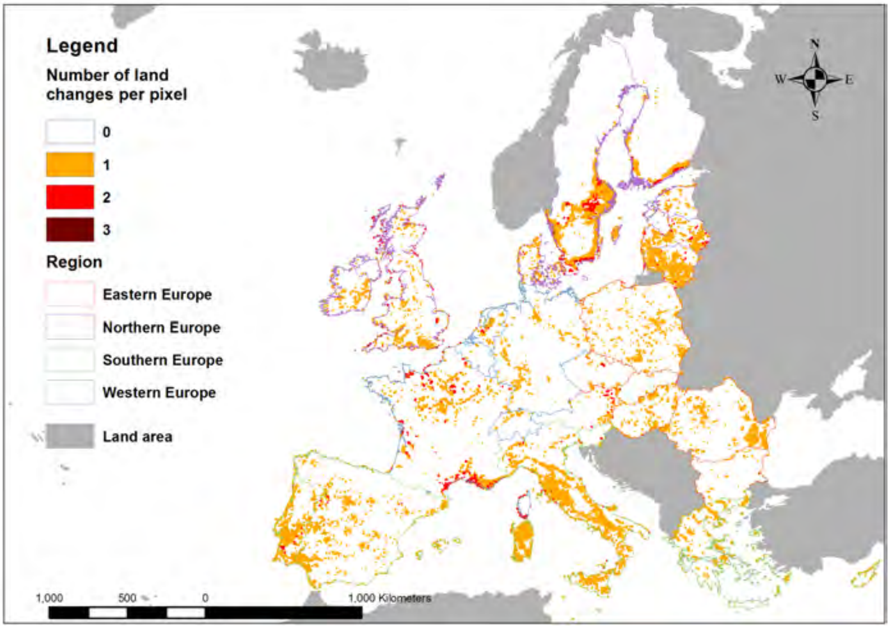

Figure 2.5: Generalized prime hotspots of Europe for the period 1950 – 2010, showing the spatial distribution of (multiple) land changes.

Table 2.2: Land change amounts for four different European regions and EU-27 plus Switzerland for the period from 1950-2010.

Region	Total area in 1000 km²	Total area affected by land changes in 1000 km² (excl. multiple land changes)	Total land changes in 1000 km² (incl. multiple land changes)
Northern Europe (IE, UK, DK, SE, FI, EE, LT, LV)	1320 (30.26%)	173 (13.05%)	201 (15.23%)
Eastern Europe (PL, CZ, SK, HU, RO, BG)	882 (20.24%)	117 (13.24%)	126 (14.29%)
Southern Europe (CY, GR, IT, SI, MT, ES, PT)	1058 (24.27%)	186 (17.50%)	201 (18.96%)
Western Europe (FR, BE, NL, LU, DE, CH, AT)	1100 (25.22%)	123 (11.19%)	147 (13.35%)
Total	4360 (100%)	601 (13.79%)	675 (15.47%)

Figure 2.6 separates the relative amount of all occurred land changes per region between 1950 and 2010 into their main land conversion types. The two main land conversion types for these regions were either grassland to forest or cropland to grassland, incorporating together 63% (Eastern Europe) to almost 85% (Southern Europe) of land change areas per region. These conversion types were followed by cropland to forest, grassland to cropland and cropland to settlement.

2.3.2 Comparative assessment and validation

One objective of this study was to compare and evaluate our land reconstruction results with Goldewijk, Ramankutty, Pongratz and Hurtt (see Table 2.1). The spatial comparison is displayed in Figure 2.7. Since the Hurtt product is based on the Goldewijk database and rescaled to 0.5 degrees it was left out for the spatial pattern analysis. Due to the fact that our approach covers grasslands (incl. pastures and natural grassland) instead of pastures, the direct comparison with the global models was only possible for croplands. Although the units of each model result are different, the quantities and allocations can be compared quite well.

In a direct comparison with the other models it is notable to which extent our approach is increasing the spatial resolution and variability. A lot more details in the allocation of cropland can be seen, and distinguished for smaller regions, although the Goldewijk model reaches a decent level of detail for a global model on a European level.

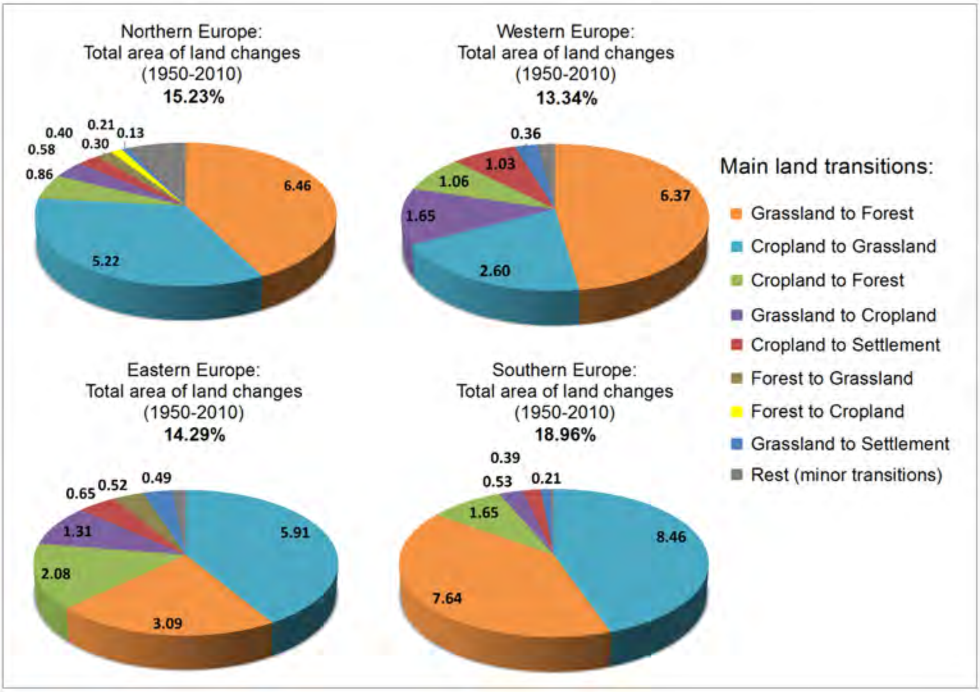

Figure 2.6: Main land transitions and relative amount of land changes per region for 1950-2010.

It can be observed that in general all models show a wide range of similar patterns (e.g. Po Valley in Italy, Danube Delta in Romania and the Hungarian cropland area along the Danube), but also a large number of differences. These are most dominant in south-east England (Goldewijk), south-east Italy (Ramankutty), Poland (Pongratz), north-west France (Goldewijk), Scandinavia (Goldewijk, Pongratz). The occurrence of some hotspots for cropland quantities as well as their absence in some models is strange. For example, one of the most intensive cropland areas of the Pongratz model is Poland, while hotspot regions of other models in Spain are just average in this model. Another missing overlap can be observed for south Sweden and Finland. While our approach and Ramankutty show a significant agglomeration of croplands for 1950, this pattern is almost missing in the Goldewijk and the Pongratz model.

In addition to a model comparison on spatial quantity patterns and land category allocations for cropland, the area fractions of cropland over time were compared for the EU27+Switzerland area and the abovementioned regions (see Fig. 2.5). The result for the cropland class in EU27+Switzerland can be seen in Figure 2.8.

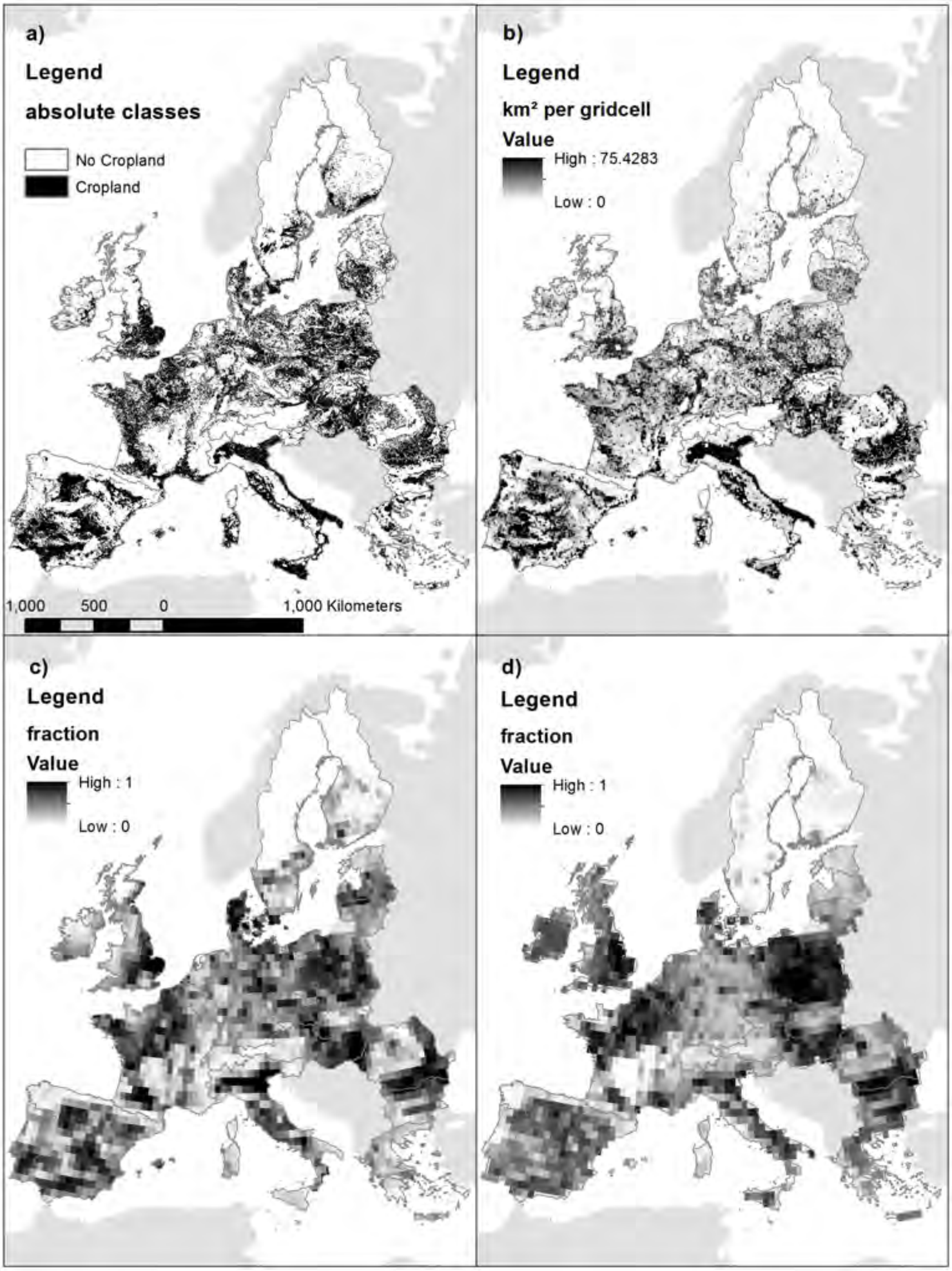

Figure 2.7: Model comparison for cropland in the year 1950 for EU27+CH: HILDA (1 km by 1 km, absolute classes) (a), Goldewijk (0.05º, km² per gridcell) (b), Ramankutty (0.5°, fractions) (c), Pongratz (0.5º, fractions) (d).

The figures per European region are shown in Appendix C (see supplemental material in the online publication). In general, all models were showing the same land conversion quantity (yearly change rates), but the absolute fractions of land coverage by cropland differed significantly. While for EU27+Switzerland this difference was in 1990 only 1% (30%-31%) for all models except Pongratz (ca. 37%) it reached a range from 31% (Hurtt) to 40% (Pongratz) for 1950. Our approach was the only one which processed the time step 2010. It is interesting to see that before 1960 all other models assume a trend change, while our land reconstruction continued with the same trend, which is likely caused by the fact that global models rely on FAOSTAT data since 1960 and before on linear model based estimates.

In order to evaluate the quality of the land cover reconstruction, a comparison with independent observation data at higher resolution was made as a means of validation. This was done with the historic aerial photographs obtained by Gerard *et al.* (2010). All 73 samples of the years 1950 and 1990 were used to validate the outcomes of the land reconstruction approach.

Four examples of representative test sites are shown in Figure 2.9. The left column shows the results of our land reconstruction, the right column the sample sites of reference data. The four examples display the year 1950 and 1990 for each data source. In general, by comparing the two data sets, it could be recognized that the historic land reconstruction could mainly cover the main land change trends of the Gerard *et al.* (2010) data set (e.g. increasing areas of settlements, reforestation, cropland decrease, etc.).

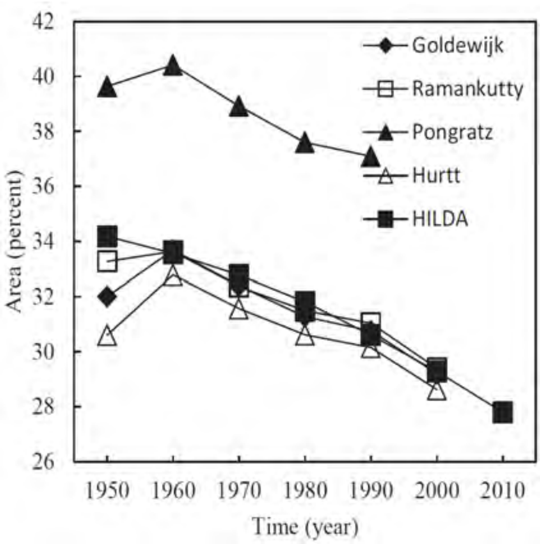

Figure 2.8: Area fractions for cropland, compared in decadal time steps from 1950 to 2010 for EU27+Switzerland.

The sample sites of Amsterdam and Haarlem (NL) and Grenobles (FR) indicate that during the backcasting to 1950, our approach was able to reduce the amount and to keep the shape of settlement areas as determined by reference data. However, in some parts differences remain. While the historic land change approach considered the south east to be more stable, the southern region existed already in the 1950s. The urbanization of the suburbs was well captured, although the area of Haarlem (middle western part) was a bit underestimated. The example of the Carpathian Mountains in Romania demonstrates that the approach was also able to cover land changes like clear-cuts in forest areas, although the patches were difficult to capture with a 1 km resolution. The fourth sample site (Vecpiebalga, LV) was in the southern section affected by afforestation. The historic land change model was capable to reconstruct this land conversion. However, it found the land change area in the middle of the southern section, whereas it was in the left southern section according to the reference data.

Besides the visual comparison in Figure 2.9, the two products were cross-validated for each of the 73 validation sites for the time steps 1990 and 1950 by comparing the area coverage per class for each validation site. As indicator we chose the Relative Root Mean Square Error of Prediction (RRMSEP) which was calculated as follows:

$$(1) \quad RRMSEP = \sqrt{\frac{\sum_{i=0}^{n}(r_i - p_i)^2}{n}} / \emptyset_r$$

Where:

r_i = reference class area

p_i = prediction class area

n = number of sites

$\emptyset_r$ = average of reference class area

For 1990 we calculated an RRMSEP for settlement of 0.21, for cropland of 0.41, for forest of 0.37, for grassland of 0.72 and for other land of 0.53. For the year 1950 the RRMSEP was for settlement 0.50, for cropland 0.50, for forest 0.46, for grassland 0.70 and for other land 0.57. The values for 1990 indicate that between our approach and the reference data already an average area disagreement ranging from 21% to 72% existed. These location errors are likely induced by the differences between our baseline map and our reference data. For instance it was noticed that in the most northern validation site in Finland, the reference data set derived almost a complete coverage of forest (94%), whereas our baseline map yielded a grassland coverage of 94%. This appeared also for some other sites.

The comparison of RRMSEP between 1990 and 1950 revealed that our approach induces more area errors, the further it models back in time. Where all reference samples sites comprise together an average area change of 4% between 1950 and 1990 for the classes studied, our approach derived for these sample sites overall an area of about 8% affected by land changes for these sample sites.

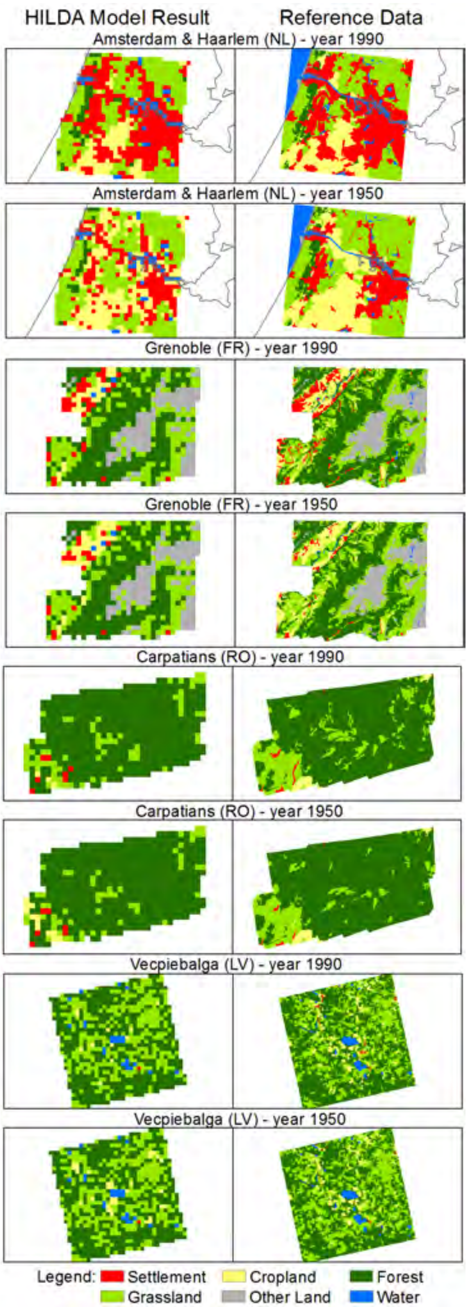

Figure 2.9: Model validation (left) for four regional case studies with reference test sites (right), each for the year 1950 and 1990.

It should, however, be noted that the small area changes in the reference data are largely the result of persistence in land cover: the overall distribution of land cover across the test sites remained the same across the two years, especially as many of the reference sites were located in relatively stable rural areas. This persistence often led to high correspondence levels in land cover model validations (Pontius *et al.*, 2008).

In general the validation with reference data revealed that our approach could capture the main land change hot spots and its conversion types correctly in many cases. Both the reference data and our approach showed an increase in urban and forest areas (mainly due to cropland and grassland losses) and a decrease in cropland and grassland areas (due to afforestation and urbanization) between 1950 and 1990. However, detailed comparison of the maps revealed larger deviations in predicting the exact location of change. The area affected by change and its change rate were smaller than those of the modelled land cover for EU-27. This was because of the sampling size and a bias towards areas containing nature reserves. Therefore, it was not possible to produce statistically reliable estimates of land cover change for larger areas (Gerard *et al.*, 2010).

Nevertheless, compared with the existing global land use reconstructions, the validation showed that the presented historic land reconstruction is capable to describe land changes at a higher spatial and thematic resolution leading to a realistic representation of the landscape composition and pattern, which is of high importance for reliable assessments based on such data (Verburg *et al.*, 2012). While our approach could provide complete thematic information on land changes within validation sites, global models could only provide information on some classes with a spatial resolution that is for some of the data as coarse as a whole reference test site.

2.4 Discussion

2.4.1 Land reconstruction

Analysing the reconstructed land conversions of the investigated period for Europe, the main conversion types were grassland to forest, cropland to grassland, cropland to forest, grassland to cropland, and cropland to settlement (Fig. 2.6). Together all changes led to 674684 km² (15.47%) of changed land within the last 60 years, an area similar to France (Table 2.2). Although we cannot determine the proximate cause and underlying driving factors of these land changes based on the analysis in this paper, some of the locations of major land changes can be related to major political decisions. Examples include the timber shortage after the Second World War, the urbanization due to the increased population, the controlled economy in countries belonging to the Russian Federation until 1990, the Common Agricultural Policy (CAP) and its accompanying afforestation actions.

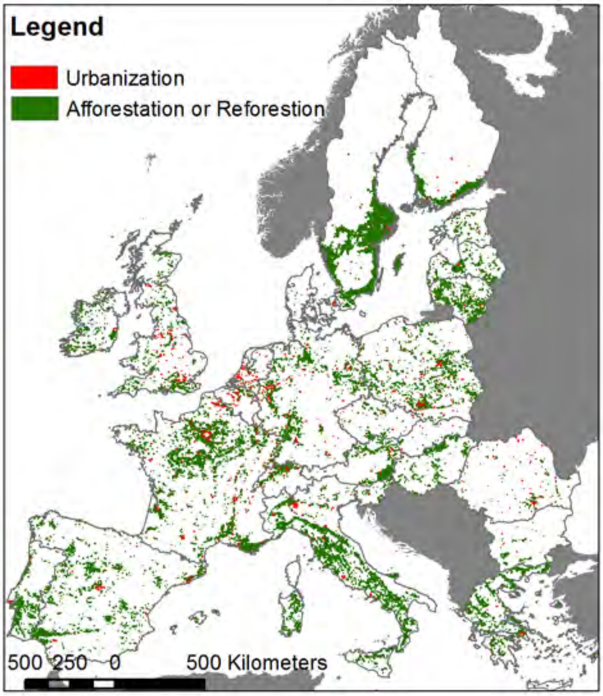

Figure 2.10: Prime areas of major urbanization and afforestation/reforestation hotspots for the period 1950-2010.

2.4.1.1 The post-war urbanization of Europe

The increase of settlement area of about 35818 km² (+24.54% of new urban area) throughout Europe since 1950 is a clearly visible effect in the results. During the investigated period the population increased by 122 M humans, who migrated from rural areas into cities. Particularly the western capitalistic counties (Germany, England, France, Belgium, Netherlands, etc.) experienced quite an economic boom after the Second World War, resulting in such urbanization (Crafts and Toniolo, 2008). These land changes occur mostly where large settlement areas already can be found, especially world and global cities and their agglomerations. They cover the highest density of commerce, money, industries and related human capital (Fig. 2.10). City clusters along the *blue banana* were mainly affected as well as cities like Madrid, Berlin and Paris.

2.4.1.2 The European timber shortage after World War II and European afforestation actions

The total area of forest increased by 314177 km² (+25.35% of new forest land) (Fig. 2.10) since 1950. This land conversion could be seen in almost every country, with the main increase in Western and Northern Europe (Fig. 2.6). After the two World Wars and rigorous resource exploitation due to former land use, the European forests were in a critical situation. The timber shortage was induced by the economic demand for wood products and led to several national afforestation actions (FAO 1947, 1948). One hotspot is southern Scandinavia. Although Sweden and Finland always exported timber for the last few centuries, they released land reforms at the beginning of the last century, which regulated the management of their forests (Meissner, 1956). Before these land reforms, in the 19^{th} and beginning of the 20^{th} century, primary forests were cut by subsistence farmers using a mixed form of management between forest, cropland and grassland. Later on, large scale forest enterprises managed the land, focusing only on wood supplies (Royal Swedish Academy of Agriculture and Forestry (KSLA), 2009). Croplands were abandoned, resulting in fallow land, and afforested by the companies with seedlings, resulting decades after the last land reform in new managed forest areas. The results show this transition, taking the temporal gap of cropland and forest demand into account (Fig. 2.5).

After the collapse of the Austrian-Hungarian Empire in 1918 and the loss of the Upper-Hungarian area to Czechoslovakia and large parts of Transylvania to Romania in 1938/40, Hungary lost the main forestry areas of its previous realm (ca. 84%) (Dauner, 1998). This loss led to subsequent afforestation actions of the remaining area, especially in the Plain, resulting in a forest area increase from ca. 12% in 1938 (Dauner, 1998) to ca. 22% in 2010.

During the same period the forest area in the Baltic States increased as well. The area increase after World War II and during the 60's took place when natural afforestation recaptured the land and the abandoned agricultural land was afforested (Ozols, 1995). In the 90's this trend proceeded after the Fall of the Iron Curtain (see section 2.4.1.4) and the introduction of the CAP (see section 2.4.1.3).

In the 1990's the EEC Regulation No 2080/92 included afforestation as forestry measure in the European Law to further decrease the deficit of European timber production. Accompanying the CAP, less productive agricultural land should be converted into forest areas to steer and optimize the production of natural goods and to support the preservation of the environment (EEC 1992, 2005). From 2000 to 2006, afforestation actions were stipulated by the Regulation (EC) No 1257/1999 (EEC 1999, 2005).

2.4.1.3 Cropland changes before and after the introduction of the Common Agricultural Policy

The CAP of the European Union came into effect in 1990. By guaranteeing farmers subsidies and a standard of living, this policy forced the reorganization of agricultural land (cropland and pastures) to be more competitive for global markets (Pinto-Correia and Vos, 2004). Several regions (e.g. the province Alentejo in Portugal) became unattractive due to their higher management effort and lower accessibility and were converted into other land forms within just a few decades (Pinto-Correia and Vos, 2004).

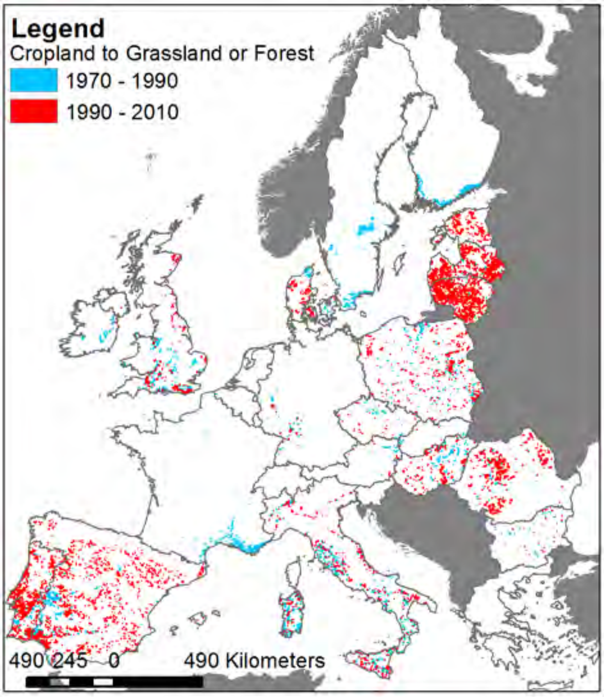

Figure 2.11: Prime areas with loss of cropland. Cropland to grassland or forest is displayed separately for two 20-year groups, before and after the introduction of the Common Agricultural Policy in 1990.

In whole Europe an area of 144733 km^2 of cropland was converted into grassland and forests since the start of the CAP (1990-2010) (Fig. 2.11). This is an increase by 150% in comparison to the same period before 1990 (1970-1990) (95990 km^2). The former socialistic states (incl. Baltic countries) and Mediterranean countries like Spain, Portugal and Italy can be clearly seen as major hotspots. In Southern Europe the increase even exceeded 200%.

During 1970 to 1990 the converted cropland area was 30638 km^2, since 1990 it was 61404 km^2. Additionally, Southern Europe experienced an amount of land changes, which were 4% above the European average (Fig. 2.6). 85% of the occurred land changes in this region were due to land conversions from cropland to grassland or grassland to forest, although it cannot be distinguished whether these land changes are cropland abandonment, conversion into pastures or driven by the reforestation actions of the EU.

Before the introduction of the CAP, main change patterns of cropland could be seen for example in Hungary as a result of the afforestation actions since the late 30's (see section 2.4.1.2) due to forest area losses after World War I. Similar patterns occur in Scandinavia, where several land reforms led to these changes (see section 2.4.1.2), and areas of France, Spain and Italy.

2.4.1.4 The Fall of the Iron Curtain

The same conversion effects as related to the CAP can be seen for the Baltic States (Fig. 2.11) mainly since 1990, but under a different political situation. Lithuania, Latvia and Estonia were part of the Soviet Union before 1990, and carried out a plan economy, resulting in large areas of cropland. After the Fall of the Iron Curtain, the agricultural system was not competitive on the international market, due to low productivity, environment polluting machinery and high energy consumption, so that the value of wood production became more important, resulting in afforestation areas and fallow cropland (Mander and Kuuba, 2004; Prishchepov *et al.*, 2012).

Before 1990 Romania has also been led by a plan economy of the Soviet Union. The main focus was on cropland due to the Mediterranean climate, but the international markets in the 1990’s entailed that the supply and the production methods were not competitive enough to survive, due to the same reasons for almost every eastern European country: low productivity, old and environment polluting machinery, high energy consumption. Large areas in the Transylvanian and Moldavian province have been turned into fallow land (Kuemmerle *et al.*, 2009; Mueller *et al.*, 2009).

The main land conversion types of Eastern Europe were cropland to grassland, grassland to forest and cropland to forest (Fig. 2.6). Together they caused 78% of all land changes in that region since 1950. Most of these changes occurred after the fall of the Iron Curtain. The effects, before and after this event, can be seen for two of these conversion types in Figure 2.11.

2.4.2 Comparative assessment and validation

The comparison with global models revealed differences in the spatial allocation of land cover. Figure 2.7 illustrated this for cropland. Differences could be attributed to the various distribution methods of each model, considering different assumptions for the allocation of land cover and its changes. However, the absolute differences (Fig. 2.8) could also originate from different baseline data sets, from processing in a non-equal area projection (all global model results are given in WGS84), a different change data basis, methods for gap filling of land change data, cross country allocation procedures and wrong assumptions for areas with poor data.

The validation with the reference data revealed that our results could capture most of the overall patterns of land change, although deviations with the observed data remain. The higher inaccuracies in the results for the grassland class can also be attributed to the known problems of CORINE to differentiate between cropland and grassland (Maucha and Buettner 2005; EEA 2006). Since our study also combines pastures and natural grassland areas it assumes the same dynamics for both land cover types, which is in reality not the case.

2.4.3 Methods

Due to the combination of new and more suitable data sets for Europe as well as better and more detailed modelling techniques, the results of our approach can be used to considerably improve GHG and climate assessments compared to existing methods. By the use of the presented method and available data for Europe new synergies have arisen, like a high spatial resolution, flexibility in processing and the consideration of a full land change balance with its land conversion types.

In comparison to other land reconstructions we have only considered a relatively short time period in which we could base the national land areas on available census data and other sources. Global historic models like HYDE (Ellis *et al.*, 2012; Klein Goldewijk *et al.*, 2010, 2011) have reconstructed land change over much longer historic periods and are therefore relying more on assumptions about management practices and class relations to process land categories over time (e.g. population/cropland ratios or livestock/pasture ratios). This is because land data are rare or often not available for their covered areas and periods (centuries to millennia) for all time steps. The higher spatial-thematic detail of our study responds to the demands by the GHG community (Ciais *et al.*, 2011; Schulze *et al.*, 2010) providing base maps for GHG inventories and further information about the influence of land change on emissions. As a baseline year we used the year 2000, where data availability, quality and overlap along the products were best. However, the approach is flexible in using different base years if new data become available.

In many cases spatially explicit land cover time series (e.g. such as Landsat from the early 70's) could support and improve on-going land reconstructions. Unfortunately, there is still no land cover product such as CORINE for the 70's and 80's available, which can be used for land reconstructions.

Although European level simulations of future land change were available (Rounsevell *et al.*, 2006; Verburg *et al.*, 2010) the underlying models were not directly applicable to provide backcasting. Many land change models used for simulation of future scenarios account for path-dependency in the land system evolvement and are therefore not suited for reconstructing land use history in a backward mode or deal with limitations in historic data availability. The land allocation approach used in this paper is much simpler and not path-dependent and therefore more suited for the specific purpose of this paper.

The assumption of constant probability maps for the whole modelling period might lead to limitations in the allocation approach. They are econometrically fitted based on the current time relations between drivers and land use. Although many factors are considered to be quite stable in time (e.g. climate-, terrain- and soil factors), this may have been different in the past for some of them (e.g., for accessibility or population density).

However, the estimation of the probability maps has been done at national scale (with country specific factors) and was widely used and tested in multiple land use modelling efforts in a foresight mode (Verburg and Overmars, 2009; Verburg *et al.*, 2008, 2010).

Furthermore, the allocation factors considered in the probability maps have been based on factors often used and mentioned in other historic case studies of land change processes such as Klein Goldewijk *et al.* (2010, 2011) (population density, soil suitability, accessibility, terrain factors, climate factors etc.), Kaplan *et al.* (2009) (population, soil and climate factors), Pongratz *et al.* (2008) (population before 1700, and from 1700 onwards factors of Klein Goldewijk *et al.* (2010, 2011) were used), Olofsson and Hickler (2008) (used factors from Klein Goldewijk *et al.* (2010, 2011)).

The chosen class hierarchy was most suitable for adapting the real land developments. However, it has implications on the final result that have to be considered. The hierarchy approach requires that all territorial claims of a higher ranked class are satisfied first, which is in reality not always valid. It is rather the case that each class has dominant and less dominant conversion types (e.g., increasing settlement area is incorporating 60% of cropland, 30% of grassland and 10% of forest areas). On the other hand, this consideration would require knowledge about gross land changes (e.g., provided by spatially explicit information or statistics which consider such a conversion matrix), instead of net land changes (e.g. provided by statistics on an administrative basis). However, a full consideration of the gross/net changes was not possible for our product as this would require the comparison of consistent spatially explicit maps or statistics covering the whole period, which account for gross changes (often these statistics were obtained from remote sensing products). The only product where a comparison would have made sense, was the CORINE data set with the time steps 1990, 2000 and 2006. Unfortunately, CORINE does not cover the whole period. The UMD data set uses data of roughly a 20 year period, which makes it difficult to account for changes when comparing with other data sets. The GlobCORINE data set comprises only a few years (2005 and 2009) and the period is covered as well by the CORINE data sets. The statistics we used only accounted for the total area of a land cover class. So, we were missing the information of the change matrix. Additionally, all these maps are affected by misclassification, which increases the uncertainty of the gross change estimation. Most often these classification errors occur for rapidly changing classes, such as cropland and grassland.

Nonetheless, we calculated the net/gross change difference for CORINE 1990 and 2000 for the entire study area to provide an order of magnitude for this difference. The land change intensity of gross land changes exceeded the net changes by roughly 160% for settlements, cropland and forest. For grasslands it exceeded even by 450%. This underestimation by our approach is similar to the difference between UNFCCC reports and our estimates (see section 2.4.4). However, the order of magnitude of the CORINE products varies very strongly if we consider another period, for example from 2000 to 2006. The land change intensity of gross changes was for settlements 170%, for croplands 1500%, for forests 250% and for grasslands 300% higher than for net changes.

2.4.4 Implications for GHG and climate models

Besides the technical improvements on spatial resolution, which enables to study more fine scale variability in land changes than before, the results include new relevant land categories for GHG assessments, such as the settlement class and other land class (including inland water). Since all land categories in the presented approach cover together thematically 100% of the land area, it enables GHG models to take a full land change balance into account. This again affects the GHG balance. The importance of historic land changes and their effect on soil organic carbon (SOC) was pointed out by Poeplau *et al.* (2011). The associated uncertainties of SOC estimation on the GHG balance without sufficient land change information was addressed by Ciais *et al.* (2011). Furthermore, our approach allows relating land changes to their underlying proximity causes on an improved level of detail. This is an important advancement for GHG and climate research, since it supports the study on the effects of human activity on our climate.

However, this land change reconstruction processes net land change information, instead of gross change information due to the input data. Therefore, the change rate will be underestimated, since the dynamic of changes within administrative boundaries is not well captured. Schulze *et al.* (2010) quantified the spatially inexplicit UNFCCC gross change rate per year to be 17800 km² for EU25, whereas our results have a spatially determined yearly net change rate of 11336 km² for EU27 and Switzerland.

Not only compared with other historic land reconstructions, but also with related novel satellite products and modern GHG reporting mechanisms, our approach has important added values for GHG studies, such as:

1. This approach and data set covers a longer period than modern reporting mechanisms for greenhouse gas emissions, which is important for legacy effects (e.g. soil carbon) and understanding of GHG processes.
2. Related remote sensing products cannot cover this time span.
3. None of the previous reconstruction products considered the most important land use classes (cropland, grasslands and forests) in one product and at an appropriate spatial resolution, in order to observe these land conversion types.
4. This approach combines and harmonizes multiple reporting mechanism in one product and often adds a spatial component.
5. Since gross changes cannot be directly derived from one product for the whole period, they have to be estimated by additional information. This difference with net changes should be applied on already existing model structures. Our approach can be used for that in future studies.

2.5 Conclusion

The aim of this paper was to investigate whether the combination of different data sources, more detailed modelling techniques and the integration of land conversion types allow us to create accurate, high resolution historic land change data for Europe suited for the needs of GHG and climate assessments. By the use of multiple harmonized data sources and our modelling approach, we were able to process the historic land reconstruction on a 1 km spatial resolution for five IPCC land categories. Thereby, we focused on allocating existing harmonized land cover change data from census data rather than modelling these changes based on assumptions of change processes. The categories cover 100% of the land area, and take a full land change balance into account. This allows the consideration of land conversion types.

The results indicate that almost 700,000 km² (15.5%) of land cover in Europe has changed over the period 1950 to 2010, an area similar to France. In Southern Europe the relative amount of change was almost 3.5% higher than this average. Based on the results the specific types of conversion, hot-spots of change and their relation to political decisions and socio-economic transitions were studied. The analysis indicated that the main drivers of land change over the studied period were urbanization, the reforestation program due to the timber shortage after the Second World War, the fall of the Iron Curtain, the Common Agricultural Policy and accompanying afforestation actions of the EU.

The validation with historic aerial photographs from 1950 and 1990 for 73 sample sites across Europe revealed that our results could capture most of the overall patterns of land change, although deviations with the observed data remain. In comparison with other land reconstructions like Klein Goldewijk *et al.* (2010, 2011), Ramankutty and Foley (1999), Pongratz *et al.* (2008) and Hurtt *et al.* (2006) it could be shown that our approach performs in line with these land reconstructions. Furthermore, the new method takes account of the harmonization of different datasets by achieving a high spatial resolution and regional detail with a full coverage of different land categories. These characteristic allow the data to be used for supporting and improving on-going GHG inventories and climate research.

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3. The potential of old maps and encyclopaedias for reconstructing historic European land cover/use change

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“Unfortunately, historians have become so absorbed in detailed research that they have tended to neglect the job of building larger-scale maps of the past.”

David Christian
“The Case for `Big History' " in The Journal of World History (1991)

Abstract

Continental to global reconstructions of historic land cover/use are important inputs for many environmental, ecological and biogeochemical studies. While local to regional reconstructions frequently make use of old topographic maps and land use statistics, continental to global reconstructions are mostly model-based reconstructions. As a result they are subject to large uncertainties. A wealth of historic land cover/use maps and statistics have been produced and these are now more accessible due to the ending of copyrights and secrecy statuses, enthusiastic hobby communities and national cartographic institutes or cadastres that have a strategy towards data sharing with society. In this paper we made use of historic statistics and old topographic maps to demonstrate the added value for model-based reconstructions of historic land cover/use for Central Europe back to 1900. We harmonized these diverse data types and different types of historic land data were incorporated into the land use reconstructions. The added value of using these data was evaluated using historical maps by performing a reconstruction with and without the historic information. The accuracy of the land allocation in the historic reconstruction was improved by 16.5% using historic maps. Additionally, historic maps improved the representation of the spatial structure of landscapes. The historic land cover/use statistics used showed a strong agreement with independent estimates, like historic maps.

3.1 Introduction

Historic land cover/use data at large scales (Hurtt *et al.*, 2006, 2011; Kaplan *et al.*, 2009; Klein Goldewijk *et al.*, 2010, 2011; Pongratz *et al.*, 2008; Ramankutty and Foley, 1999) have improved our understanding on how humankind altered our planet during the Anthropocene (Ellis *et al.*, 2013) and helped to study effects of land change trends and transitions on environmental and ecological processes (Foley *et al.*, 2005). Information on historic land cover/use provides insights in the cultural heritage of landscapes (Plieninger *et al.*, 2006). Moreover, historic reconstructions are a fundamental data source to estimate greenhouse gas emissions and to understand the evolution of the biogeochemical cycle (IPCC, 2013). Many local to regional reconstructions are based on old topographic maps and land use records (Bicik *et al.*, 2001; Carni *et al.*, 1998; Godet and Thomas, 2013; González-Puente *et al.*, 2014; Jawarneh and Julian, 2012; Marull *et al.*, 2014; Orczewska, 2009; Petit and Lambin, 2002; Skaloš *et al.*, 2011; Skokanová *et al.*, 2012). However, at continental and global scales, most reconstructions of historic land cover/use are modelled based on population statistics and scarce historic land cover/use data. As a result, there is a large uncertainty in these reconstructions (Klein Goldewijk and Verburg, 2013). Several authors have mentioned that more historic data are needed to reduce the uncertainties in reconstructions (Fuchs et al., 2015a; Gaillard et al., 2010; Klein Goldewijk and Verburg, 2013).

A broader use of available historic input data would help to verify, correct or withdraw assumptions used in historic reconstructions. It is hypothesized that the use of multiple harmonized land cover/use statistics and maps would lead to improved estimates of change trends and better spatial allocation of historic change.

The current use of historic data is limited due to a number of constraints: the need for harmonization across different inconsistent data sources, the different acquisition techniques used (sampling, aerial photographs, remote sensing) and the data formats (from analogue prints to digital data and from hand drawn survey maps via aerial photographs to digital remote sensing data). In addition, in many cases land cover/use data were published in local languages, requiring local knowledge to read them. Copyright, national interest, competition and secrecy (e.g. military maps) prevented the accessibility. Furthermore, changing country borders, especially in Europe, made it hard to compare any area related statistics.

Despite these constraints, a wealth of historic land cover/use data have been produced over decades and centuries. Nowadays, this type of data is becoming more and more accessible due to the ending of copyrights, e.g. for historic land cover/use maps (Schlueter, 1952, 1953, 1958) and encyclopaedias with statistical information (Bibliographisches Institut, 1909; Chisholm and Phillips, 1911). The ending of secrecy statuses for historic military maps eases accessibility, e.g. for soviet military topographic maps (Vlasenko, 2008). Many enthusiastic communities have started to collect and share historic land cover data (e.g. Rumsey, 2014). National cartographic institutes and cadastres have an increased willingness for transparency, open data policy and data sharing with society (Bundesamt fuer Kartografie und Geodaesie, 2014; Centro National de Information Geografica, 2013; Eötvös University Department of Cartography and Geoinformatics, 2013; Geoportail, 2013a, 2013b; Koningklijke Bibliotheek van België, 2014; Mapster, 2014; National Libary of Scotland, 2013; University of Stockholm, 2013a, 2013b).

The objective of this paper is to make use of historic statistics and topographic maps to improve a historic reconstruction of land cover/use for Europe and evaluate the added value of using such additional data. In this paper the focus will be on the forest/non-forest classification. Section 3.2 describes the methods used to harmonize historic statistics and incorporate historic maps into land use reconstructions for Europe. Section 3.3 explores the added value of such data in reconstructions of land cover/use. This is followed by a discussion in section 3.4.

3.2 Material and Methods

3.2.1 Study area and period

The different data types (historic statistics and maps) explained in this section were available for almost whole Continental Europe for different time steps. However, in order to demonstrate the application of the methods and their added value we focused for this paper on the time around 1900 and an area that we defined as Central Europe. This area comprised in our definition the following countries: Germany, Luxemburg, Poland, Czech Republic, Slovakia, Austria, Hungary, Romania, Bulgaria and Slovenia (Fig. 3.1). In total, the study area covers more than 30% of the EU27 area. We have chosen this study area to prove the added value of historic maps and statistics, first, for a considerable large area of Europe and, secondly, to avoid the explanation of too many different data sets that otherwise would have been required for this study. Furthermore, we focused on the year 1900 since this year was the starting year of our model reconstruction of historic land cover/use, later on explained in this paper.

3.2.2 Data

3.2.2.1 Historic Maps

For our analysis we used historic maps from two large scale surveys: The ‘Generalkarte’ (general map) of the 3rd Military Mapping Survey of the Austrian-Hungarian Empire (Eötvös University Department of Cartography and Geoinformatics, 2013) and the Central European land cover map of the protohistoric settlement areas in Europe (Schlueter, 1952, 1953, 1958).

Figure 3.1: Overview of the study area.

Table 3.1 gives an overview of the features of the maps and Figure 3.2 illustrates the coverage for each data set. The Schlueter map was scanned full colour with 600 dots per inch (dpi) in TIFF and A0 format in order to get a digital version. A high number of dpi assured that linear features in the map (letters, roads, land cover class borders) could be represented with enough detail and later on be classified separately. Furthermore, a high number of dpi prevented blurring of colours around edges of land cover classes. The map tiles of the Austrian-Hungarian Empire were already scanned. The ‘Generalkarte’ of the Austrian-Hungarian Empire map is the coarsest map (1:200000) with the largest area coverage of all three mapping activities of the 3rd Military Mapping Survey (namely ‘Aufnahmeblaetter’ (1:25.000), ‘Spezialkarte’ (1:75.000) and ‘Generalkarte’). The ‘Generalkarte’ consisted in total of 265 map sheets of which the first tiles were printed in 1887. The Schlueter map only consisted of one map sheet that was printed in the 1950’s. Both maps display the land cover/use around the year 1900, the starting date of our historic reconstruction.

3.2.2.2 Statistics

We used sub-national statistics of the Meyers Conversation Encyclopaedia of 1909 (Bibliographisches Institut, 1909), which refers to official statistics around the year 1900.

Table 3.1: Features of used historic maps for the reconstruction of historic land cover back to 1900.

Map Name	Area Coverage	Covered period	Land cover/use classes	Spatial scale
3rd Military Mapping Survey of Austria-Hungary (‘Generalkarte von Mitteleuropa’, 265 map tiles)	2122916 km²	Around 1900	1 forest, 2 settlements and roads 3 agricultural areas	1:200000
Otto Schlüter – Die Siedlungsräume Mitteleuropas in frühgeschichtlicher Zeit	916513 km²	Around 1900	1 forest (around 1900 A.D.) 2 forest (cleared since 900 A.D.) 3 forest (cleared before 900 A.D.) 4 forest-heath areas 5 ice and rocks 6 natural high-altitude grazing areas 7 settlement areas in prehistoric times 8 swamp (around 1900 A.D.) 9 former swamp 10 sea marshes	1:1500000

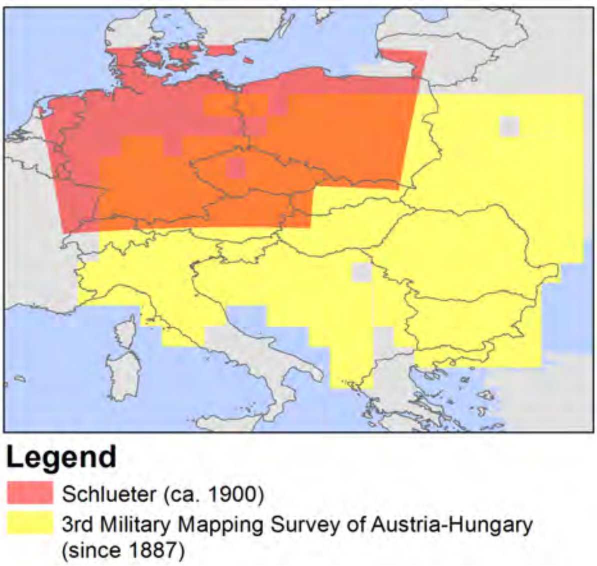

Figure 3.2: Overview of historic map coverage

The encyclopaedia is digitally available at www.zeno.org and statistics can be found under the German name of the countries and provinces.

A list of available statistics for countries and provinces within todays territory of the European Union can be found in Appendix A (see supplemental material in the online publication). We provided their German and English name. For this paper we only made use of country and province statistics that fall within our study area.

3.2.3 Overview of the methods

The methodological approach of this paper consists of three major steps (Fig. 3.3). The first step comprised the georeferencing and classification of the historic maps into forest/non-forest, followed by a qualitative analysis of the classification results. Secondly, we performed the collection and reconstruction of historic statistics of around 1900. This included the border correction of historic to present borders and consistency checks of the reconstructed statistics with statistics of recent decades, but also with independent statistics of the same time. The third step integrated both previous steps into a reconstruction approach of historic land cover/use. Two data sets were produced (one with using historic map information, one without; both used the same historic statistics) to assess the added value of using historic maps as data input for historic reconstructions.

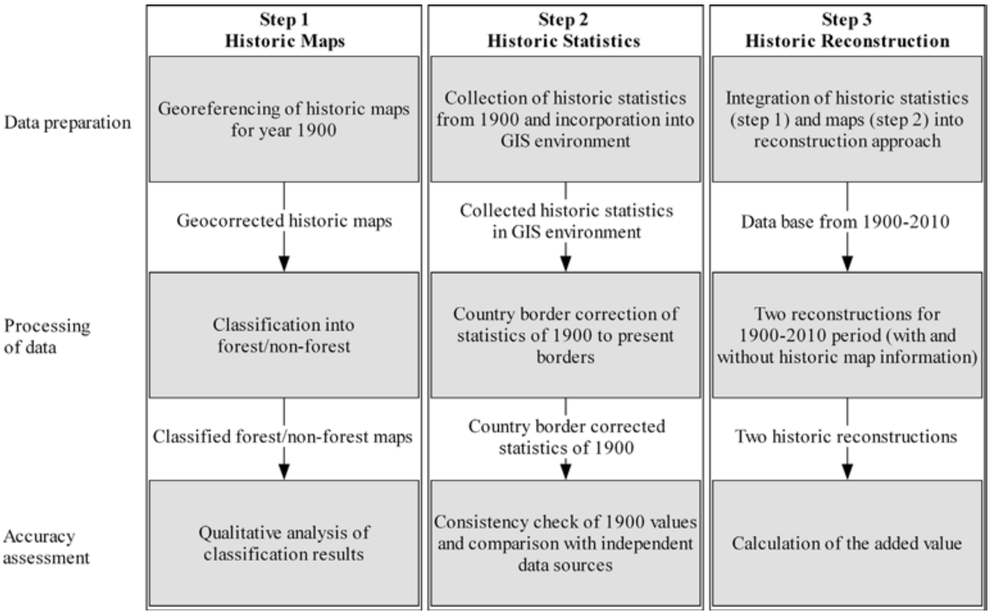

Figure 3.3: Methodological approach of this paper

3.2.4 Methodology

3.2.4.1 Pre-processing and classification of historic maps

We georeferenced and projected the maps into an equal area projection (ETRS Lambert) in order to enable comparing areas. The age difference of the prints and probably also the storage of the maps explained why some map tiles were more affected by bleaching than others. The bleaching altered the colour information of each map tile differently and prevented an automated classification by colour. Therefore, we had to digitize the individual map tiles of the 3rd Military Mapping Survey of Austria-Hungary by hand. The Schlueter map on the other hand was hardly affected by bleaching.

We collected 100 training areas for each land cover/use class, including letters printed on the map, and performed a supervised maximum likelihood classification. To remove the letters from the final land cover/use classes, we first used an expand filter, which creates a buffer zone around pixels of a class, of three pixels (1 pixel = ca. 77.45 m) to remove enclosed letters within a land cover/use class area. In a second step a shrink filter, which removes the buffer zone again, of three pixels was applied to return the outer edges of a land cover/use class area to its original state. The threshold of three pixels for each filter in our case proved to be the optimum to remove letters.

In order to assess and compare the quality of both classifications we analysed the classification results of each data set with 100 randomly stratified sample points and calculated the overall accuracy. Half of the sample points were taken from the forest stratum and half from the non-forest stratum.

3.2.4.2 Data preparation and border correction of historic statistics

Land cover/use statistics for reconstructions are commonly gathered and compared on national scale. Due to the frequently changing national borders in Europe our statistics of 1900 had to be corrected for present-day borders to make them comparable with recent data. To allow such corrections, we first had to reconstruct historic national and sub-national borders for the year 1900 to give all available statistical information a consistent spatial identity. Sub-national statistics enable merging different provinces together in ways that the merged provinces resemble present countries. Present country borders often developed from former sub-national administrative units. An example is Czech Republic, which evolved from the former provincial borders of Moravia, Bohemia and Austrian Silesia. We used political maps of the year 1900 from the Meyers Conversation Encyclopaedia (Bibliographisches Institut, 1909) to digitize and georeference historic borders. Map coordinates and unique landmarks (churches, coastal shapes, crossroads) were used for georeferencing.

After the reconstruction of historic national and sub-national borders, we linked the resulting vector data set with land cover/use statistics for cropland, forests, grassland (including pastures and natural grassland) and other land (including urban and infrastructure) of the Meyers Conversation Encyclopaedia (Bibliographisches Institut, 1909). Land cover/use statistics were used and aggregated, where necessary, to the four abovementioned target classes (Appendix A - see supplemental material in the online publication).

The final vector file with statistical information of 1900 was converted into a raster data set in equal area projection (ETRS Lambert) and overlaid with a vector file of current national borders. Thereby a spatial resolution of 1 km by 1 km was chosen that was sufficient to represent the details of the country border shape. In a final step, we calculated the average land cover/use fraction of all raster cells within the individual country borders for each land cover/use class. We reconstructed the statistics for all EU27 member states including Switzerland (Appendix A and B - see supplemental material in the online publication), but for this paper we focused only on the reconstructed statistics within our study area. For some of the sub-national units of 1900 (Appendix A and B - see supplemental material in the online publication) the land cover/use information could not be reconstructed due to missing statistics. These administrative units were then not considered in the calculation of the average land cover/use fraction. In order to assess the quality of the reconstructed statistics we cross-checked their values with independent data sources of the same time (e.g. with historic maps) or with recent statistical data sources (e.g. Barátossy *et al.*, 1996, 2001; Czuraja, 1982; Food and Agriculture Organization of the United Nations (FAO), 1947a, 1947b, 1948, 2012a, 2012b).

3.2.4.3 Integration of historic maps and statistics into reconstructions

We integrated the results of the maps and statistics into a model-based reconstruction approach (Historic Land Dynamics Assessment (HILDA-v2.0) (Fuchs *et al.*, 2013, 2015a). The approach is based on allocating national level land cover/use statistics through probability maps derived from associations between location factors and current land cover/use. We modified the approach of Fuchs *et al.* (2013) by incorporating our country border corrected historic land cover/use statistics into our data base of stable country border statistics for recent decades. This allowed us to generate a time series for each land cover/use class over the last 110 years on a national scale.

To fully use the potential of historic maps, we fed these maps directly into the spatial allocation algorithm of the reconstruction approach. Figure 3.4 gives an overview of how the historic statistical and map data were used for the historic reconstruction. The information from the classified historic maps was integrated into the probability maps used for spatially allocating land use. In case of areas covered by both maps the map information of the 3rd Military Mapping Survey of Austria-Hungary was chosen, since the maps of the survey had a higher spatial detail than the Schlueter map. Based on the historic maps we modified the probability maps in such a way that forest would always first be allocated to areas that have forest in the historic maps while retaining the relative probabilities of allocation in the forest and non-forest area. This was achieved by scaling the probability for forest in forest areas between 0.5 and 1, while probabilities were scaled between 0 and 0.5 outside the forest area as indicated in the historic maps. This allows spatial allocation of the statistical areas also in case of absence of a perfect match between historic statistics and forest area in the historic maps.

Probability maps mainly provided information where a change had likely taken place, but rarely when. By incorporating historic land cover/use maps for allocation purposes, the difference between maps related to different time periods only provided information whether a land change had taken place within the period the maps covered. Sometimes these periods could span several decades, which made it hard to assign the change of a certain location to a certain time.

To improve the forest probability maps for different time periods, we incorporated volume stock maps of Gallaun *et al.* (2010). Volume stock information contains temporal information of the age of a forest, which can be related to forest changes. The assumption was that the higher the volume stock of a forest the older the trees are and therefore the forest. The age of trees in a forests was used to describe the persistence or vulnerability of a forest to change. In the back-casting reconstruction procedure for decreasing forest area this meant that pixels with the lowest volume stock value were converted first to other land cover/use classes, while pixels with the highest values were converted last. We scaled the volume stock maps between 0 and 1 and multiplied them with our forest probability maps. Then we rescaled the probability maps again between 0 and 1.

3.2.5 Assessment of the added value of historic maps in reconstructions

In order to demonstrate the added value of historic maps for the allocation process, we processed one reconstruction of the last century with historic map information and one reconstruction without that information. We compared the forest areas of the two classification results with the forest areas of the historic maps and calculated the producer's accuracy, user's accuracy, overall accuracy and the total error. The forest areas of the historic maps are considered in this case as reference. The different accuracies can be expressed as follows:

$$\textit{Producer's accuracy} = \frac{\#\ \textit{of pixels correctly classified as forest in the model}}{\#\ \textit{of all forest pixels in historic maps}} \times 100$$

$$\textit{User's accuracy} = \frac{\#\ \textit{of pixels correctly classified as forest in the model}}{\#\ \textit{of all forest pixel in the model}} \times 100$$

$$\textit{Overall accuracy} = \frac{\#\ \textit{of pixels correctly classified}}{\textit{total}\ \#\ \textit{of pixels}} \times 100$$

$$\textit{Total error} = 100 - \textit{Overall accuracy}$$

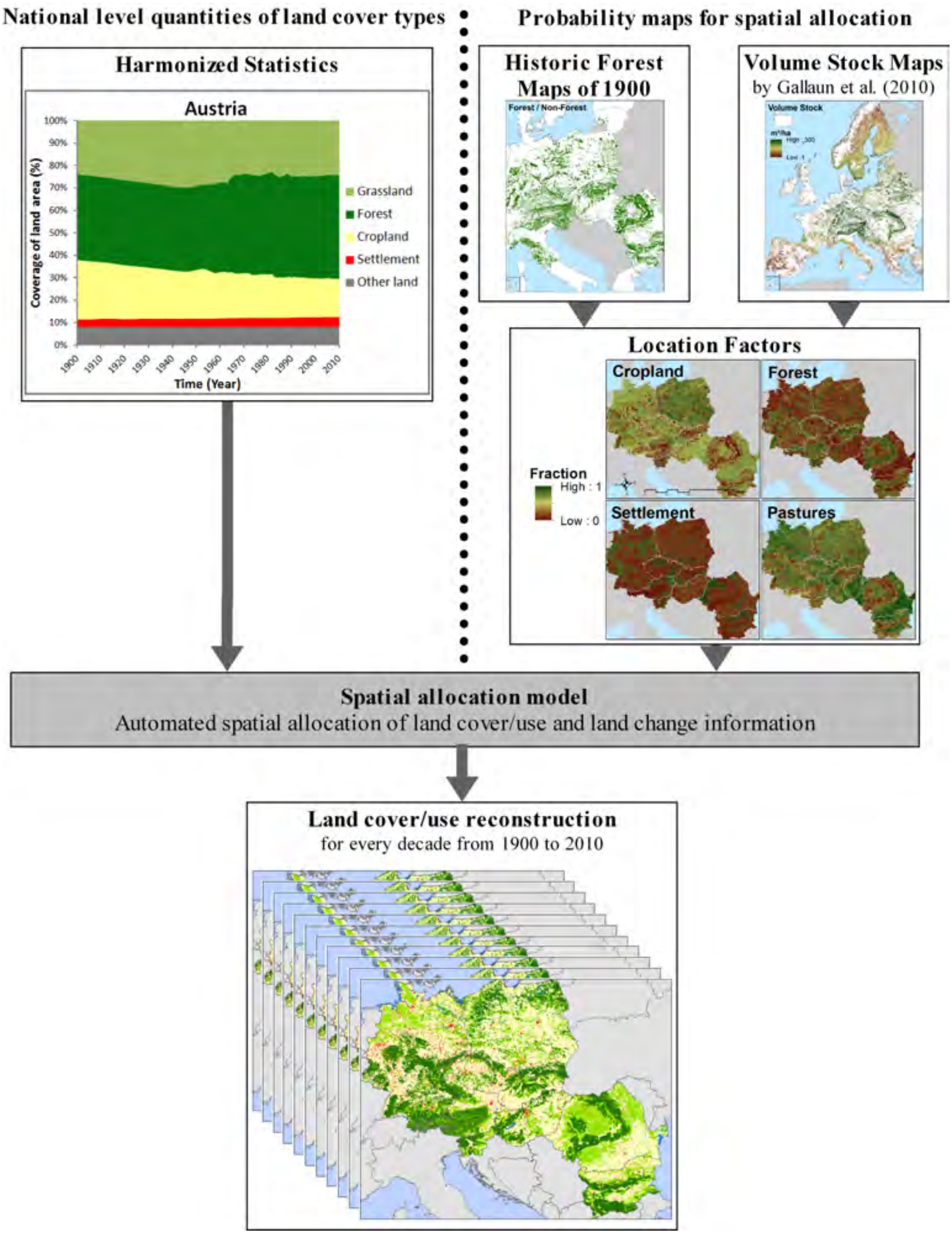

Figure 3.4: Approach used in this study for the reconstruction model.

The land cover/use statistics of 1900 from the encyclopaedia were used as input for our model approach to reconstruct the area extent for each class in 1900.

Due to the reconstruction method of the encyclopaedia statistics these national values might differ from the derived forest area of the historic maps. The difference of these two independent estimates affects the total error in our assessment. However, in our accuracy assessment we want to describe the quality of our model reconstruction. Therefore, we have to calculate the final model error, which was calculated as follows:

$$\boldsymbol{Final\ model\ error = total\ error - area\ difference\ between\ maps\ \&\ encyclopaedia\ statistics}$$

We calculated each of the accuracy parameters for the combination of all countries that were part of the study area.

3.3 Results

3.3.1 Classified historic maps for the year 1900

The results both of the automated and manually classified forest areas around 1900 are highlighted in purple in Figure 3.5. The Schlueter map and all available mapping tiles of the 3rd Military Survey of the Austrian-Hungarian Empire are shown in the background.

A detail of the two map types and their classification results can be seen in Figure 3.6. The top left (Schlueter) and top right (3rd Military Mapping Survey) of Figure 3.6 show the original maps without the classification results but both with the same map extent, depicting the greater area of Vienna in Austria. Figure 3.6 bottom left and bottom right highlight the classification results of forest in purple on top of the maps. Figure 3.6 bottom left shows the result of the maximum likelihood classification after additional filtering to remove letters. Figure 3.6 bottom right shows manually digitized forest areas, again with the same map extent.

Due to the different scale of both maps (see Table 3.1), the map of the 3rd Military Mapping Survey shows a higher level of detail than the Schlueter map. However, bleaching effects of the map tiles and shading made it difficult to distinguish the colour information. The automated classification with filtering was adequate in the Schlueter map, but parts of some letters could not be removed. The original Schlueter map did not distinguish between wooded wetlands and non-wooded wetlands. For that reason the wooded wetlands of the Danube river were not classified as forest in the Schlueter map.

We assessed the quality of both classification techniques with 100 randomly stratified sample points for each data set. Thereby 50 sample points covered classified forest and 50 points non-forest areas. In the Schlueter map 47 sample points of non-forest and 41 sample points of forest were correctly classified, leading to an overall accuracy of 88%. The assessment of the 3rd Military Mapping Survey of Austria-Hungary showed that 47 sample points of non-forest and 44 sample points of forest were correctly classified that totalled up to an overall accuracy of 91%.

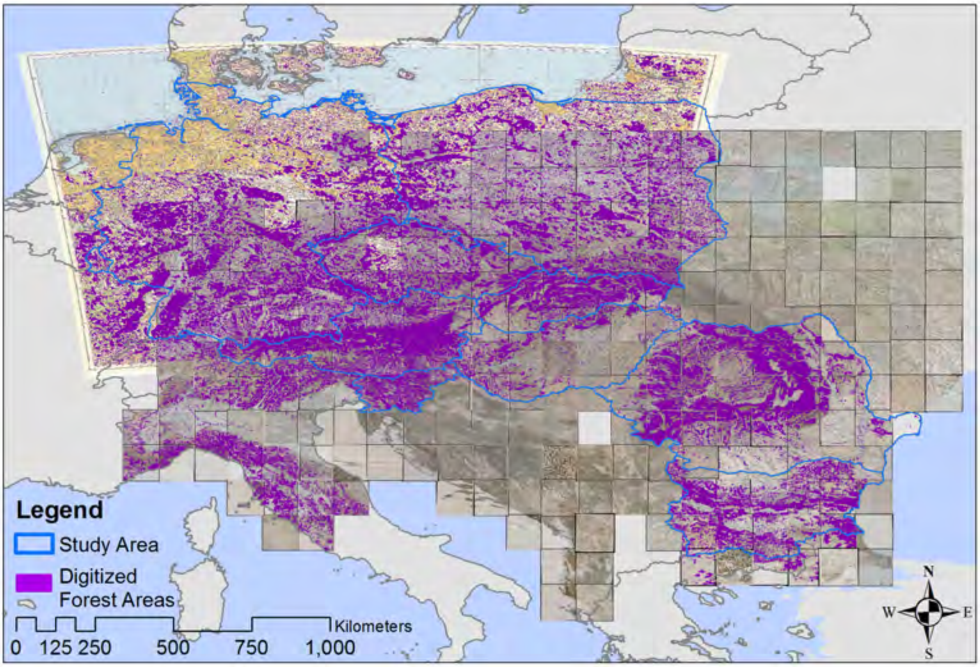

Figure 3.5: Results of both the automated and manually classified forest areas around 1900 highlighted in purple.

3.3.2 Historic land cover/use statistics for the year 1900

Figure 3.7 (left) illustrates the reconstruction of historic national and sub-national borders for forest (a), cropland (b), and grassland (c), respectively. The reconstruction of borders enabled to assign land cover/use statistics to every administrative region for the year 1900. Administrative regions with no information of specific classes were left blank. In Figure 3.7 (right) the current country borders and the conversion of land cover/use statistics of the year 1900 into raster format with 1 km spatial resolution is depicted. With the conversion into raster format every 1 km grid cell contained the information of its former administrative unit. This enabled to assign every grid cell value to a country and calculate the average per administrative unit. The derived values represent the relative area coverage of a class for the associated country. Appendix A contains a complete list of derived land cover/use statistics for forest, cropland and grassland from the Meyers Conversation Encyclopaedia for every national and sub-national unit.

Through a closer look at the time series for individual countries we compared the reconstructed land cover/use values of 1900 with the reported numbers derived from other sources. Figure 3.8 shows examples for changes in forest cover/use, such as Germany and Poland (Fig. 3.8 top). Both countries have a lot of statistical information available, especially after the end of the Second World War.

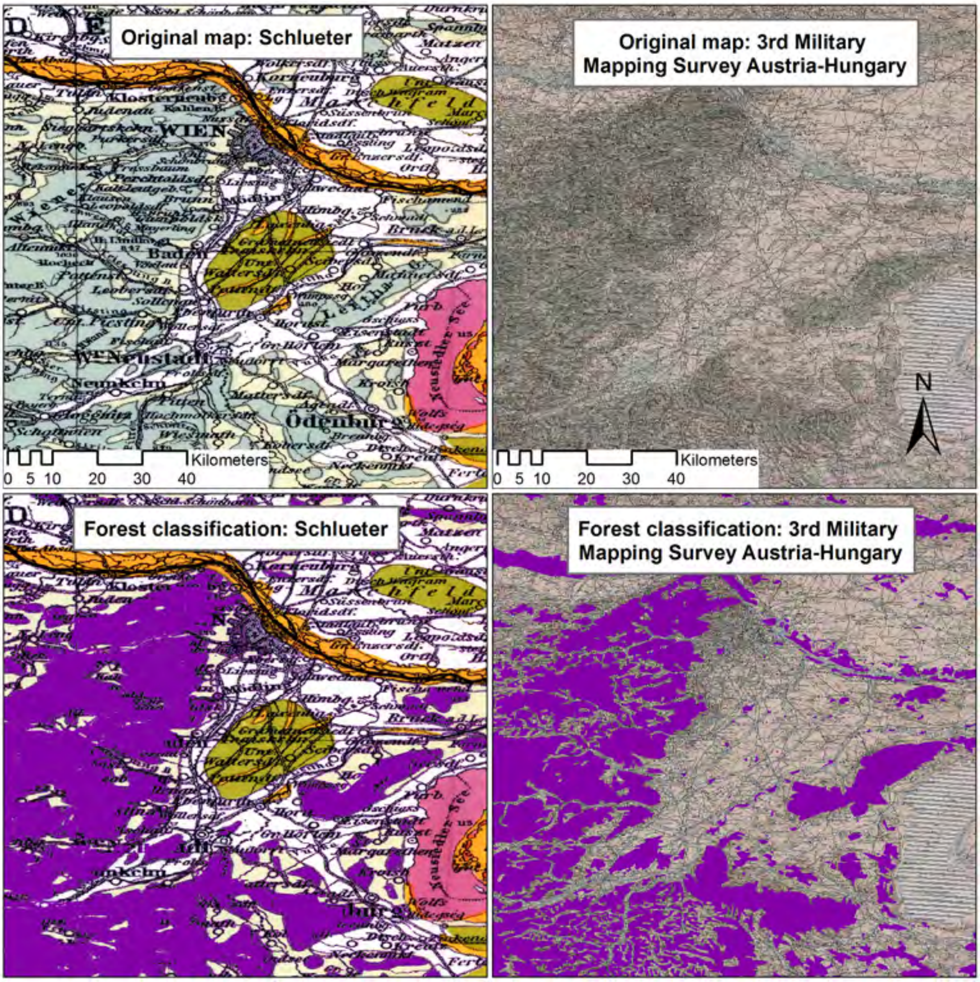

Figure 3.6: Original maps and classification results of historic forest area around 1900 (in purple) showing greater Vienna (AT). Left: Schlueter (forest area is result of the maximum likelihood classification with additional filtering to remove letters) Right: 3rd Military Mapping Survey Austria-Hungary (forest area is manually digitized).

During the period between the two World Wars there were hardly any data available. For that reason it was important to derive forest estimates for the year 1900 that could be used as a starting point for modelling. The blue cross symbol in 1900 visualizes the land cover/use estimates from encyclopaedia statistics. Although both countries experienced frequently changing country borders throughout the century the statistical information for 1900 could be derived from sub-national land cover/use information of that time.

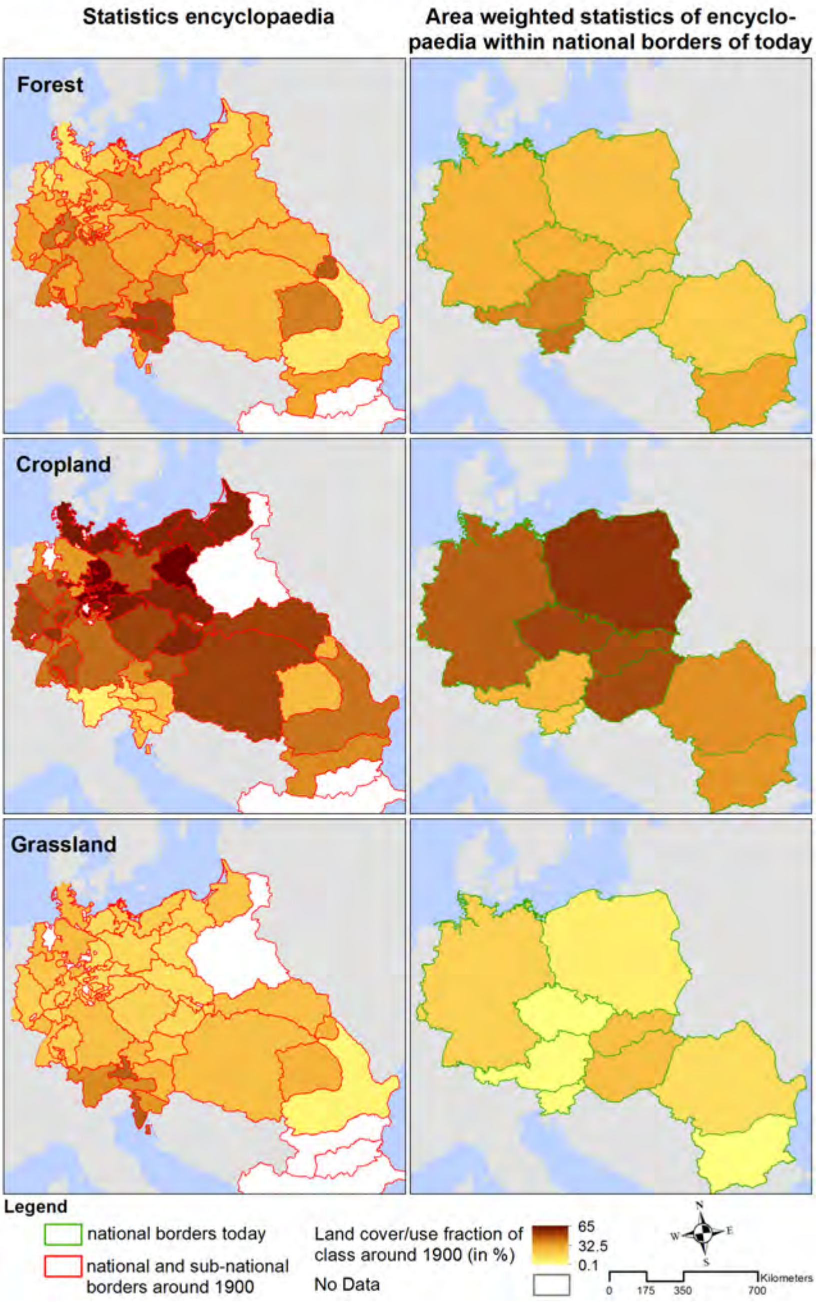

Figure 3.7: Reconstruction result for historic national and sub-national statistics around 1900 derived from encyclopaedia.

Figure 3.8 shows that the reconstructed values for the two countries were in agreement with the independent estimates from historic maps (red diamonds) and with the overall land cover/use trend. The reconstructions for Hungary and Slovakia were deviating compared to the previous example (Fig. 3.8 bottom). Similar to Germany and Poland, Hungary and Slovakia had frequently changing country borders throughout the last century. However, in 1900 both countries were part of the Kingdom of Hungary (not to be confused with the Hungarian Empire). For the Kingdom of Hungary we only had national statistics available and no sub-national data of the different regions. The Kingdom of Hungary consisted mainly of the agricultural plains around Lake Balaton and the mountainous region with forests in the north. Therefore, the land cover/use classes were unequally distributed in the kingdom. One drawback of using area statistics found in encyclopaedias is that an equal distribution of the land cover types across the territory is assumed. After the fall of the Kingdom of Hungary the country was split into the different countries. The present areas of Hungary and Slovakia were part of it. Slovakia mostly contained the mountainous forest areas, whereas Hungary comprised the agricultural plain area. Figure 3.8 nicely shows how this spatially unequal distribution affected our time series. The blue crosses are clearly deviating from the overall land change trend. The estimates for forest seem to be too high for Hungary and too low for Slovakia. The comparison with historic maps for the same time indicates how far off the statistics might be.

3.3.3 Reconstruction of historic land cover/use and assessment of the added value

We incorporated the classification of the historic forest areas into our reconstruction approach to support the spatial allocation of historic statistics and compared it with the reconstruction that had no supporting information of historic maps. For all countries of our study area the result of that comparison is shown in Figure 3.9. In the upper part of the Figure 3.9 (top left and right) the different results of the historic reconstruction for the year 1900 can be seen. Figure 3.9 top left depicts the reconstruction results with no supporting information by historic maps and Figure 3.9 top right depicts the results of the reconstruction with historic map information. Although both methods allocate the same amount of land cover/use area per class to each country it can be seen that the reconstruction results in Figures 3.9 top left and right clearly differ. The forest in Figure 3.9 top left is allocated predominantly to the mountainous areas in the region, indicating a strong dependency of the probability maps on terrain features. Instead, the forest in Figure 3.9 top right appears more heterogeneously distributed, reflecting the influences of landscape fragmentation. The accuracy of the allocation process in both reconstruction methods is shown in the lower parts of Figure 3.9 (bottom left and right). The green and white colours in both parts of the Figure highlight the agreement in forest and non-forest areas, respectively, between the reconstruction and the historic maps. The red colour indicates where the forest was found in the historic maps but not in the historic reconstruction (false negative).

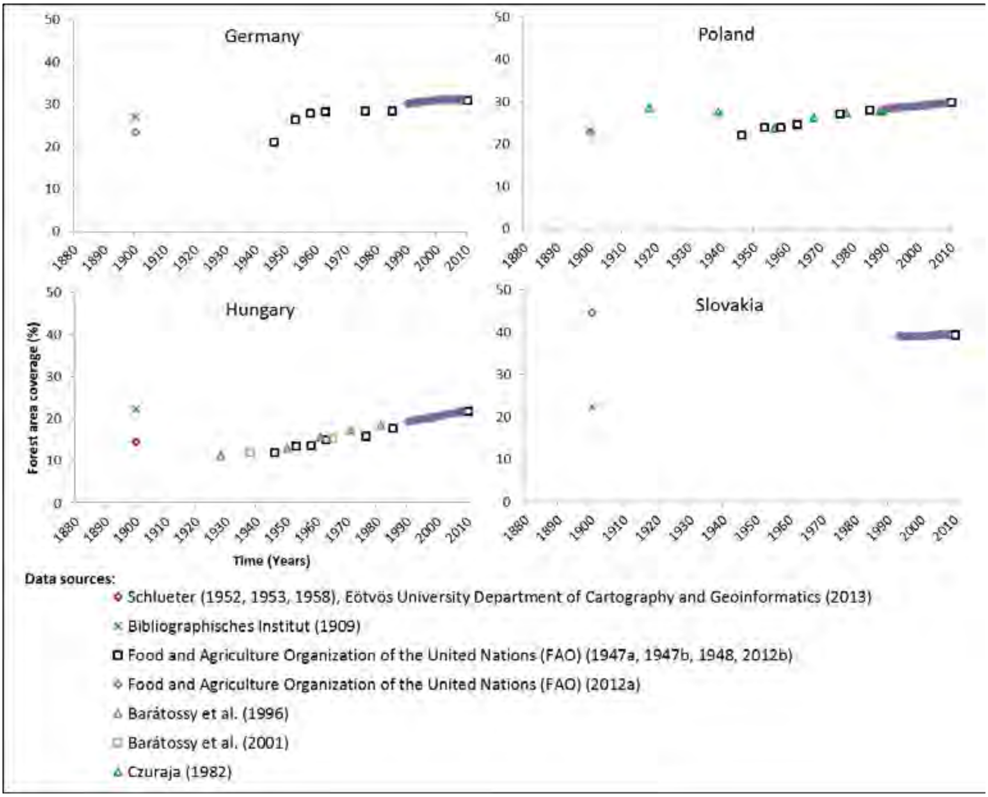

Figure 3.8: Integration of reconstructed forest statistics of 1900 with other statistical forest data sources for different countries.

Orange shows where the historic reconstruction allocated forest areas differently from the historic maps (false positive).

By comparing the two accuracy results spatially, it can be seen that the reconstruction with historic maps as support information for allocation (Fig. 3.9 bottom right) achieved a better agreement with the historic maps than the reconstruction without historic map information (Fig. 3.9 bottom left). The agreement in forest cover between maps and the reconstruction that made no use of historic maps was mainly obtained in mountainous regions. Instead, the reconstruction with historic maps had major areas of disagreement in some specific countries, like Slovakia, Romania, Czech Republic and Austria.

The overall accuracy of the reconstruction without historic maps was 73.71 %. For the reconstruction with historic maps the overall accuracy was 90.15 % (Table 3.2). Both reconstruction methods used statistics as input data for the forest area coverage per country. This amount could differ from the forest area coverage per country obtained by the historic maps. In total this difference was 2.78 % for the whole area.

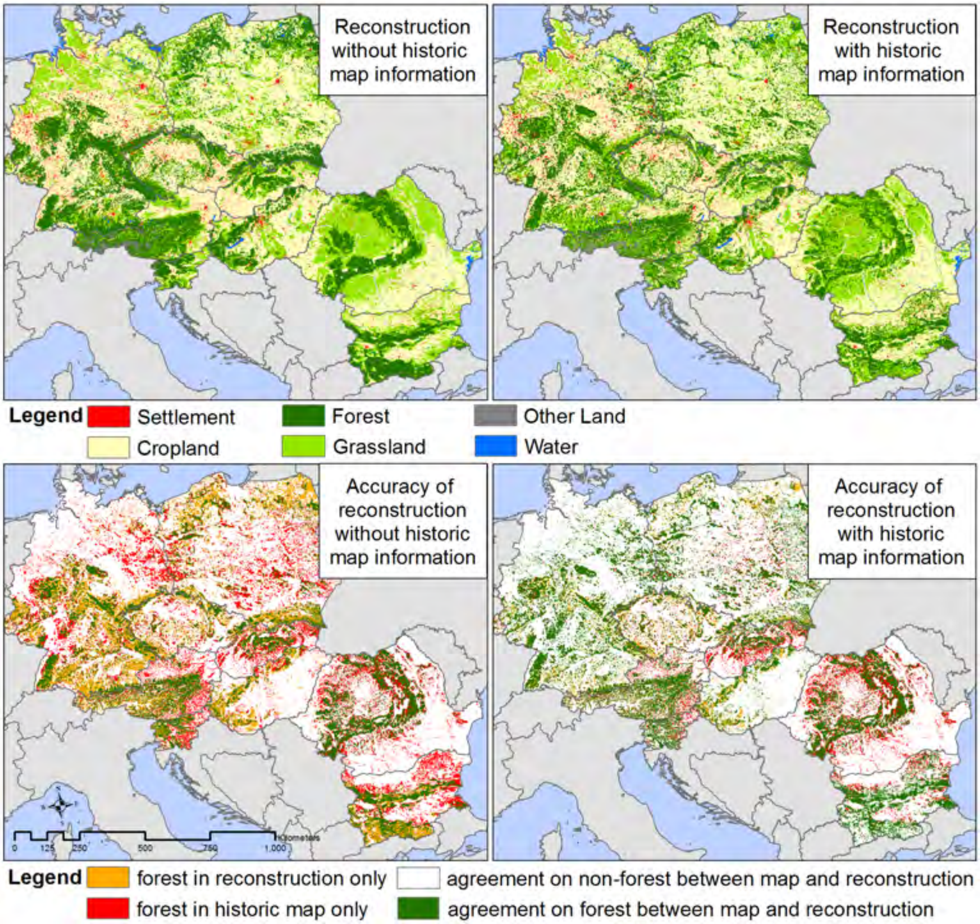

Figure 3.9: Reconstruction results for the year 1900 for countries which were completely covered by historic maps (top) and accuracy assessment of the reconstruction results (bottom).

In order to calculate the model error by the reconstruction approach the difference between statistics and maps had to be subtracted from the total error, which is the complement of the overall accuracy.

The reconstruction without historic maps had a final model error of 23.51 %, whereas the model error with the use of historic maps was reduced to 7.07 %. In other words, the accuracy of the reconstruction was improved by using historic maps as supporting information for allocation by almost 16.5 %. A detailed overview of country specific accuracies is given in Appendix C (see supplemental material in the online publication). The overview shows that the majority of the disagreement shown in Figure 3.9 bottom right is subject to the difference in forest area coverage between statistics and maps.

Table 3.2: Overview of accuracy assessment for the whole study area showing results for the reconstruction with and without the use of historic maps. A detailed overview of accuracies per country can be found in Appendix C (see supplemental material in the online publication).

All 10 countries	**Reconstruction with historic maps**	**Reconstruction without historic maps**
Producer’s accuracy	77.70 %	48.80 %
User’s accuracy	86.15 %	53.93 %
Overall accuracy	90.15 %	73.71 %
Forest area in historical statistics	25.52 %	25.52 %
Forest area in historical maps	28.30 %	28.30 %
Area difference between map and statistics	2.78 %	2.78 %
Total error (reconstruction + historic maps)	9.85 %	26.29 %
Final model error	**7.07 %**	**23.51 %**

For instance, Romania gave an overall accuracy of ca. 85 %, but only 0.16 % of the error is explained by the reconstruction method. The vast majority is explained by the difference between statistics and maps. The same effect also appeared for countries like Slovakia or Slovenia.

3.4 Discussion

3.4.1 Accuracy of data and data processing

Most of the techniques used in this study, such as digitalization of analogue maps, automatic land cover/use classification or spatial allocation of information, are standard tools in geographic information science and remote sensing image processing, and have proven to be valuable for optimally using the information available in historic sources.

Historic maps usually contain already a spatial reference and thematic content, which makes them often easier to process than raw satellite images or aerial photographs. However, the spatial scale, text, contour lines and the quality of the paper print (bleaching) influenced the required effort and final quality of our classification.

Very old printed maps like the 3rd Military Mapping Survey had to be classified manually, significantly increasing the effort. The accuracy assessment of the classified maps with the chosen classification technique showed an overall accuracy of 88% relative to the original Schlueter map and 91% relative to the original 3rd Military Mapping Survey of Austria-Hungary. Problems in the manual digitization arose mainly when the green forest areas were covered by contour lines or when the green colour in the maps was bleached. It was to the judgement of the digitizer to decide which areas belonged to forests. In case of doubts, additional expert judgement was consulted and/or colour contrast was enhanced to improve visibility of the green forest areas.

To consistently use historic maps in a land use reconstruction model the minimum mapping unit (MMU) for the historic maps should at least match the spatial resolution used in the reconstruction model. Preferably, the spatial resolution of the historic maps should be several orders of magnitude higher. In our case the maps had a MMU of 62 m^2 (3rd Military Mapping Survey) and 77 m^2 (Schlueter) while the reconstruction model was applied at a 1 km^2 resolution, thus ensuring a good match.

We also assessed the quality of the used historic maps itself. Our encyclopaedia data confirmed the forest areas in the maps with relatively small deviations (on average 2.78%, but up to 22.5% for some countries). Reasons for deviations could be attributed to the mapping technique, the minimum mapping unit and the used forest definition.

3.4.2 Added value of historic data in historic reconstructions

We demonstrated that historic national and sub-national data for Europe from around 1900 could be gathered from various sources, such as maps and statistics, and incorporated into reconstructions of historic land cover/use. Many large scale historic reconstruction models rely on assumptions for the period before the end of the Second World War. In this context, large scale historic data before that period are a valuable data input for these models. We showed that reconstruction models could reduce their modelling error by using historic data and we presented a set of tools in this study that allowed to expand and apply these tools to other periods and to other regions.

The reconstruction approach without the use of historic maps tended to allocate forest as large continuous areas preferably in mountainous regions as a result of the assumed strong influence of terrain factors (e.g. slope or altitude) on the allocation. This approach ignored fragmentation effects of landscapes and could be seen as an artefact of the reconstruction approach if no historic maps are used. In order to assess the difference in spatial allocation pattern amongst the reconstruction approaches we calculated the number of patches and the average area of the patches for the original historic maps, the rescaled historic maps to 1 km spatial resolution and the two different reconstruction results for their overlapping areas (Table 3.3). Table 3.3 confirms our visual interpretation of Figure 3.9 that the reconstruction approach using historic maps is better able to represent the spatial structure and fragmentation of forest areas. The reconstruction using historic maps was, for both historic maps, closest to the number of patches and average patch size of the comparable historic map at 1 km spatial resolution. The reconstruction without historic map information resulted in more ‘clumped’ forest areas (less patches but bigger patch sizes).

3.4.3 Implications of using historic data in land reconstruction approaches

Historic data, especially from multiple data sources, can be used in reconstructions for verification and each implemented data set can potentially correct for biased assumptions used during the interpolation of data between years and areas.

Table 3.3: Difference in forest fragmentation effects amongst the different reconstruction approaches and historic map sources.

Feature	No. of patches	Avg. area of patches (in km²)
Data set		
Austria-Hungary map original resolution (62m x 62m)	34838	7.55
Austria-Hungary x 1 km resolution	18922	13.88
Reconstruction *with* historic 1 km map information for Austria-Hungary map area	16924	12.14
Reconstruction *without* historic 1 km map information for Austria-Hungary map area	8446	25.37
Schlueter map original resolution (77 m x 77 m)	1048575	0.09
Schlueter map 1 km resolution	36408	6.88
Reconstruction *with* historic 1 km map information for Schlueter map area	17728	11.98
Reconstruction *without* historic 1 km map information for Schlueter map area	14645	14.52

Historic land cover/use data can hardly compete with current data as they mostly lack the spatial detail and coverage, the temporal frequency or the thematic class depth of present products. However, most of the historic land cover/use products are of surprisingly good quality, since they were intended for census, taxation or military purposes where quality standards were high and crucial. Mapping techniques, map projections and statistical methods at the beginning of the 20th century were at advanced levels. Old topographic maps have several advantages. Historic maps are already georeferenced and classified. They do not suffer from atmospheric influences (e.g. cloud cover or haze) as is often the case in remote sensing images. This sometimes makes them more valuable than early satellite products (e.g. Landsat images of the 70's) that have many limitations. Historic mapping surveys measured land cover/use directly in the field, providing field measurements, semantic expert classification (e.g. for land use) and validation in a single source. Europe is a special case where the wealth of historic land cover/use data is a result of the existence of the many small countries where each country conducted its own surveys. The frequent military conflicts among the European countries (e.g. the two World Wars and the Cold War) led to a vast amount of data sets. This allows a comparison of multiple data sources for the same time period. Colonisation, the Cold War and proxy wars (Korea, Vietnam, Afghanistan, Middle East, etcetera) expanded the mapping and statistical activities of industrialized countries to many other regions in the world (Bibliographisches Institut, 1909; Chisholm and Phillips, 1911; Mapster, 2014; Nyssen and Petrie, 2013; Rumsey, 2014; University of Texas Libraries, 2014; Vlasenko, 2008).

Global land cover/use reconstructions can make use of historic statistics and extend their input data base in many regions of the world by several decades up to centuries.

Another possibility would be to validate the assumptions and allocation approaches of global reconstructions by comparing their results with historic maps and statistics. In some regions, especially in Continental Europe, data sets from the 18th century onwards exist that allow to analyse the industrial revolution period (Centro National de Information Geografica, 2013; Geoportail, 2013a, 2013b; Koningklijke Bibliotheek van België, 2014; Mapire, 2015; Mapster, 2014; Rumsey, 2014).

Different research fields, such as environmental, ecological and biogeochemical sciences (e.g. on climate change), will benefit from improved, extended and less uncertain land cover/use change databases at large scales.

3.5 Conclusion

In this paper we described a set of methods required to enable the use of historic data in model-based reconstructions of historic land cover/use, including changing historic national borders, correction of statistics for such changing borders and the automatic classification of historic land use maps. Our results confirmed that the concept of a data driven reconstruction model for historic land cover/use improved the modelling accuracy as compared to a traditional approach based on assumptions and proxy variables for the spatial allocation and land change trends. We showed that historic reconstruction models can make use of historic statistics when statistics are corrected for changing country borders. By implementation of historic forest maps we reduced the modelling error of forest/non-forest areas by about 16.5%. Furthermore, historic maps not only improved the reconstruction of the quantity and location of forest/non-forest areas, but also the structure and shape of these landscape elements. The current trend of open data policy with historic land cover/use data should be seen as a chance to close data gaps and to promote model-based reconstructions of historic land cover/use. The open access of archives offers a unique opportunity and potential to look back in Europe's land cover/use history, over large areas and multiple centuries.

Acknowledgements

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4. Gross changes in reconstructions of historic land cover/use for Europe between 1900 and 2010

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"Conservation is a state of harmony between men and land."

Aldo Leopold
"The Land Ethic", in A Sand County Almanac (1949)

Abstract

Historic land-cover/use change is important for studies on climate change, soil carbon, and biodiversity assessments. Available reconstructions focus on the net area difference between two time steps (net changes) instead of accounting for all area gains and losses (gross changes). This leads to a serious underestimation of land-cover/use dynamics with impacts on the biogeochemical and environmental assessments based on these reconstructions. In this study, we quantified to what extent land-cover/use reconstructions underestimate land-cover/use changes in Europe for the 1900–2010 period by accounting for net changes only. We empirically analysed available historic land-change data, quantified their uncertainty, corrected for spatial-temporal effects and identified underlying processes causing differences between gross and net changes. Gross changes varied for different land classes (largest for forest and grassland) and led to two to four times the amount of net changes. We applied the empirical results of gross change quantities in a spatially explicit reconstruction of historic land change to reconstruct gross changes for the EU27 plus Switzerland at 1 km spatial resolution between 1950 and 2010. In addition, the reconstruction was extended back to 1900 to explore the effects of accounting for gross changes on longer time scales. We created a land-change reconstruction that only accounted for net changes for comparison. Our two model outputs were compared with five commonly used global reconstructions for the same period and area. In our reconstruction, gross changes led in total to a 56% area change (ca. 0.5% yr^{-1}) between 1900 and 2010 and cover twice the area of net changes. All global reconstructions used for comparison estimated fewer changes than our gross change reconstruction. Main land-change processes were cropland/grassland dynamics and afforestation, and also deforestation and urbanization.

4.1 Introduction

Historic land-change information is essential to understand the impact of land conversion on the temporal dynamics of environmental and ecological factors like soil organic carbon (SOC) (Don *et al.*, 2011; Guo and Gifford, 2002; Poeplau *et al.*, 2011), greenhouse gases (GHG) (Ciais *et al.*, 2011; Houghton *et al.*, 2012; Schulze *et al.*, 2010), and climate (Pielke *et al.*, 2011). Historic reconstructions are also important as baseline analysis for projections of future land cover/use (Hurtt *et al.*, 2011), food security (Foley *et al.*, 2011), climate (Brovkin *et al.*, 2013; Zaehle *et al.*, 2013), and biodiversity (Ellis *et al.*, 2012; Foley *et al.*, 2005).

Many of the available reconstructions of historic land cover/use have a global coverage and span several centuries and millennia (Hurtt *et al.*, 2006, 2011; Kaplan *et al.*, 2009, 2010; Klein Goldewijk *et al.*, 2010, 2011; Olofsson and Hickler, 2008; Pongratz *et al.*, 2008; Ramankutty and Foley, 1999). The reconstructions have been widely applied in international biogeochemical and environmental assessments, such as in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2013) and have provided new insights on land-cover/use dynamics during the history of mankind (Ellis *et al.*, 2013).

Reconstruction approaches rely on available land cover/use databases containing country level statistics, population statistics, and model assumptions, due to a lack of available historic datasets for long time periods. Strong assumptions are made to fill data gaps and identify subnational patterns of land cover/use. For example, the frequently used HYDE database (Klein Goldewijk *et al.*, 2010, 2011) allocated historic cropland, pastures, and urban area based on per capita land-use estimates and population maps, after using FAO inventories for calibration of the per capita land-use areas. Hurtt *et al.* (2011) used the land-use classes of HYDE as input in combination with harvest statistics and an assumed gross change rate for shifting cultivation. Kaplan *et al.* (2012) based their reconstruction of historic natural vegetation for 1500–1850 on historic population records. Historic population density was used with nonlinear relationships to land use to reconstruct historic land use. For the 1850–2000 period, the dataset was merged with the HYDE dataset. Ramankutty and Foley (1999) extrapolated historic cropland inventories (mostly from FAO) back in time by the use of a hindcast method. The reconstruction method of Pongratz *et al.* (2008) used the database of Ramankutty and Foley (1999) for cropland and pastures with slight adjustments and overlaid it with maps of natural vegetation.

Current global reconstructions of historic land cover/use provide valuable estimates of land cover/use for a certain historic period, but do not give detailed insights into the dynamic changes in land cover/use that may have taken place over time. Most reconstructions are based on the difference in land cover/use areas between two time steps (net changes) as given by FAO data (Fig. 4.1). For larger areas, these net change estimates deviate from the sum of all area gains and losses of the different land-cover/use types (gross changes). Only accounting for the net changes can lead to serious underestimation of the land-cover/use changes, which may have implications for biogeochemical, ecological, and environmental assessments. Studies by Stocker *et al.* (2014) and Wilkenskjeld *et al.* (2014) revealed the sensitivity and impact of gross changes on biogeochemical assessments using simple gross change factors. However, these studies made only simple assumptions on gross changes and did not consider the full dynamics of gross changes, as can be derived from empirical datasets.

The difference of net land changes and gross land changes can be demonstrated by a simple example (Fig. 4.1). Taking the forest cover of Sweden from the Food and Agriculture Organisation statistics (Food and Agriculture Organization of the United Nations (FAO), 2012a) for the year 2000 with an area of 273890 km² and for the year 2001 with an area of 275510 km², the net difference for the 2 years was 1620 km². Over the same time period (2000–2001), the United Nations Framework Convention on Climate Change (UNFCCC) data (United Nations Framework Convention on Climate Change, 2013) accounted for roughly the same net changes in Sweden (1530 km²), but provided a forest gain of 4200 km² and a forest loss of 2670 km². Therefore, the gross area change totalled 6870 km², about 4.5 times the net change.

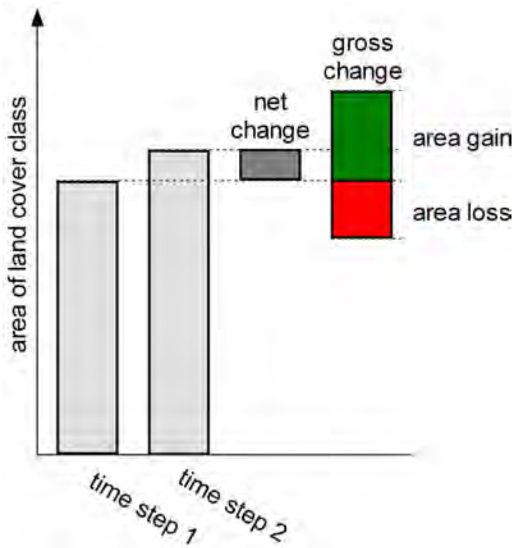

Figure 4.1: Illustration of the difference between net and gross changes.

The overall objective of this paper was to asses differences between gross and net change accounting methods for Europe (EU27 plus Switzerland, henceforth EU27CH) for the period 1900–2010. Based on an empirical analysis of gross change observed in historic land cover/use datasets, we calculate the extent of underestimation of land-cover/use dynamics when only accounting for net changes in reconstructions. Empirical results are applied to a historic reconstruction for EU27CH for the period 1950–2010 supplemented by an extrapolation back to 1900 to study the long-term effects of accounting for gross changes on land-cover/use reconstruction results. Our results for Europe are compared with five of the most used global reconstructions of historic land cover/use for the same area and time period (Hurtt *et al.*, 2011; Kaplan *et al.*, 2012; Klein Goldewijk *et al.*, 2010, 2011; Pongratz *et al.*, 2008; Ramankutty and Foley, 1999). Section 4.2 explains the methods to collect and analyse empirical data of historic net and gross changes in land cover/use and how these were used in a reconstruction of European land cover/use for the 1900–2010 period. We present the results and discuss the implications of our study for biogeochemical, ecological, and environmental assessments in sections 4.3 and 4.4, respectively.

4.2 Materials

4.2.1 Overview of approach

To assess the impacts of accounting for gross change in historic land-cover/use reconstructions three steps are taken (Fig. 4.2): We first performed an empirical analysis of gross land changes for the study region based on a collection of historic gross land-cover/use change datasets (Table 4.1). As the available data cover different time periods and spatial scales (both in terms of extent and resolution), a careful analysis is needed to summarize the results in overall measures of the difference between net and gross land changes per land-cover/use class. We present these in the form of an overall gross/net ratio and a land-change matrix.

In a second step, the impact of these empirical findings on a historic land-cover/use reconstruction for Europe was assessed using a historic land-cover/use reconstruction approach, called HIstoric Land Dynamics Assessment (HILDA) (Fuchs *et al.*, 2013). This approach was used to allocate non spatially explicit historic land-cover/use and land change information spatially. The approach was modified to account for the magnitude of gross changes in land cover/use, based on the empirical data for the period 1950–2010, while a further extrapolation was made back to 1900 to assess the long-term impacts. In addition, a net change reconstruction was derived for comparison.

In a third step, the results of the spatially explicit reconstruction of historic land changes (gross and net changes) were compared with five commonly used global land-cover/use reconstructions to demonstrate the quantitative differences in the accounting methods and the implications for global reconstructions.

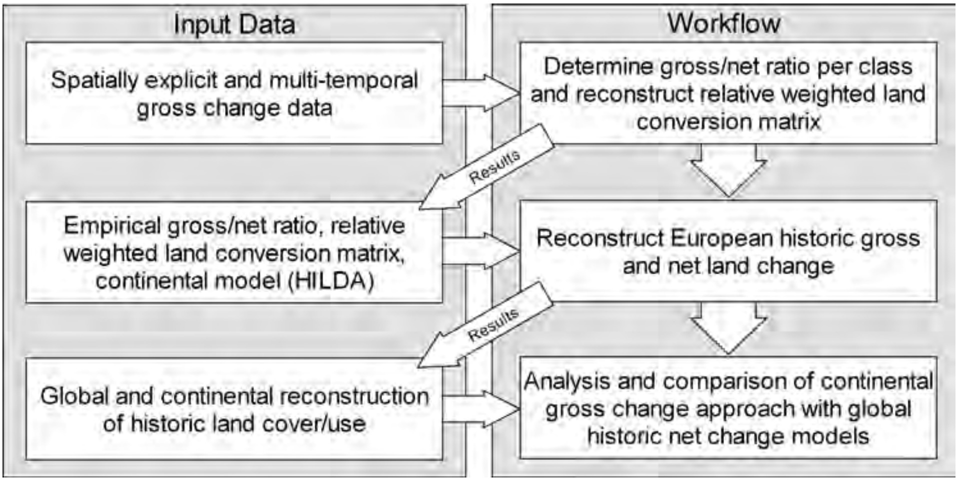

Figure 4.2: Workflow and related input data used for each step.

Table 4.1: Features of used gross change datasets for gross change analysis.

Data Set	**UNFCCC**	**FAO-RSS**	**CORINE CLC**	**BioPress**	**HGN**
Features					
Spatial resolution/ Minimum mapping unit (MMU)	National estimate	5ha (MMU)	100m (raster) 25 ha with 5 ha MMU	5ha MMU	25m & 50m
Temporal cover	1990-2010 (yearly)	1990, 2000, 2005	1990, 2000, 2006	1950, 1990, 2000	1900, 1960, 1980, 1990
Data type	Statistics	Vector data	Raster/vector data	Vector data	Raster data
Land cover classes	6 land cover classes (plus land cover conversion types	3 land cover classes (plus land cover conversion types)	44 land cover classes	44 land cover classes	7 land cover classes
Area coverage	2920680 km^2	47400 km^2	4422661 km^2	59.297 km^2	Max. 41543 km^2 (land area)
Countries covered/ represented	EU27, CH (w/o FR, BG, UK, LT, LV, PT, IT & SI)	EU27, CH	EU27, CH	EU27 (w/o DK, IR, PT, BG, SE, SI, LT, EE)	NL
Chosen time steps for empirical analysis	1990 to 2000, 2000 to 2010	1990 to 2000, 2000 to 2005	1990 to 2000, 2000 to 2006	1950 to 1990, 1990 to 2000	1900 to 1960, 1960 to 1980, 1980 to 1990, 1900 to 1990

4.2.2 Data

A precise quantification of gross changes requires a complete thematic coverage of an area to provide a full land change matrix of gains and losses for each land class. This is only possible in case of availability of a set of at least two maps with identical features or a proper statistical representation [e.g. UNFCCC national GHG reporting (United Nations Framework Convention on Climate Change, 2013)]. Historically, the availability of gross land-change data has been very scarce, as acquiring most of the land-cover/use data required considerable effort over long periods. The collected map data were often meant for one-time surveys only. Most land-cover/use statistics, for example from UN-inventories [e.g. FAO (start 1960) (Food and Agriculture Organization of the United Nations (FAO), 2012a), FRA (start 1946) (Food and Agriculture Organization of the United Nations (FAO), 2012b)] and national or international statistics [e.g. EUROSTATS (start 1974) (European Commission, 2012)], report only net area changes.

We have used a number of different datasets at varying spatial and temporal extent and resolution to estimate the differences between gross and net changes for Europe. We used the following datasets: United Nations Framework Convention on Climate Change (UNFCCC) national reporting data for EU27CH from 1990 to 2010 (yearly estimates) (United Nations Framework Convention on Climate Change, 2013), CORINE land-cover data for EU27CH (1990, 2000, and 2006) (European Environment Agency (EEA), 2012), Historisch Grondgebruik Nederland (HGN) for the Netherlands (1900, 1960, 1980, 1990) (Kramer and Dorland, 2009), Food and Agriculture Organisation Global Remote Sensing Survey (FAO-RSS) data with sample sites for every one-degree intersection of longitude and latitude (1990, 2000, and 2005) (JRC and FAO, 2012) and BioPress data with classified aerial photographs of 73 sample sites (roughly 30 km x 30 km) across Europe (1950, 1990 and 2000) (Gerard *et al.*, 2010). The main features of each data set are given in Table 4.1.

We detected some countries in the UNFCCC data with very large change rates per land-cover/use class, for instance, more than 10% of forest change per year on average and more than 15% of cropland or grassland change per year on average. For comparison, the average change rate for forest was ca. 1.2% and for cropland and grassland 3.3% (excluding the out of range changes). The unrealistic change rates appeared for France, United Kingdom, Bulgaria, Lithuania, Latvia, Slovenia, Italy, and Portugal. We excluded these countries from our initial empirical analysis.

The legend of each land-cover/use class of the original product was harmonized, where possible, by the use of the Land Cover Classification System (LCCS) (DiGrigorio and Jansen, 2000) toward five land categories based on the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change (IPCC), 2003), namely settlement, cropland, forest, grassland, and other land. The wetland class was integrated in the grassland class to guarantee integrity in the following processing steps. An overview of the harmonization procedure is given as supporting information in Appendix S1 (see supplemental material in the online publication).

4.2.3 Methods

4.2.3.1 Empirical analysis

We calculated the area affected by net and gross change for each class per time step for each dataset given in Table 4.1. Net changes were retrieved by the area gains minus area losses. Gross changes were retrieved by the absolute sum of area gains and losses. The gross/net ratio was calculated to estimate the underestimation of changes by the net change approach compared to the gross change approach. To derive the gross/net ratio, we divided our gross changes by the net changes and multiplied it with 100 to get the gross/net ratio in percent.

The gross/net ratio had to be calculated for the whole area of each dataset, due to the limited amount of data for separate countries. Gross change estimates are sensitive to scale and vary with the length between the time steps and the spatial resolution. To study the effects of these variations on the gross/net ratio, we separated each product into different lengths of time steps (Table 4.1). We grouped them into clusters of time steps with a period of less than 10 years, 10 years, and longer than 10 years. Every time step was normalized to a 10-year period to make the clusters comparable. The gross/net ratio was calculated for the original spatial resolution (if they had one) and for an aggregated spatial resolution of 1 x 1 km. The resampling was done using a majority filter. The data normalized to 1 km and the temporal normalization to 10 years were used to study the effect on gross/net ratio, and to feed the result into the historic reconstruction that operates at these resolutions.

We calculated a land-change matrix of all datasets to derive the weighting of bidirectional land conversion dynamics (e.g. cropland to grassland vs. grassland to cropland). This weighting determines the relevance of transition types between land cover/use classes, which are needed to reconstruct gross changes. Except for the FAO-RSS data (as FAO-RSS has only forest information), we derived the land-change matrix by averaging all land conversion types of all datasets and time steps and normalizing them to 100% of land changes. The result was an overview of the relative importance of 20 different land conversion types (according to five land classes). The available data did not allow to differentiate between different time periods or regions.

4.2.3.2 Spatially explicit reconstruction for Europe.

The spatially explicit historic reconstruction was made by using the land cover/use allocation algorithm of the HIstoric Land Dynamics Assessment (HILDA) model that is described in detail in Fuchs *et al.* (2013). The model was run at 1 km spatial resolution for EU27CH over the period 1950–2010 in decadal time steps, considering the previously mentioned five land cover/use classes. The water class in our figures is a subclass of the land class ‘other’, and was separated for visualization purposes only. The model uses an aggregated version of the CORINE 2000 dataset (European Environment Agency (EEA),

2012) for our base year 2000. The same approach was used to project land-cover/use changes forward (from 2000 to 2010) and backward in time (back to 1900).

Fuchs *et al.* (2013) document the underlying net change datasets used for the reconstruction of the 1950–2010 period. For this study, we extended the historic land-cover/use database with national/subnational statistics and land-cover/use statistics of old encyclopaedias [e.g. Meyers Conversation Encyclopaedia of 1909 (Bibliographisches Institut, 1909)]. The additional data covered whole Europe and dated back to 1900. This way a complete statistical representation of land cover/use per country for that period could be ensured. The allocation algorithm allocated these changes to grid cells by the use of probability maps for each class. Probability maps represented the likelihood of a land cover/use at a location and were derived using historic land-cover/use maps back to 1900 covering over 40% of the study area [e.g. 3rd Military Mapping Survey of Austria-Hungary (Eötvös University Department of Cartography and Geoinformatics, 2013), Die Siedlungsräume Mitteleuropas (Schlueter, 1952, 1953, 1958), Prussian Military Maps (Bundesamt fuer Kartografie und Geodaesie, 2014), Historisch Grondgebruik van Nederland (Kramer *et al.*, 2011)] and supposed location factors (e.g. volume stock maps, soil properties, climate factors, terrain factors and socio-economic factors involving accessibility to settlements based on settlement size and population density). Detailed information on the allocation process and the input datasets used to construct the probability maps can be found in Fuchs *et al.* (2013).

To account for gross changes, we applied our empirically derived gross/net ratio and land conversion matrix on our country-specific net change database to reconstruct historic gross changes. This way, country-specific net change time series are modified by (European wide) gross change parameters for each land-cover/use class to represent the gross change dynamics in the allocation algorithm. The extrapolation back to 1900 uses the same gross change parameters as applied to the 1950–2010 period. Although the first half of the century was underrepresented by empirical gross change data, the available data showed that the relative gross/net ratios for the different land-use types and the transition matrix were stable and consistent with known land-change processes and observations in other world regions. Given the uncertainty of this assumption of stability in gross/net ratio for the 1950–1900 period, the reconstruction for this period should be interpreted with care.

4.2.3.3 Comparison with global reconstructions of historic land cover/use

Table 4.2 gives an overview of the relevant properties for the comparison with other available global reconstructions, as well as the harmonization scheme applied to the classes used for the land-cover/use reconstruction. We clipped the global datasets to cover the same study area and data period as our study. We used the merge product of the KK10 dataset of Kaplan *et al.* (2012) with the HYDE dataset (see Kaplan *et al.*, 2012), which combines the methodological approach of Kaplan and the land-cover/use statistics of the HYDE database, to consider the KK10 product as well. The original KK10 dataset starts in the year 1850 to model back in time (see Table 4.2). All data were re-projected into an equal area projection (ERTS – Lambert), up-scaled to 1 x 1 km to cut off overlapping pixels at borders and clustered to decadal time slices. The class pastures in global models comprised only managed grassland areas, whereas the IPCC category grasslands additionally implied natural grasslands including shrubland areas. For global models, this led to a thematic mismatch with our European approach, as natural grasslands and shrubs were excluded from pastures and were instead considered as primary/secondary vegetation or natural vegetation, which overlaps with forests. To provide a full comparison for all possible IPCC categories, this mismatch had to be taken into account for the comparison and discussion. Finally, all gains and losses of each class per time step were summed as absolute value and compared for each decade and for the maximum overlapping modelling period (in this case 1900–1990). In our study, the LUH (Land Use Harmonization) dataset by Hurtt *et al.* (2011) is considered as net change dataset because land changes for pastures, cropland, and urban are retrieved from the HYDE database, which represents net changes only. Shifting cultivation, which is considered by Hurtt *et al.* (2011) as a gross change factor, was not applied by the LUH model for Europe.

4.3 Results

4.3.1 Gross change vs. net change

In Fig. 4.3, the gross/net ratio is presented as a function of the clustered time steps for four land-cover/use types (settlements, cropland, forest, grassland) for different data periods. The clustered data periods were lower than 10 years, equal to 10 years, and larger than 10 years. The left column of Fig. 4.3 shows results without any spatial or temporal normalization of the original data, the middle column shows results with a temporal normalization to 10 year periods, and on the right the temporal normalization together with a spatial normalization to 1 km resolution is shown.

The temporal normalization showed a decrease in the median with increasing time step studied for each land-cover/use class (Fig. 4.3). Some land-cover/use changes were not detected if the time steps get longer, because, e.g. back and forth changes between cropland and grassland may occur within one-time step and thus will not be detected. The spatial normalization showed hardly any effect. Grasslands (>10-year cluster) and forests (10-year cluster) had a very wide range for the gross/net ratio due to some outliers, which are shown as whiskers in the box plots.

Table 4.2: Overview of features of the global historic reconstructions. *Harmonization schemes for the land-cover reconstruction are given as abbreviations in brackets behind each thematic class (S = Settlement, C = Crop, G = Grassland, F = Forest)

Data set	**Date of Access / version**	**Spatial coverage**	**Temporal coverage**	**Spatial resolution**	**Temporal resolution**	**Thematic classes (harmonization*)**
Ramankutty and Foley (1999) SAGE	23-10-13 / net changes	Global	1700-2007	0.5 degree (fractions)	Yearly	Crop (C) Pastures (G)
Hurtt *et al.* (2011) LUH	19-4-13 / net changes (for Europe)	Global	1500/1700 - 2005/2100	0.5 degree (fractions)	Yearly	Urban (S) Crop (C) Pastures (G) Secondary vegetation (F) Primary vegetation (F)
Klein Goldewijk *et al.* (2010, 2011) HYDE 3.1	28-10-13 / v3.1 / net changes	Global	10000 B.C. – 2005 AD	0.05 degree (fractions)	Up to yearly	Urban (S) Crop (C) Pastures (G)
Pongratz *et al.* (2008) LSCAN	5-12-12 / net changes	Global	800 AD – 1992 AD	0.5 degree (fractions)	Yearly	Tropical evergreen forest (F) Tropical deciduous forest (F) Temperate evergreen broadleaf forest (F) Temperate/boreal deciduous broadleaf forest (F) Temperate/boreal evergreen conifers (F) Temperate/boreal deciduous conifers (F) Raingreen shrubs (G) Summergreen shrubs (G) C3 natural grasses (G) C4 natural grasses (G) Tundra (G) Crop (C) C3 pasture (G) C4 pasture (G)
Kaplan *et al.* (2010, 2012) KK10	15-11-13 / net changes	Global	8000 BC – 1850 AD / 1850-2005 (merged with HYDE)	0.05 degree (fractions)	Up to yearly	Natural vegetation (F)

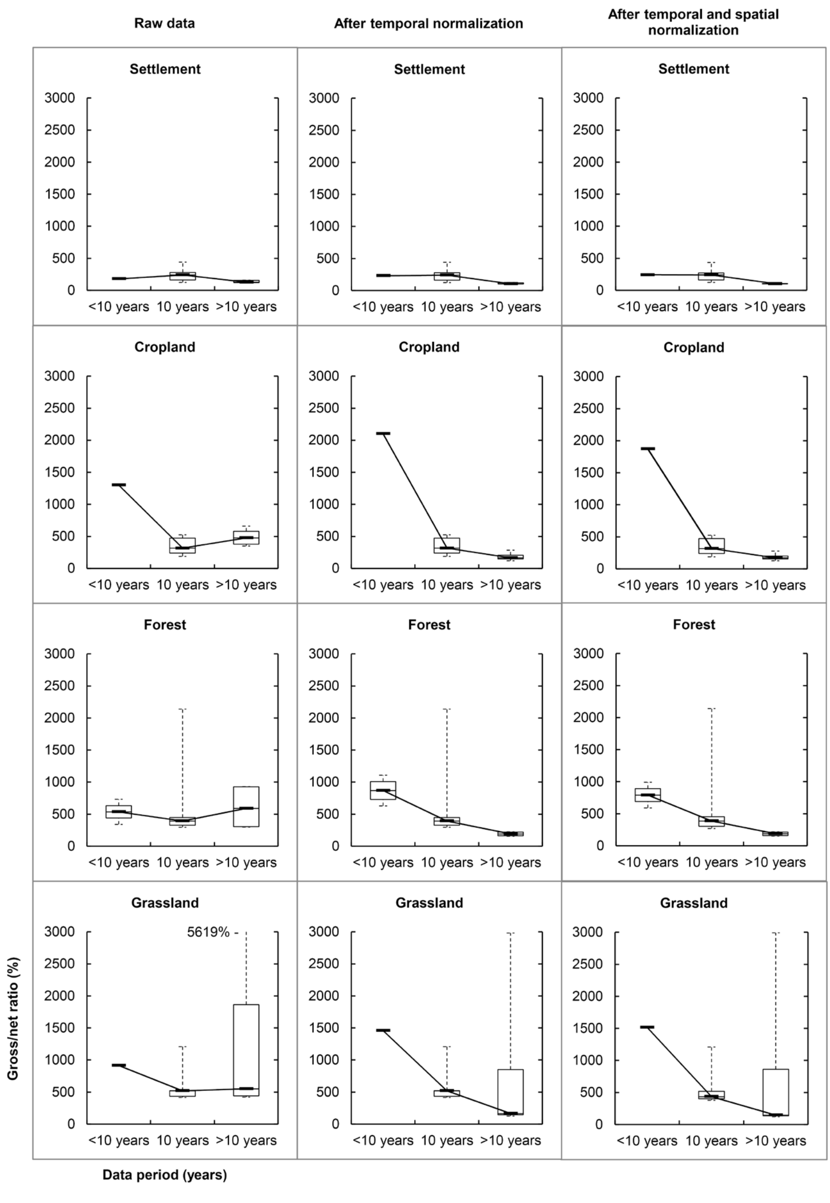

Figure 4.3: Gross/net ratio in percent as box plots clustered for data periods lower than 10 years (FAO-RSS 2000–2005, CLC 2000–2006), equal to 10 years (UNFCCC 1990–2000 and 2000–2010, CLC 1990–2000, FAO-RSS 1990–2000, HGN 1980–1990 and BioPress 1990–2000) and larger than 10 years (HGN 1900–1960, 1960–1980, 1900–1990 and BioPress 1950–1990) for four land-cover types, without any corrections (left), with temporal normalization (middle) and with temporal and spatial normalization (right). The black solid line between the clusters connects the median values to show the change in the gross/net ratio.

Figure 4.4 shows a comparison of gross vs. net land changes after spatial and temporal normalization. The closer to the 1 : 1 line, the lower the gross/net ratio, implying that the land changes behave more directional. For example, settlement changes are mainly directional (urbanization), which is only an area gain. Therefore, gross changes do not differ a lot from net changes. On the other hand, a large gross/net ratio implies a large discrepancy between net and gross land changes. This pattern reflects more non-directional changes, which is typical for cropland and grassland areas in combination with large area changes. Grassland and cropland are known for their large change dynamics, as these classes can be adjusted to socio-economic and political demands faster and with less effort than other changes.

The gross/net ratio can be substantial if relative gross changes are large and the net change is approximately zero [e.g. HGN grassland data (1960–1980) or FAO-RSS forest data (1990–2000)]. Interestingly, some datasets tend to have either large net and gross changes or small ones for both. UNFCCC data generated the largest net and gross land changes for all classes, whereas BioPress data in general had the lowest values for both net and gross changes. This shows how differently change is detected either by the method of observation or the defined change criteria.

The derived land conversion matrix is displayed in Table 4.3. It shows that 41% of all changes were caused by grass to crop or crop to grass conversions. Almost 29% of the changes relate to forest activities in combination with cropland and grasslands. Roughly, 18% of all changes were caused by urban sprawl. A de-urbanization of 6% seems still too much, probably due to including ecological restoration of former mining areas (e.g. in Germany), which were considered as settlement areas in the chosen harmonization scheme. The large deforestation rate partly could be caused by misclassifications as some of the former forest areas are ploughed before afforestation. This might be wrongly classified as cropland. Other areas affected by felling and clear cut might look as grasslands in remotely sensed data and therefore be misclassified.

In preparation for the reconstruction of historic land-cover/use changes, we derived a single gross/net ratio per class by calculating the median ratio for all datasets used in this study. The results showed that gross changes exceeded net changes for settlement by ca. 143%, for cropland by 259%, for forest by 309%, and for grassland by 419%. In combination with the land conversion matrix, the gross/net ratios were used as input for the historic net and gross land-change reconstructions.

4.3.2 European-wide historic gross land-change reconstruction

Two different historic reconstructions were generated; one based on net land-change data and one based on gross land-change data (download at www.wageningenur/hilda). Figure 4.5 shows an example of the different results of the two reconstructions for the year 1900, whereby both used the same baseline year 2000.

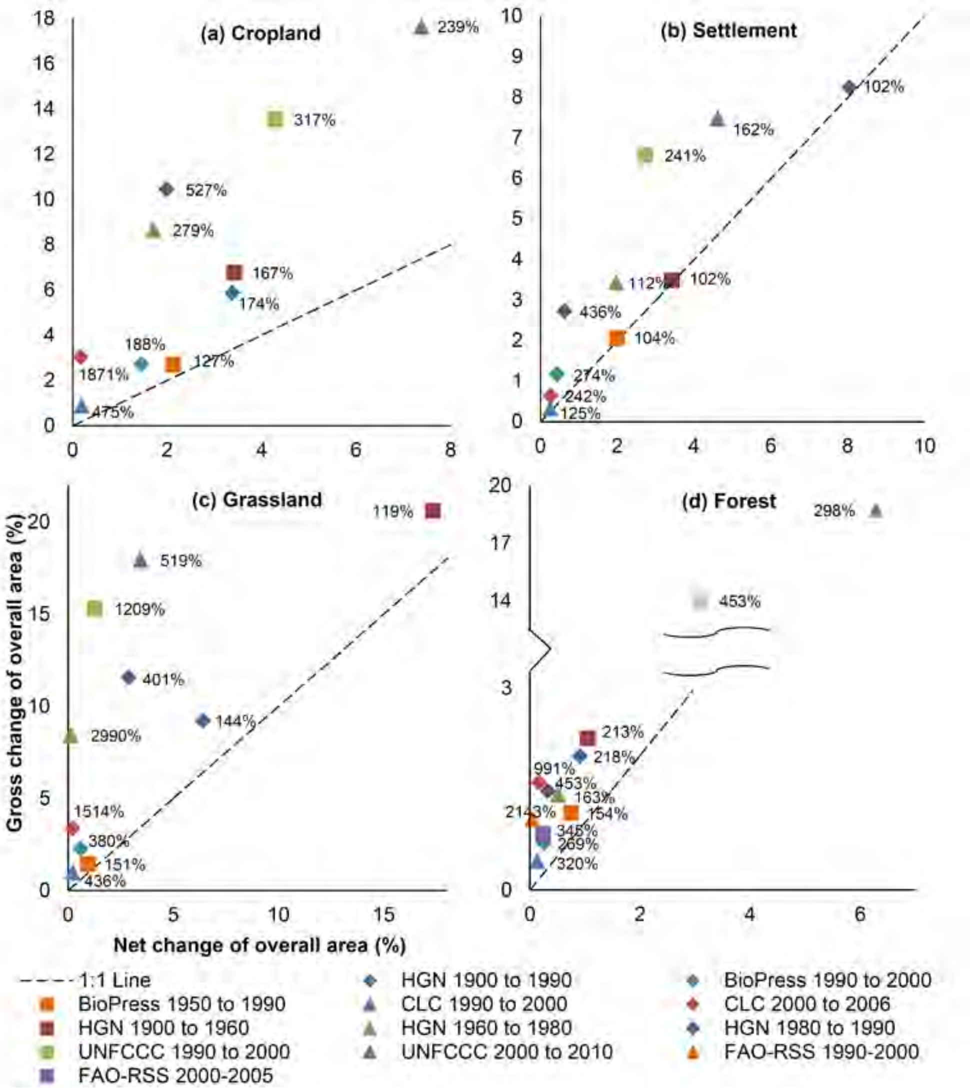

Figure 4.4: Comparison of gross vs. net land changes per dataset, period (after temporal and spatial normalization) and class, with (a) cropland, (b) settlement, (c) grassland, (d) forest. Percent values next to data points indicate the gross/net ratio. Note: Forest (d) has a y-axis break.

The difference in the result is caused by the different change frequencies. Gross changes have a larger land-change frequency and affect larger areas. This leads to different land-change patterns in the reconstructions. By using the net change accounting method, the total amount of reconstructed land changes was 30.6% of the total area within the whole modelling period for the EU27CH area.

Table 4.3: Averaged and normalized results of land conversion types derived from all gross land-change products of Table 4.1 for the entire period and area they covered

Conversion:	*From*	Settlement	Cropland	Forest	Grassland	Other Land	**Total area "to"**
Area in %	*To*						
	Settlements		10.0	2.1	5.5	0.4	**17.9**
	Cropland	2.4		4.8	20.8	1.2	**29.2**
	Forest	1.4	7.5		9.4	0.7	**19.1**
	Grassland	1.6	20.4	7.1		1.3	**30.4**
	Other Land	0.6	0.6	1.0	1.3		**3.5**
	Total area "from"	**6.0**	**38.4**	**15.0**	**37.0**	**3.5**	**100.0**

Contrary to that, we derived 56.0% area change with the gross change method. That is almost double the amount of net land change. Both numbers include the area of multiple changes per grid cell. Without considering multiple changes per grid cell an area of 25.9% was affected according to the net change approach, while 35.8% of the area was affected according to the gross change approach.

In Fig. 4.6, we visualized the location and number of occurred land changes within the modelling period of 110 years for the net changes (Fig. 4.6a) and the gross changes (Fig. 4.6b). This shows that the frequency of changes was very different. The increased dynamic in the gross change dataset implies a higher speed of change per change as well as a higher change frequency. Less than 0.3% of the pixels in the gross change mode were affected by five or more land changes.

Based on the conversion matrix for the historic reconstruction of gross land changes, the major land-change processes can be determined. The three most important ones, urbanization (all settlement gains), re-/afforestation (forest gains on basis of cropland and grassland areas), and cropland/grassland dynamics (changes of cropland into grassland and vice versa) are visualized in Fig. 4.7 (compare Figure S1 for all change processes - see supplemental material in the online publication).

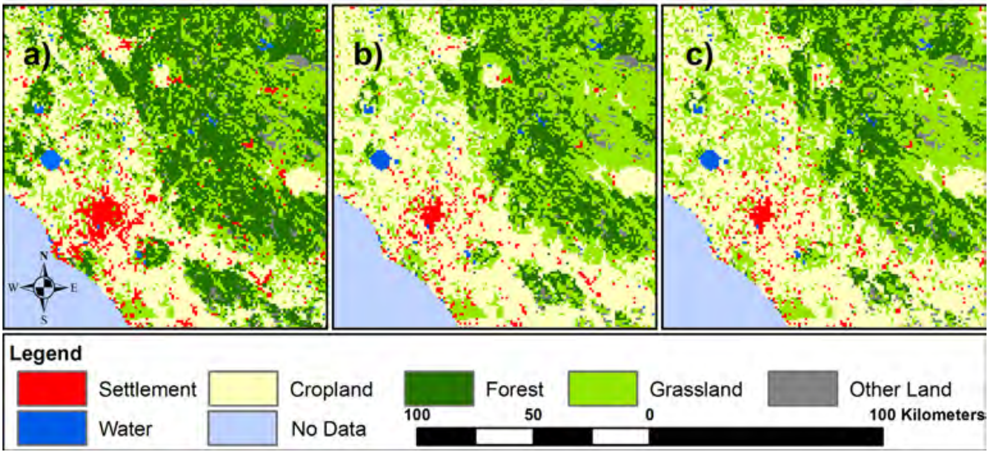

Figure 4.5: Differences in reconstruction for a zoomed region (greater Rome, Italy), with (a) baseline year 2000, (b) the net change reconstruction for the year 1900, and (c) the gross change reconstruction for the year 1900.

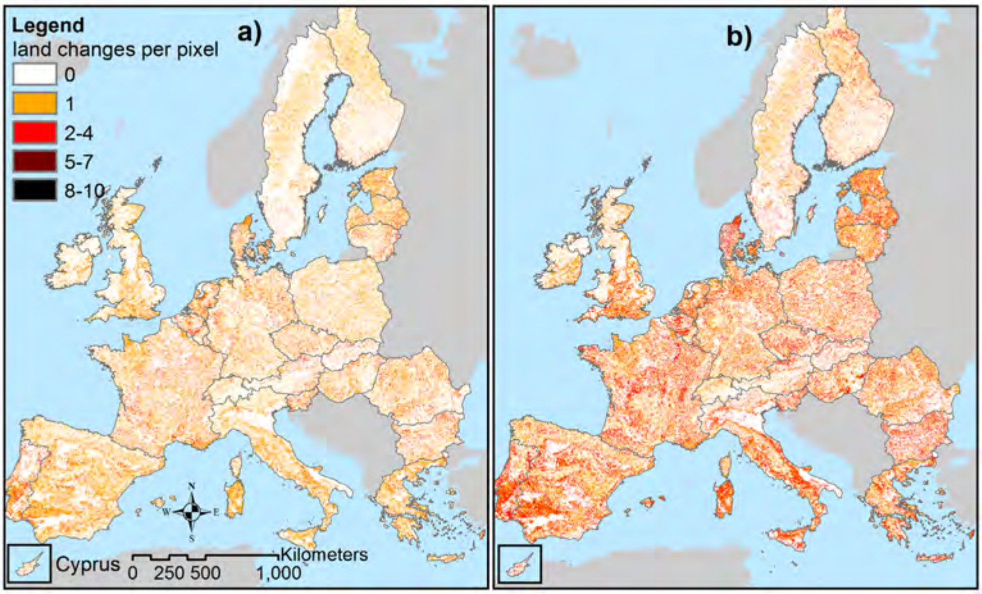

Figure 4.6: Comparison of frequency of land changes per pixel within the last 110 years for (a) net land changes, and (b) gross land changes.

Urbanization mainly occurred in settlement agglomerations, such as the population belt along the blue banana (Brunet, 1989) or around major cities like London, Paris, Berlin, and Madrid. After the timber shortage during the Second World War re-/afforestation actions came into effect in many mountainous regions of Europe, such as the Pyrenees, Alps, Carpathians Apennines, and Scandinavia. Cropland and grassland dynamics occurred everywhere throughout Europe. Reasons for those dynamics might be the cultivation of wetland regions (North Sea region along the Netherlands, Germany, and Denmark), improved irrigation systems in Mediterranean regions, several land reforms and resettlement actions after the Second World War, but also the Fall of the Iron Curtain and the introduction of the Common Agricultural Policy.

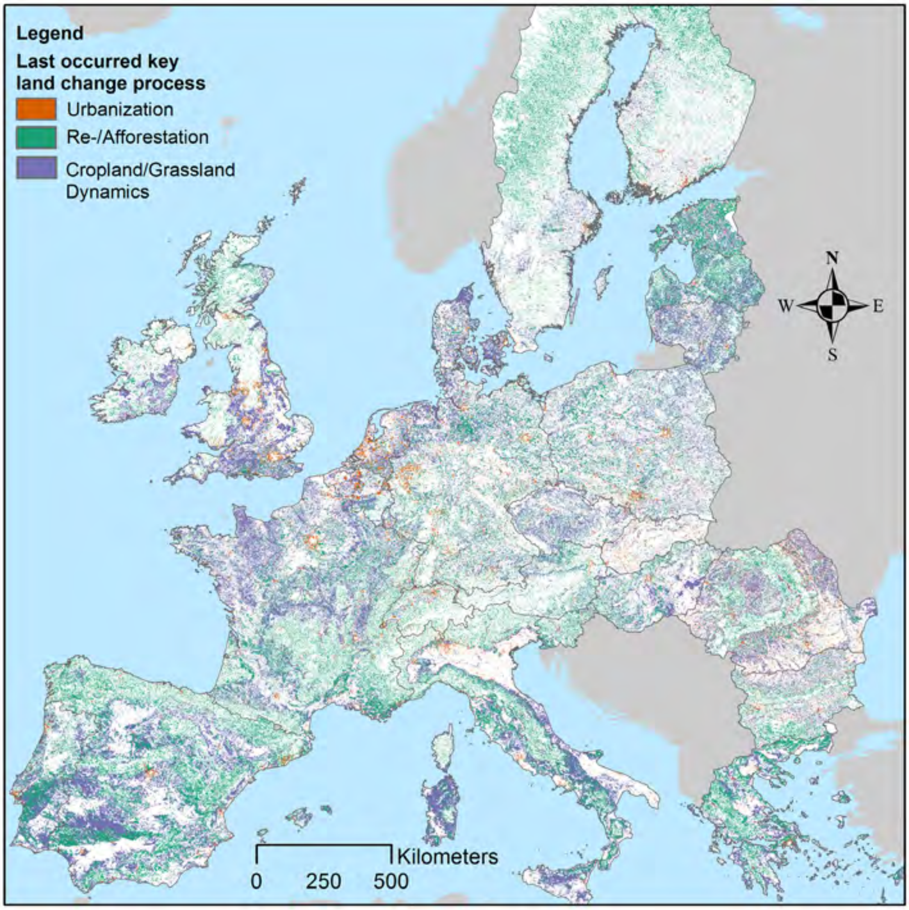

Figure 4.7: Major land-change processes of the last 110 years. Note: Only the last process of multiple processes per pixel is visualized. A complete high resolution map with all processes may be found in Figure S1 (see supplemental material in the online publication).

Figure 4.8 shows how the area affected by these processes changed in time. Similar to the land-change matrix, the dominating processes were forest management activities such as afforestation/reforestation or deforestation but also grass to crop conversions (e.g. cropland expansion), crop to grass conversions (e.g. land abandonment or pasture expansion) and urbanization. Af-/reforestation was the main driving change process of the last century in Europe, increasing until 1980 and then slowing down again.

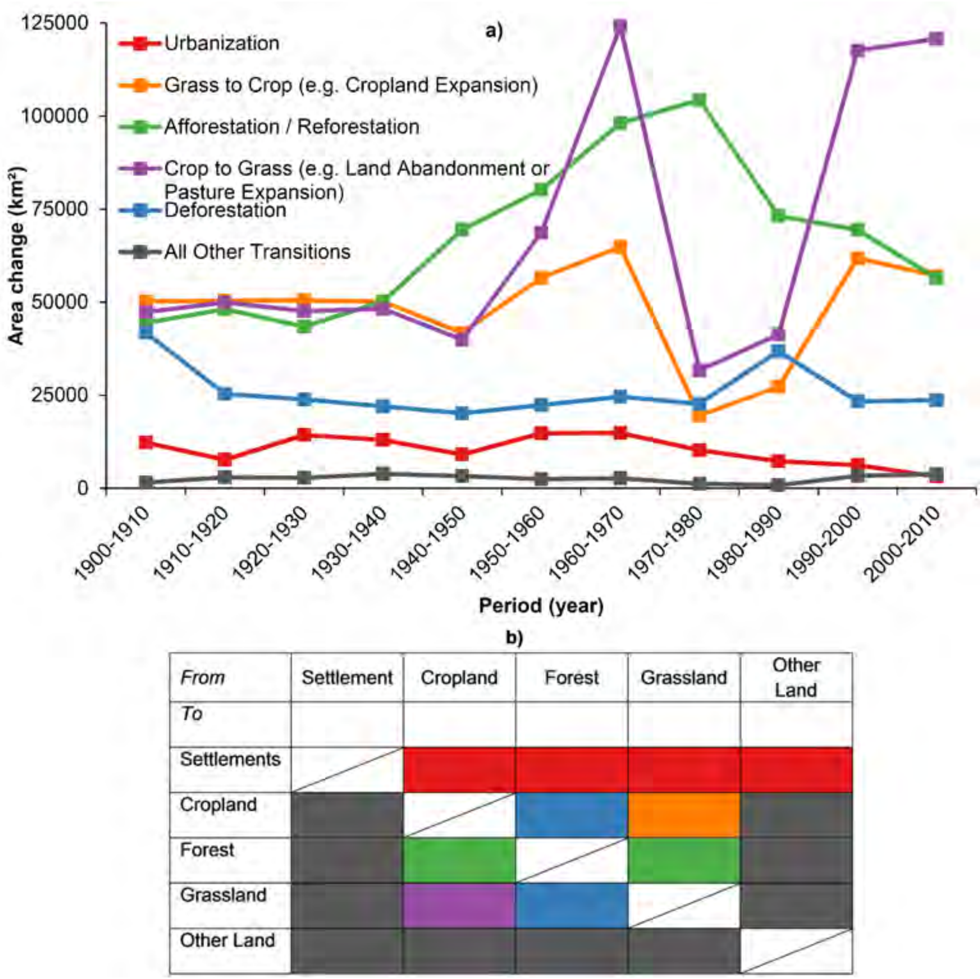

Figure 4.8: (a) Major land-change processes for EU27CH per decade in km². (b) Colour table with land conversions referring to land-change processes**.**

Crop to grass and grass to crop conversions had their first peak between 1960 and 1970, probably as a late result of resettlement activities after the Second World War causing land abandonment (crop to grass conversion) and the introduction of more productive cultivation methods, such as fertilizers, mechanization, and increased field sizes (grass to crop conversion). Between 1990 and 2000, both had their second peak, most likely as a result of the Fall of the Iron Curtain and the introduction of the Common Agricultural Policy.

4.3.3 Comparison with existing land-change reconstructions

We compared our gross and net land changes with those from the five global datasets given in Table 4.2 for the main classes for the EU27CH area (Fig. 4.9). On the left side, the change is shown per decade (within the interval 1900–2010, whereby only complete decades of data were considered) and on the right, all changes are summed per class for the modelling period that all models have in common (1900–1990, since the most recent decade for LSCAN is until 1990).

The upper graphs in Fig. 4.9 show results for cropland. For cropland, our net change estimate was consistent with HYDE, LSCAN, and SAGE. However, SAGE showed a peak between 1910 and 1940, due to decreases of cropland area in Belgium and France and area increases in Poland and Romania. The LUH dataset was offset to the HYDE dataset for cropland, although they were based on the same input data. Between 1990 and 2000, the HYDE dataset had a strong peak, which appeared globally and probably is due to adjustments between the baseline crop map and crop statistics. The HILDA gross change version estimated the highest amount of cropland changes, roughly 6% higher than the second largest ones, the LUH and SAGE reconstructions, and clearly showed as upper envelope of all reconstructions.

For pastures/grasslands, three reconstructions (LUH, HYDE, and LSCAN) estimated a similar amount of total changes (5–9%). The SAGE dataset showed a peak in the period 1910–1920 for pasture conversions and therefore yielded 16% area change over the whole period (1900–1990). The HILDA net change version was the second highest due to the inclusion of natural grasslands and shrubs. The HILDA gross change version was highest, with a difference of 16.5% compared to its net change counterpart.

The urban/settlement class was reconstructed by the HYDE and LUH dataset with similar temporal patterns. However, the LUH dataset yielded higher estimates. Our net change version estimated a value slightly above the LUH reconstruction, but showed dips for the two world wars. The HILDA gross change version reconstructed the largest changes for urban areas.

Forest/natural vegetation areas reconstructed by LSCAN showed similar patterns as the HILDA reconstructions; however, the net and gross change versions estimated larger amounts of land changes. Although having different patterns, the LUH and KK10 datasets estimated a similar amount of land changes as the HILDA gross change version. Natural grasslands and shrubs were considered as part of primary/secondary vegetation or as natural vegetation in the LUH and KK10 models, which resulted in a larger amount of changes in comparison to reconstructions considering only forests. Moreover, the LUH and KK10 reconstructions showed a mutual shift of one decade.

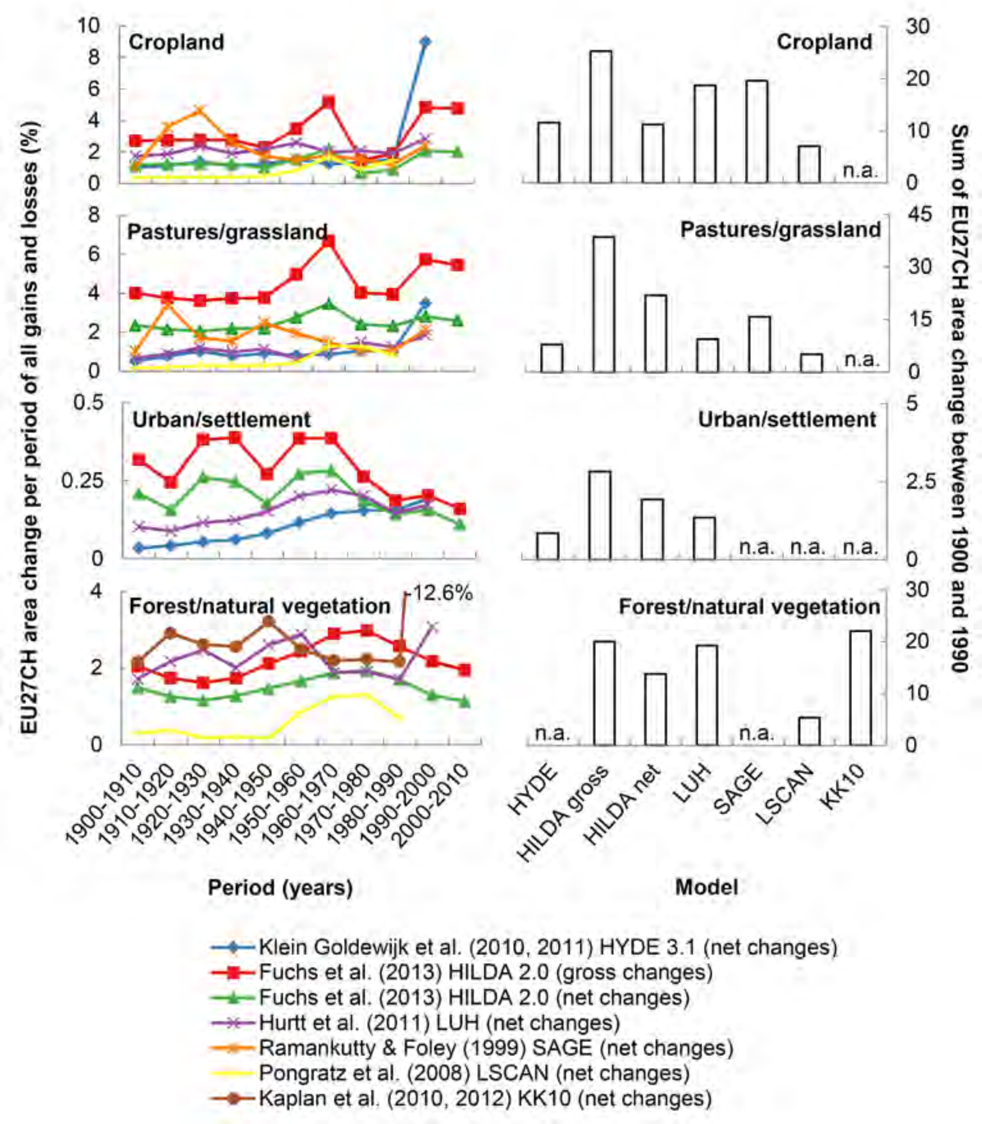

Figure 4.9: Comparison of land changes by the five global datasets studied, our gross change and our net change reconstruction per class for the EU27CH area. Left: all detected changes per completely covered decade. Right: sum of all changes per model for the 1900–1990 period.

4.4 Discussion

4.4.1Empirical analysis of gross vs. net changes

The gross/net ratio is very sensitive to the length of the time steps, with longer time spans logically resulting in lower gross/net ratios. The gross/net ratio is also prone to errors by the original products (e.g. misclassifications). The temporal effect and the sensitivity to misclassification by the original products always function as multiplier for the gross/net ratio. Therefore, the quality and accuracy of the original data is crucial for gross change analysis. The observation of gross/net change is dependent on the spatial resolution of the original data. However, in our analysis, the aggregation of the datasets to 1 km did exhibit only a minor effect on the resulting gross/net change ratios (Fig. 4.3). Possible explanations are that upon scaling both gross and net change are reduced, leaving the gross/net ratio unaltered. Another reason may be that in spite of the high spatial resolution of some of the studied datasets, the minimum mapping units applied in these datasets were relatively large, decreasing the differences between the original resolution and the aggregated resolution. The possible effects of spatial scaling on the gross/net ratio need to be accounted for when applying the results in land-cover/use models and reconstructions, requiring a recalculation of the gross/net ratio when the model resolution is different. Settlements are characterized mainly by area increase (directional changes) and show a low gross/net ratio. Forest had higher gross/net ratio values and emphasized that despite a net trend of increasing forest area, loss of forest is still a significant process in Europe. Cropland and grassland have high rates of simultaneous area increase and decrease (non-directional changes) with more than 41% of all land changes taking place between cropland and grassland. These two classes usually are more easy and cheaper to convert and, thus, are subject to varying socio-economic and political demands or part of a rotational land-use system.

4.4.2 Reconstruction and comparison of historic gross and net land changes

The historic land-cover/use reconstruction for Europe revealed that, extrapolated to long periods, the difference in estimated land changes between gross and net changes has serious consequences on the quantity of overall change in land use. In our simulation, the consideration of gross change led to almost double the amount of change and increased the dynamics of change per grid cell. This resulted in higher amounts of land changes for all land categories compared to existing global reconstructions that adopt a net change approach.

The focus of our empirical gross change analysis was on the 1950–2010 period, as result of the better availability of gross change data. The different datasets for the 1950–2010 period and the longer term data revealed stability in the differences between land-use types both in terms of the gross/net ratio, e.g. the ratio was always highest for grassland and lowest for settlements, as well as in terms of the dominant conversion types (e.g. primarily change in cropland to grassland and vice versa, or settlement gains primarily on cropland areas). These patterns also follow observations in other world regions as described by Gutiérrez and Grau (2014) and Nanni and Grau (2014). In reality, the gross/net ratio and conversion matrix may not be constant. The exact gross/net ratios and transition matrices are likely to vary to some extent by time period and region. Drivers for varying gross/net ratios and land dynamics could be the degree of mechanization and technology, speed of progress in land management, as well as changing demands for land-based resources, (dis-) continuity of policy or tenure systems and the availability of spare, unmanaged or abandoned land areas, all leading to potential non-linearity in land-cover/use transitions. Additional empirical work is needed to account for such variations.

Only the two reconstructions presented in this paper (HILDA net/gross) and the reconstruction made by the LUH model covered all four land categories. If all detected land changes for each of the three reconstructions are summed up for their overlapping decades (1900–2000), LUH estimated 28.1% changes, HILDA net 27.6%, and HILDA gross 49.8%. This last number means that, if gross land changes are accounted for, every year about 0.5% of Europe's land is converted on average in the context of the categories studied.

Our approach showed that major change processes and their spatial patterns can be derived from available datasets considering historic gross land changes. Considering gross change allows a much deeper analysis of land conversion processes. Many changes in land cover/use identified in our study can be associated with socio-economic and political decisions that occurred in parallel, such as urban migration as aftermath of two World Wars, the Fall of the Iron Curtain, the timber shortage after the Second World War, the Common Agricultural Policy or intensification and cultivation of dry- or wetlands.

In the approach described in this paper, aggregated land-cover/use change information at the level of countries was allocated based on empirically derived probability maps (see Fuchs *et al.*, 2013). Although the probability maps were estimated based on many different input data representing the location factors that were supposed to influence allocation decisions as well as historic land-cover/use maps which covered 40% of Europe's land area, regional and local deviations from reality might appear.

For the forest class, we had the most accurate and spatially explicit allocation parameters of all land-cover/use classes. We used historic forest masks from 1900 (Bundesamt fuer Kartografie und Geodaesie, 2014; Eötvös University Department of Cartography and Geoinformatics, 2013; Kramer and Dorland, 2009; Schlueter, 1952, 1953, 1958), timber line maps (Päivinen *et al.*, 2001; Schuck *et al.*, 2002), volume stock maps (Gallaun *et al.*, 2010) besides other indicators as decision support for allocation. In contrast, the allocation of cropland and grassland information relied mostly on environmental parameters, such as terrain, soil, and climate information and the exclusion from forest areas as a result of the forest probability map. In comparison, our forest probability maps can be seen as more accurate than those for other land-cover/use types as they are partly based on measured land-cover/use data, instead of indirect parameters that only correlate with land cover/use.

4.4.3 Future challenges

Despite the spatial and temporal normalization in this paper, some datasets and data periods in the empirical analysis remained as outliers due to other unknown issues. This increased the uncertainty of our estimation. Furthermore, our analysis showed the relative deviation between gross and net changes for the various datasets used in the empirical analysis (Fig. 4.4). Some products showed more area changes than others, although they covered the same period and area (e.g. CLC and UNFCCC). This difference might be a result of misclassifications. Reasons for misclassification could be the chosen method of observation, the thematic detail, and definition of land-cover/use classes or the used land-change criteria. Many land-cover/use classes are hard to classify due to heterogeneity, like mixed land cover/uses (e.g. agroforestry), mosaic patterns (e.g. complex cultivation, transitional shrub, and woodland), or the type of farming (rotations). More gross change data would be needed to accurately derive more robust gross/net ratios. Although gross change data remain scarce, they should be used in historic reconstructions where available as much as possible to avoid underestimation of land changes.

Through the harmonization of current global datasets with other available sources, like historic land-cover/use maps or land statistics from old encyclopaedias, a full land conversion matrix (including forest) may be obtained, uncertainties reduced and knowledge gained. Empirically derived gross/net ratios and transition matrices for different parts of the world and for different time periods could be implemented in global reconstruction models to account for gross changes. Several land-cover/use products based on remote sensing for multiple time steps exist to derive gross changes for other parts of the world (European Environment Agency (EEA), 2012; European Space Agency (ESA), 2011; Hansen *et al.*, 2013). FAO-RSS data, used in our analysis, are globally available for every one-degree Lat/Lon intersection (JRC and FAO, 2012). UNFCCC data are available for Continental Europe, USA, Australia, Canada, Japan, Kazakhstan, New Zealand and Russia (United Nations Framework Convention on Climate Change, 2013).

4.4.4 Implications of accounting for gross changes

Our results, based on an empirical analysis of historic land-cover/use data, indicate that there is strong evidence that gross land changes make an important contribution to overall change dynamics. Not accounting for gross land-change dynamics in historic land reconstructions leads to serious underestimation of land change.

The historic reconstruction presented in this paper is currently the only reconstruction that accounts for empirically derived gross change dynamics in land cover/use. Although some models exist which include a factor for shifting cultivation and forest harvest (e.g.

Hurtt *et al.*, 2006), none of these models reflect the full dynamics of gross land changes, largely due to a lack of sufficient data at global scale representing long periods of time.

Underestimation of land-cover/use dynamics affects the outcomes of biogeochemical, ecological and environmental impact assessments that use historic land-cover/use reconstruction data. Many GHG pools are time dependent, as they accumulate or release GHG over time. Land changes can alter these pools dramatically. Often legacy effects of previous land changes influence the assumption of current states and trends of GHG pools. Studies on SOC dynamics (Don *et al.*, 2011; Poeplau *et al.*, 2011; Schulp and Verburg, 2009) demonstrated how dependent SOC estimations are on historic land-change information (e.g. land conversion type and persistence of land cover/use) and to what degree land changes affect SOC pools and the carbon cycle. Similar effects could be shown as well for NO^2 (Nol *et al.*, 2008). Gross land-change information also affects the estimation of forest age structure and related harvest potentials (Vilén *et al.*, 2012). A higher dynamic of changes in forest areas would influence the development and increment of the growing stock and the resulting net carbon exchange patterns. These effects would also change the temporal variability in GHG budgets and potential contributions of forest management to the long-term removal of carbon from the atmosphere (Vilén *et al.*, 2012).

Wilkenskjeld *et al.* (2014) analysed the global impact of net and gross change approaches on the carbon cycle, based on the Hurtt *et al.* (2006) historic reconstruction. The authors report an underestimation of net change methods by 38% during the historic period (1850–2005). It is expected that a consideration of full gross change dynamics may lead to an even more severe underestimation by net anthropogenic land-cover/use change.

Many Earth System Models (ESMs) and global reconstructions operate on coarser spatial resolution than our approach. Land-change processes or transition types can be aggregated as fractional classes to the desired spatial resolution, similar to Hurtt *et al.* (2011). Differences between the temporal intervals could be overcome by division of the amount of change area (per process or transition) within the desired grid cell by, for instance, 10 to get 1-yr intervals, or by deriving empirical gross/net ratios valid at shorter time intervals.

Also for other research fields that rely on land-cover/use data, such as biodiversity, food system, and ecosystem service studies proper accounting for land changes is essential and can improve the assessment.

Acknowledgements

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cover/use reconstructions presented in this paper can be obtained at www.wageningenur.nl/hilda.

5. Assessing the influence of historic gross land changes on the carbon fluxes of Europe

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"CO_2 is the exhaling breath of our civilization, literally... Changing that pattern requires a scope, a scale, a speed of change that is beyond what we have done in the past."

Al Gore
New thinking on the climate crisis (2008)

Abstract

Legacy effects of land cover/use on carbon fluxes require considering both present and past land cover/use change dynamics. To assess past land use dynamics model-based reconstructions of historic land cover/use are needed. Most historic reconstructions consider only the net area difference between two time steps (net changes) instead of accounting for all area gains and losses (gross changes). Studies about the impact of gross and net land change accounting methods on the carbon balance are still lacking.

In this paper we assessed historic changes of carbon in soils and forests in Europe for the period 1950 to 2010, while accounting for legacy effects and gross change dynamics with decadal time steps at 1 km spatial resolution using a bookkeeping approach. To assess the implications using gross land change data we also performed an assessment with net land changes for comparison.

Main contributors to carbon sequestration between 1950 and 2010 were afforestation and cropland abandonment leading to 14.6 PgC sequestered carbon (of which 7.6 PgC was in forest biomass). Sequestration was highest for old growth forest areas. A sequestration dip was reached during the 70's due to changes in forest management practices. Main contributors to carbon emissions were deforestation (1.7 PgC) and stable cropland areas on peaty soils (0.8 PgC). In total, net fluxes summed up to 12.3 PgC (5.9 PgC in forest biomass and 6.3 PgC in soils). For areas that were in both reconstructions subject to land changes (35% of total area) the differences in carbon fluxes were about 68%, and highest over forested areas. Overall for Europe the difference between accounting for either gross or net land changes led to 7% difference (up to 11% per decade) in carbon fluxes and systematically higher fluxes for gross land change data as compared to net land change data.

5.1 Introduction

Land cover (biophysical cover on the Earth's surface), land use (arrangements, activities and inputs people undertake in a certain land cover to produce, change or maintain it) (DiGrigorio and Jansen 2000) and their changes influence the atmospheric gas composition and alter carbon stocks in soils and vegetation (IPCC, 2013). The amount of carbon stored in the soil and in vegetation varies amongst different land cover/use types (Arrouays *et al.*, 2001; Bellamy *et al.*, 2005; Don *et al.*, 2011; Guo and Gifford, 2002; Poeplau *et al.*, 2011). While forests store large amounts of carbon in biomass (Freibauer *et al.*, 2004) and are known to have a high soil organic carbon (SOC) stock, pastures and grasslands tend to have less SOC than forests, although some of these areas are on peaty soils with a high SOC stock. Croplands have low SOC stocks. Land cover/use changes alter these carbon pools (Don *et al.*, 2011; Guo and Gifford, 2002; Poeplau *et al.*, 2011).

Some land changes lead to rapid changes in carbon pools (e.g. deforestation), but legacy effects, meaning delayed carbon emission or sequestration, can occur as a result of a slow decomposition of dead biomass and a long-term uptake of carbon in re-/afforested areas (Houghton *et al.*, 2012). Poeplau *et al.* (2011) and Schulp and Verburg (2009) showed, in different case studies, that SOC equilibrium was not even reached after hundred years, depending on the conversion type considered.

This time lag of carbon fluxes makes it necessary to consider both present and past land cover/use change dynamics when assessing carbon fluxes. To enable such assessment, data or model-based reconstructions of historic land cover/use are needed (Arora and Boer, 2010; Kato *et al.*, 2011; van Minnen *et al.*, 2009; Poulter *et al.*, 2010; Shevliakova *et al.*, 2009; Stocker *et al.*, 2011; Strassmann *et al.*, 2008; Yang *et al.*, 2010; Zaehle and Dalmonech, 2011). However, many continental to global historic land cover/use reconstructions, such as the frequently used HYDE data set (Klein Goldewijk *et al.*, 2010, 2011) or the SAGE data set (Ramankutty and Foley, 1999), provide only limited detail in change dynamics, have a rather coarse spatial resolution (0.05 degrees to 0.5 degrees) and reconstruct only a few land cover/use classes. Furthermore, most of them consider only the net area difference between two time steps (net changes) instead of accounting for all area gains and losses (gross changes), which leads to serious underestimation of the area that has been changed in the past (Fuchs *et al.*, 2015a; Wilkenskjeld *et al.*, 2014).

For historic carbon accounting the distinction between gross and net land changes is important, since gross land changes are taking the full land change dynamics into account that lead to a larger total land area that is facing change (Fuchs *et al.*, 2015a). The amount of changes determines the dynamics of carbon fluxes and the type of land conversions determine to which carbon stocks the land changes have to be allocated. The specific land cover/use history of each grid cell determines the legacy effects of carbon within that grid cell. Studies of the impact of gross and net land change accounting methods on the carbon balance are still lacking (IPCC, 2013). However, the spatial, temporal and thematic detail are essential for estimating carbon fluxes, since they provide valuable information about regional differences in land distribution, land transitions and pathways of changes and thus have a direct impact on the legacy effects of carbon fluxes. Many sophisticated carbon accounting models work at a coarse spatial resolution (0.5˚ to 2º) and ignore the land change processes occurring below that spatial resolution by only accounting for the net change in land cover fractions. Moreover, large-scale historic reconstructions currently lack sufficient detail to account for more detailed histories of carbon fluxes. Furthermore, there is still a lack of process understanding of how gross land changes influence the carbon accounting (Houghton *et al.*, 2012; IPCC, 2013; Stocker *et al.*, 2014; Wilkenskjeld *et al.*, 2014).

The objective for this paper is to make an assessment of historic changes of carbon in soils and forests in Europe (EU27 plus Switzerland, henceforth EU27CH) for the period 1950 to 2010, while accounting for legacy effects and gross change dynamics. In the methods section we explain how we used gross land change data at decadal time steps and 1 km spatial resolution with a spatially explicit bookkeeping model approach with the same resolution. The results section shows the differences in assessment outcomes as compared to an assessment only accounting for net changes in land cover while the discussion section addresses the implications of the findings for large scale carbon studies.

5.2 Data and Methods

5.2.1 Overview of the methods

An overview of the approach for this paper is presented in Figure 5.1. Reconstruction results of historic gross and net land changes of EU27CH for the period 1950 to 2010 were used as input data set for the carbon budget calculation (Fuchs *et al.*, 2015a) (upper left box in Fig. 5.1). Additionally, we used a modified forest age reconstruction by Vilén *et al.* (2012) and a spatially explicit reconstruction of historic carbon stocks (Hengeveld *et al.*, 2012). We performed two carbon budget calculations (lower box in Fig. 5.1) based on the approach of Schulp *et al.* (2008). The first one accounted for historic net land change data and the second one for historic gross land change data. Both carbon budget calculations used the same forest age and carbon stock reconstructions. All the model components shown in the boxes in Figure 5.1 are explained in more detail in the Sections 5.2.2-5.2.5.

5.2.2 Reconstruction of historic gross and net land cover/use changes

For the reconstruction of historic land cover/use changes we used a model-based approach (Historic Land Dynamics Assessment (HILDA-v2.0) (Fuchs *et al.*, 2013, 2015a). The approach allocated national level land cover/use statistics using probability maps derived from associations between location factors, current and historic land cover/use. Digitized large-scale historic land cover/use maps of around 1900 and a contemporary map of standing wood volume in forest (Gallaun *et al.*, 2010) were fed into the spatial allocation algorithm to improve allocation of national and subnational historic land cover/use statistics from old encyclopaedias and national land cover/use records back to 1900 (Fuchs *et al.*, 2015b). Empirical gross change data sets were analysed and corrected for spatial-temporal effects. The results of empirical gross change quantities were applied to our historic reconstruction in order to derive historic gross changes for the period 1900 to 2010.

In parallel, a historic net land change reconstruction was processed for comparison. Details of this approach can be found in Fuchs *et al.* (2015a). For this study we used the time steps from 1950 to 2010 as data input for the carbon budget model.

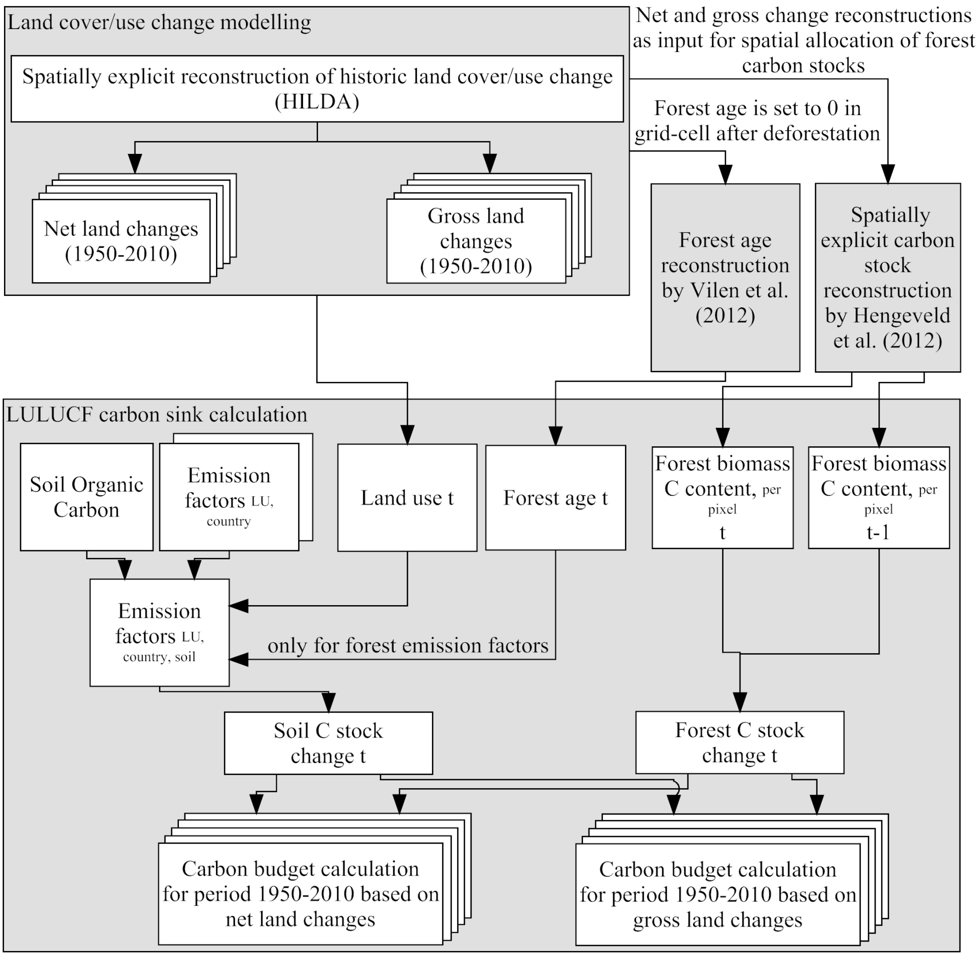

Figure 5.1: Overview of the carbon budget calculation approach

5.2.3 Reconstruction of historic forest age

We used the historic forest age reconstruction by Vilén *et al.* (2012) as input data for the carbon model. This data set contains the area per 10-year age class at national level for EU27CH, except for some Mediterranean countries, covering the period from 1950 to 2010. For our analysis we calculated the mean forest age for each country within that data set.

The Mediterranean region (Portugal, Spain, Italy, Greece, Cyprus, Malta) was mostly dominated by coppice (Morin *et al.*, 1996). Due to the missing data for Greece, Spain, Cyprus and Malta and the poor data quality for Italy and Portugal we assumed a constant forest age of 30 years for the period from 1950 to 2010 to represent the coppice.

5.2.4 Reconstruction of historic carbon stocks

Historic carbon stocks were implemented following the CARBONES-global forest biomass methodology (Hengeveld *et al.*, 2012). This method is based on country reports of forest resources to the United Nations Economic Commission for Europe (UN/ECE), the Food and Agriculture Organisation (FAO) and the Ministerial Conference on the Protection of Forests in Europe (MCPFE) for the period 1948 to 2010 (FAO, 2012). Data of different assessments were harmonised to reflect both forest area and other wooded land in order to assure comparability between countries and assessments. Data on growing stock in m^3 were converted to biomass and carbon using default factors from the IPCC Good Practice Guidance (IPCC, 2006).

More in detail, reported data on forest area and growing stock were harmonised and interpolated to decadal intervals. From these data, the average stocking density in m^3/ha was calculated for each country for each period. This stocking density was combined with the forest maps from Fuchs *et al.* (2015a), resulting in a series of maps of growing stock in m^3. One set of maps was generated based on gross land change data and one based on net land change data. From this growing stock aboveground biomass was estimated using an interpolation of the IPCC default biomass conversion and expansion factors (BCEF) given the average stocking density, the share of conifers and the relevant ecozones. For estimation of the below ground biomass, IPCC default root-to-shoot ratio’s (R-values) were used. Forest biomass was converted into forest carbon stocks using a biomass carbon content of 47%. Details of this approach can be found in Hengeveld *et al.* (2012).

For afforested areas we used a 50 year transition to full forest (Nabuurs, 2001; Pussinen *et al.*, 2001). We assumed areas with an afforestation age equal to or larger than 50 years to have 100% of the mean national carbon content per grid cell. For all other ages we scaled the carbon content proportional to the age (i.e., new forest grid cells received 10%, second decade forest 30%, etc.).

As a result of this approach we consider gains through forest growth (aging) and losses due to harvesting activities as well as natural mortality as implicitly incorporated in the development of the average growing stock per country. Because we allocate the total forest carbon for each country to the pixels covered with forest proportional to their age, we can disentangle the effect of deforestation and afforestation from the implicit effect of aging and harvesting.

5.2.5 Carbon budget modelling

Carbon stock changes were calculated using a modified bookkeeping approach developed by Schulp *et al.* (2008). Carbon stock changes were modelled with discrete time steps based on empirical data. This is a common approach to model the effect of land cover/use change on carbon stocks for large-scale studies (Houghton, 1999; Houghton *et al.*, 2012; Nabuurs *et al.*, 2003).

Carbon sequestration and emission were calculated for each grid cell of 1 km^2 using emission factors (EFs) that quantified the sequestration or emission of a particular location. We used country-specific, land use type specific EFs for cropland, pasture, peatland (Janssens *et al.*, 2005) and forest (Karjalainen *et al.*, 2003) (Table 5.1). For other land use types, EFs were derived from the EFs as given by Janssens *et al.* (2005) and Karjalainen *et al.* (2003) (Table 5.2). Cropland emission factors were modified based on the SOC content (Schulp *et al.*, 2008), while for pastures on peat soils the peatland emission factor from Janssens *et al.* (2005) was used. For all land use types but forest, we only considered SOC stock changes, because carbon stocks in biomass are negligible compared with SOC stocks (Janssens *et al.*, 2005). In order to harmonize the land use classes and related EFs of Schulp *et al.* (2008) with the land cover/use classes of our historic reconstruction we used the harmonization scheme shown in Table 5.2.

Since the carbon emission factors are mainly controlled by soil and climatic characteristics, they were kept constant throughout the simulated timeframe. For forests, emission factors are strongly influenced by the management regime. For forest carbon stock we used the approach described in section 5.2.4. Changes in carbon stock were calculated per pixel based on the difference between two time steps. Land cover/use changes other than deforestation were assumed not to cause sudden releases of carbon from biomass, but only resulted in a change in EF.

5.3 Results

In this section we first analyse the results of the total historic net carbon fluxes using the methodology described in section 5.2.5. Figure 5.2 gives an overview of the total historic net carbon fluxes at 1 km^2 spatial resolution for the period 1950-2010 using gross land change data. It can be seen that long-term forest and grassland areas in Europe were a net carbon sink (in blue) over the entire period. However, the amount of net sequestration varied throughout Europe. The highest sequestration (10,000 MgC per km^2 and higher) appeared in known old growth forest areas, such as the Carpathians, the Alps and medium mountain ranges in Central Europe, which were mostly undisturbed throughout the study period due to less accessible terrain with steep slopes and locations remote from bigger urban centres. Production forests, coppice and forest areas with climatic limitations (e.g. due to temperature, water supply or sunlight), such as the Mediterranean and Scandinavian forests, had in total a lower net sequestration compared to old growth forest areas and they ranged roughly from 2,000-10,000 MgC per km^2. Stable grassland areas, for example in the United Kingdom, Ireland, the Massif Central in France and the Mediterranean basin with Sclerophyllous vegetation (e.g. Macchia, Garrigue), resulted in a net sink over the last 60 years with a low sequestration of 1-2,000 MgC per km^2 throughout the study period.

Table 5.1: Country-specific and land use type specific EFs (Mg C km^{-2} $year^{-1}$). Negative EFs denote emission, positive EFs denote sequestration.

Country	Emission factors (Mg C km^{-2} $year^{-1}$)			
	Pasture[1]	Cropland[1]	Wetlands[1]	Forest/ nature[2]
Austria	25.5	-16.2	0.1	127
Belgium +Luxembourg	15.8	-9.1	-9.1	127
Bulgaria	6.8	-19.8	-0.3	54
Cyprus	2.8	-10.1	-0.5	42
Czech Republic	6.6	-35.8	-0.7	23
Denmark	2.6	-39.9	-6.0	119
Estonia	2.2	-39.7	-26.2	87
Finland	5.6	-5.5	-12.8	43
France	12.0	-19.1	-0.7	43
Germany	13.6	-28.3	-6.4	134
Greece	2.8	-10.1	-0.5	42
Hungary	6.3	-44.8	-6.4	111
Irish Republic	21.2	-12.3	-52.7	192
Italy	12.7	-19.5	-2.8	67
Latvia	2.9	-44.1	-7.9	87
Lithuania	3.2	-60.8	-2.4	87
Netherlands	18.4	-25.4	-47.1	111
Poland	8.5	-36.6	-26.2	87
Portugal	-4.5	-28.1	-2.0	92
Romania	11.1	-30.7	-0.2	166
Slovakia	12.2	-24.7	-0.7	91
Slovenia	3.7	-8.2	0.5	65
Spain	20.7	-4.7	-0.4	33
Sweden	1.2	-6.5	0.4	68
United Kingdom	24.2	-13.7	-27.5	165

[1]: (Janssens *et al.*, 2005)
[2]: (Karjalainen *et al.*, 2003)

Table 5.2: Harmonization of land cover/use classes and emission / sequestration behavior including data sources of land use types, and data sources for forest biomass C content.

Land cover/use classes of historic reconstruction	Land use type in Schulp *et al.* (2008)	Emission / sequestration behaviour
Settlements and Other Land	• Built-up areas; Glaciers and snow; Sparsely vegetated areas; Beaches, dunes and coastal flats; Salines	No emission or sequestration
Cropland[6]	• Cropland (Non-irrigated and irrigated)	Cropland EF[1]; depends on initial SOC content[2]
	• Permanent crops	0.2 * Forest EF[3]
Grassland[6]	• Pastures	Pasture EF[1]
	• Inland wetlands	Peatland EF[1]
	• Heath and moors	Pasture EF[1]
	• Semi-natural vegetation	Forest EF[3]; age dependent[4, 5]
Forest	• Forest	Forest EF[3]; age dependent[4, 5]

[1]: Janssens *et al.*, 2005
[2]: Bellamy *et al.*, 2005; Jones *et al.*, 2005; Sleutel *et al.*, 2003
[3]: Karjalainen *et al.*, 2003
[4]: Nabuurs, 2001
[5]: Pussinen *et al.*, 2001
[6]: Multiple land use types of Schulp *et al.* (2008) were merged into a specific land cover/use class of the historic reconstruction by weighting their shares of classes per country based on CORINE Land Cover 2000 (European Environment Agency (EEA), 2012)

Regions that act as a total net source were mostly (former) cropland areas. The emission ranged mostly between 1 and 1,000 MgC per km² for the entire period. Higher total emissions can be seen towards the north-east of Europe, because of the higher peat content of soils. Emissions reached partly up to 6,000 MgC per km² for the whole modelling period. Scattered deforestation with high emissions (up to 16,000 MgC per km²) were most apparent in the Massif Central and south-west Alps of France, in Central Europe, the Baltics and Scandinavia. Deforestation effects occurred very scattered without bigger patterns. Settlements, water bodies and sparsely vegetated or bare areas had no significant carbon fluxes throughout the study period.

In Table 5.3 we show all different types of carbon fluxes for different pools (forest biomass and soils) and how they added up for the whole of Europe and the entire modelling period, based on gross land change data. The total net flux added up to 12.2 PgC. However, there was in total 14.6 PgC of carbon sequestration and 2.5 PgC of carbon emissions (both soils and forest biomass), that led to 17.1 PgC of gross fluxes, so roughly one third more than the total net fluxes. Soils had a positive net balance with 7.1 PgC of sequestered carbon and 0.8 PgC of emitted carbon. Forest biomass sequestered ca. 7.6 PgC, due to re-/afforestation and it emitted 1.7 PgC due to deforestation. Unlike for soils, where the net and gross carbon flux were of a similar order of magnitude, the total gross flux of carbon in forest biomass was almost double the amount of the total net flux.

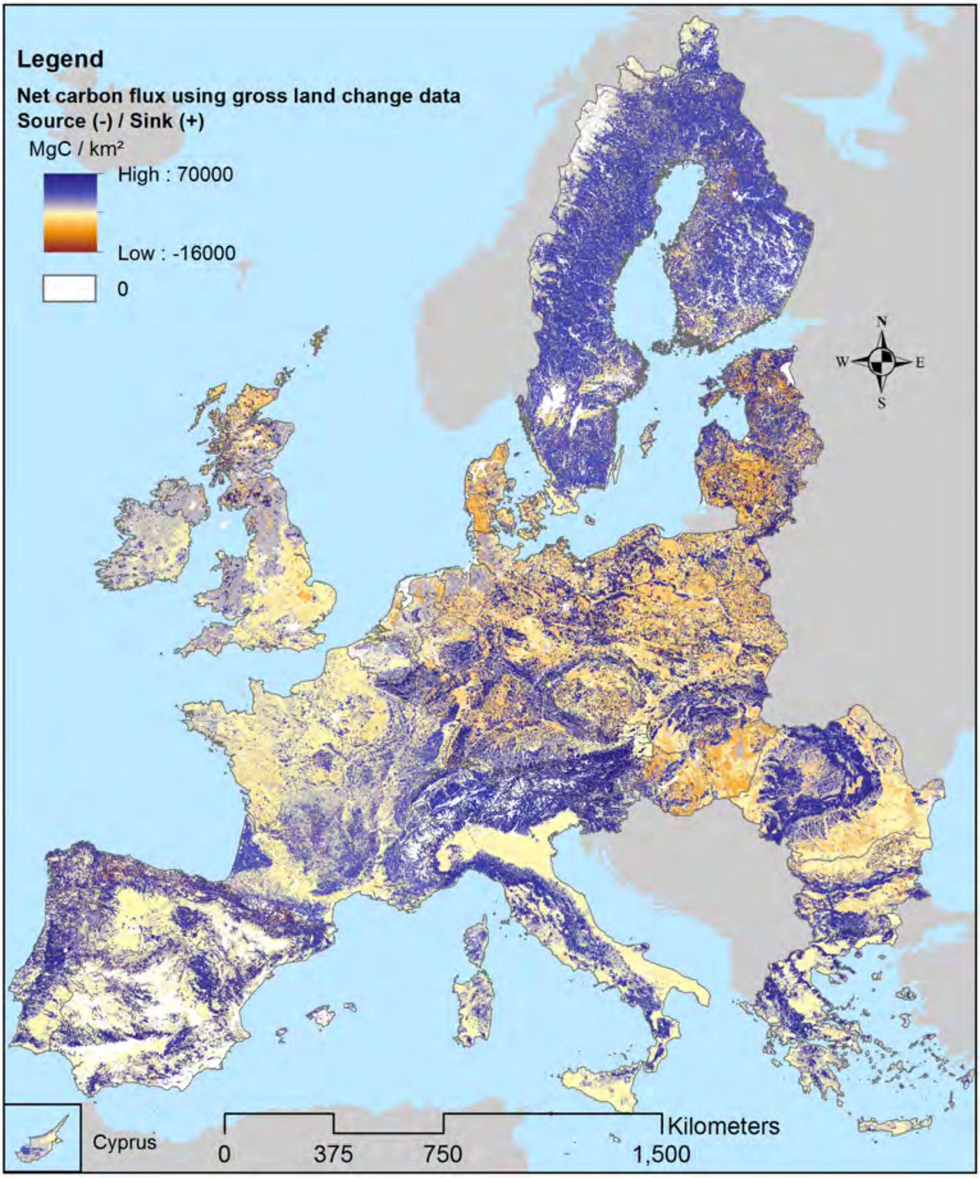

Figure 5.2: Total net carbon flux at 1 km² spatial resolution for the period 1950-2010 using gross land change data. Positive values indicate a sequestration, negative values emission.

When presented per decade the dynamics in carbon emission and sequestration for soils and forest biomass become visible (Fig. 5.3). Throughout the last 60 years SOC sequestration steadily increased from 107 TgC/yr in 1951-1960 to 127 TgC/yr for 2000 to 2010. This increase could be attributed to the massive afforestation actions during the last century and cropland to grassland conversions, which was due to several reasons (e.g. higher yields, improved drainage and irrigation, Common Agriculture Policy and Fall of the Iron Curtain, see Fuchs *et al.*, 2015a, 2015b for more information). Emissions from soils decreased from 14 TgC/yr in 1950 to 11 TgC/yr in 2010. Compared to Schulze *et al.* (2010), who estimated a net soil flux of 114 TgC/yr for EU25 between 2003 and 2007 based on UNFCC data (United Nations Framework Convention on Climate Change, 2013), our yearly net soil flux of 115 TgC for 2000 to 2010 and EU27CH is in the same order of magnitude.

During the modelling period most carbon fluctuations occurred in forest biomass, which increased since the 50’s. An emission peak of 49 TgC/yr was reached during the 80’s. At the same time a sequestration peak of 218 TgC/yr occurred. The difference in carbon fluxes between net and gross land changes for whole Europe was in total 7% (up to 11.1% per decade). Gross land changes caused systematically higher carbon fluxes throughout the modelling period.

This gets more apparent when zooming to regional levels (Fig. 5.4). Although the net flux over the whole period using net land change (Fig. 5.4a) and gross change data (Fig. 5.4b) shows similar spatial patterns, the carbon fluxes in areas that were affected by land changes during the study period (Fig. 5.4c) could be considerably different (Fig. 5.4d). Over the last 60 years an area of roughly 35% of the study area was subject to land changes in one or both of the reconstructions. In these areas gross fluxes can vary up to 85,000 MgC per km².

Table 5.3: Overview of total carbon fluxes of EU27CH for different pools over the period 1950-2010.

	Total (1950-2010)	**Forest biomass (1950-2010)**	**Soils (1950-2010)**
Gross flux (gross land changes)	17.08 (PgC)	9.26 (PgC)	7.82 (PgC)
Net flux (gross land changes)	12.16 (PgC)	5.86 (PgC)	6.30 (PgC)
Sequestration	14.62 (PgC)	7.56 (PgC)	7.06 (PgC)
Emission	-2.46 (PgC)	-1.70 (PgC)	-0.76 (PgC)

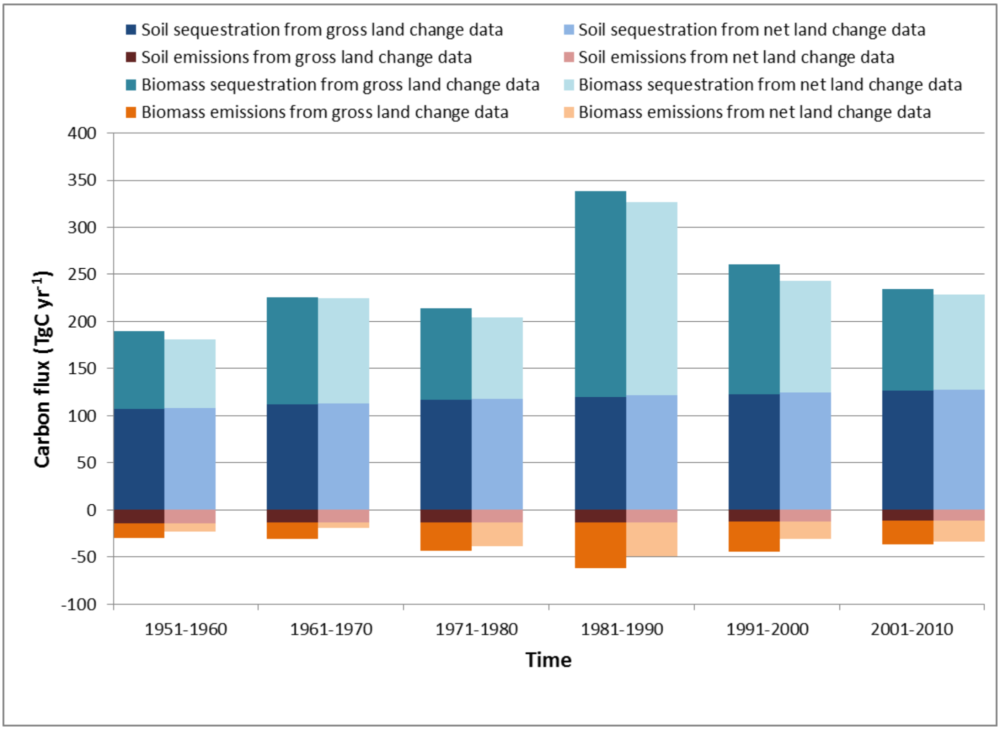

Figure 5.3: Yearly carbon emission and sequestration dynamics for different decades from biomass and soil pools over the period 1950-2010 separated for gross (dark shades) and net land change data (light shades).

For areas of land changes the gross flux differences between net land change data and gross land change data was 1.06 PgC over the whole period, which is 67.8% difference in fluxes in these areas.

This means that other than at the European scale, where the difference in fluxes is more or less averaged out, the differences in regional patterns could be very large in areas that underwent land changes. This difference is most critical for forested areas, where large amounts of biomass over time could be sequestered or emitted, such as in Scandinavia, the Baltics, Central Europe and the Carpathians (Fig. 5.4d).

5.4 Discussion and conclusions

5.4.1 Evaluation of methods and processing

Many assessments on historic carbon fluxes from land cover/use change, including those of the 5th Assessment Report of the Intergovernmental Panel on Climate Change

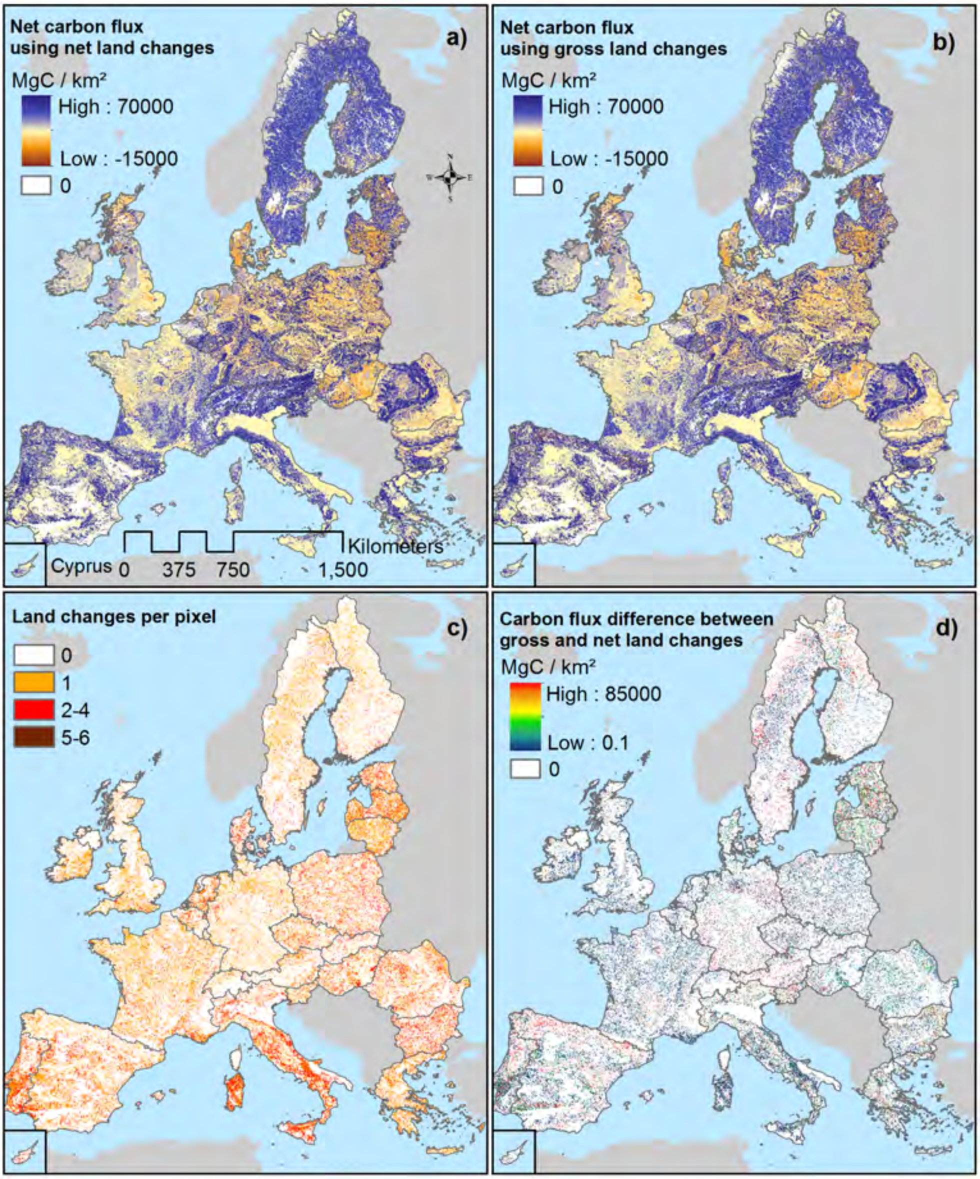

Figure 5.4: Difference in net carbon flux for the period 1950-2010 using net land change data (a) and gross land change data (b). Frequency and areas affected by land changes (c) and differences in gross carbon fluxes on areas affected by land changes (d).

(IPCC, 2013), are limited by the level of detail of the historic land cover/use data themselves and use strongly simplified representations of effects of land cover/use change dynamics in their approach (Arora and Boer, 2010; Klein Goldewijk and Verburg, 2013). An important step forward was taken in the data by Hurtt *et al.* (2006, 2011) that provided five land cover/use classes, allowing the full dynamics of land conversion types. However, the quantities of change were based on net change data from Klein Goldewijk *et al.* (2010, 2011) combined with a gross change factor for shifting cultivation and wood harvest. This not only underestimated the amount of land changes in Europe (Fuchs *et al.*, 2015a), but also impacts related carbon fluxes.

As compared to previous studies our approach for long-term and large-scale continental carbon assessments provided a new level of detail with respect to historic carbon fluxes for different pools at high-spatial resolution and separated net and gross land change approaches. Our carbon reconstruction was based on a data-driven approach using land cover/use change, carbon stock, forest age and emission factors for various land cover/use types from national reports and measurements. This made the approach more robust than approaches that solely focus on simulations. However, the data sets we used also implied uncertainties, such as uncertainties and spatial variation of EFs, definitions of forest and forest area, uncertainties in carbon stock measurements, spatial allocation procedures used by the historic carbon stock method and the historic land reconstruction method.

5.4.2 Reconstruction of carbon history of Europe

An area larger than one third of the size of Europe has undergone land cover/use change during the last 60 years. Often specific areas changed multiple times (Fig. 5.4c). The forest areas have increased by roughly one third from 1950 until 2010. The same happened to the settlements. At the same time the cropland area has decreased roughly by 18% due to technological innovations and increased import. This means that the main contributor to SOC emissions, namely cropland, over the course of the last 60 years, decreased in its total contribution to emissions. At the same time, Europe got greener in the last 60 years, mainly because of afforestation actions after the Second World War, due to timber shortage, and land abandonment as a result of the Fall of the Iron Curtain, the Common Agricultural Policy and outsourced agricultural production to other world regions. This decrease in cropland area on the one hand, and the increase in grasslands and forests on the other hand, meant a steady increase of soil carbon sequestration from 107 TgC/yr in 1950 to 127 TgC/yr for 2000 till 2010.

After the Second World War the massive afforestation actions and accompanied forest area increase throughout Europe not only led to a decrease in mean forest age (Vilén *et al.*, 2012), but over the course of the last 60 years it also led to an increase in biomass and forest carbon stock per country (Fig. 5.3). Old non/less-productive forests were cut after the Second World War by selective felling of mature and pre-mature forests in western, central and eastern European countries (Gold *et al.*, 2006). For some countries this was part of war reparations, so payments that covered damage or injury inflicted during the Second World

War (e.g. Finland) (Vilén *et al.*, 2012). In the 70's many European countries replaced old and low density forests by fast growing young forests (Vilén *et al.*, 2012). At the same time the afforestation rate slowed down (Fuchs *et al.*, 2015a; Gold *et al.*, 2006). Forests changed into production forests, leaving clear cut systems behind. Management switched to selective logging systems and integrated forest management (Den Ouden *et al.*, 2011). This slowing down in afforestation rate and switch in management practice can be seen in our reconstruction (Fig. 5.3). Studies by Ciais *et al.* (2008), Nabuurs *et al.* (2003) and Rautiainen *et al.* (2010) already identified that these transitions in European forest areas and management had a significant impact on the European carbon balance. This was underpinned by our findings and could be disentangled to grid-cell level in order to reveal the regional differences. While Nabuurs *et al.* (2003) calculated the forest carbon stock in the 1950s to be 5.3 PgC in Europe (30 countries) and in 1999 7.7 PgC, we estimated 6.6 PgC for 1950 and 10.6 PgC for 2000 (EU27 plus Switzerland).

5.4.3 Implications of using gross land changes for carbon accounting

The inclusion of gross land changes and related carbon/greenhouse gas fluxes in environmental assessments was mentioned by many authors to be important (Houghton *et al.*, 2012; IPCC, 2013; Stocker *et al.*, 2014; Wilkenskjeld *et al.*, 2014). However, gross land changes have yet not been operationalized in major assessments. Therefore, the IPCC mentioned that the distinction between gross and net land changes is critical for the estimation of fluxes (IPCC, 2013). For land-atmosphere interaction carbon gross changes play an important role. While deforestation or fires lead to almost instantaneous emissions, the carbon uptake from afforestation can take several decades (Houghton *et al.*, 2012). Since gross land change accounting increases the dynamics in land change processes of historic reconstructions, the consideration of these accounting methods in environmental assessments, such as climate change research, is crucial. In that respect, our study provides a valuable contribution to this field of research and helps to improve the understanding of ongoing processes and the implications of using gross land change data.

We showed that for Europe the differentiation between gross and net land changes led to considerable differences in carbon fluxes. The difference was 7% on the overall balance for the whole modelling period, with decadal maximum differences went up to 11%. This contrasts the statement from Schulze *et al.* (2010) that gross changes had hardly any effect on the estimation of the overall carbon balance. Schulze *et al.* (2010) used non-spatially explicit gross change data for their European study.

Recently, Stocker *et al.* (2014) and Wilkenskjeld *et al.* (2014) analysed the sensitivity and impact of gross changes on biogeochemical assessments using the gross change factors of Hurtt *et al.* (2006, 2011). For comparison, Stocker *et al.* (2014) estimated 19% higher mean annual carbon emissions and Wilkenskjeld *et al.* (2014) ca. 38% for the period 1850-2005 using gross land changes, both on a global scale. Stocker *et al.* (2014) and

Wilkenskjeld *et al.* (2014) based their estimates on land cover/use data from Hurtt *et al.* (2006, 2011). However, Hurtt *et al.* (2006, 2011) assumed the same amount of gross land changes as net land changes over Europe. Therefore, the differences in carbon fluxes between gross and net land changes in Stocker *et al.* (2014) and Wilkenskjeld *et al.* (2014) were not present for Europe. This assumption is not realistic, since parallel land transitions happened also in Europe (European Environment Agency (EEA), 2012; Fuchs *et al.*, 2015a). We therefore assume that on global level the impact of full dynamics of gross land changes might still be significantly underestimated as shifting cultivation only captures part of the full amount of differences between gross and net change in land cover. For integrated assessments, such as in climate change research, that are capable to implement gross land change transitions, as well as in upcoming Coupled Model Intercomparison Phase 6 (CMIP 6) model runs this underestimation of changes and carbon fluxes might have implications at global level.

Acknowledgements

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6. Synthesis

"People don't want more information. They are up to their eyeballs in information. They want faith–faith in you, your goals, your success, in the story you tell."

Annette Simmons
The Story Factor (2006)

6.1 Main results

Recognizing the need of the scientific community for better historic land cover/use change data inputs for climate change research, this thesis contributes to improving the representation of land change dynamics of Europe throughout the last century at an improved level of detail. It explores new methods and concepts for historic reconstructions in order to decrease uncertainties in estimations of historic land cover/use change. One goal of this thesis was to show how regional/local data streams can be harmonized and merged together into a 'bigger picture'. This thesis shows new approaches to substitute assumptions used in reconstructions of historic land cover/use by data and enables potential users of the land cover/use reconstructions to consistently address a wide range of different land use/cover categories and land change processes.

The main objective of this thesis was to explore new reconstruction methods that improve the spatial, temporal and thematic detail and reduce the uncertainty in the estimates at continental level. Based on this objective, three research questions were raised (section 1.5). Each of them is answered below.

6.1.1 Research question A

Does the combination of different data sources, more detailed modelling techniques and the focus on land change dynamics allow the creation of an accurate, high resolution historic land change reconstruction for Europe covering the period 1900 to 2010?

We addressed this research question in chapter 2, 3 and 4. In a first stage, described in chapter 2, we used a combination of multiple harmonized data sources and a new data driven reconstruction method to process historic net land changes consistently on a 1 km spatial resolution for five IPCC land categories (*settlement, cropland, grassland, forest* and *other land*) back to the year 1950 for the EU27CH area. In this first stage existing harmonized land cover/use change data from census data and from remote sensing were intensively used to feed into the reconstruction. Compared to other large-scale reconstruction approaches it was possible to make use of a high-resolution baseline map with 1 km spatial resolution and reconstruct land cover/use back to 1950 based on this high spatial resolution. The five different land categories addressed covered 100% of the land area, but at this point only the net changes in area of the different land cover types were considered.

In comparison with other large scale land reconstructions like Klein Goldewijk *et al.* (2010, 2011), Ramankutty and Foley (1999), Pongratz *et al.* (2008) and Hurtt *et al.* (2006) it was shown that the first version of our reconstruction performed in line with these land reconstructions. However, with the data driven reconstruction method a higher spatial resolution and regional detail with a full coverage of different land categories could be achieved based on harmonized input datasets. These characteristics allowed the data to be used for supporting and improving on-going climate research.

One shortcoming of the first reconstruction study was the short modelling period from 1950 to 2010 and the missing focus on gross land changes to study land change dynamics. Many land change processes in the aftermath of the Second World War were a result of decades of warfare before. The start date of 1950 for the method applied in chapter 2 hindered the direct comparison of land change processes during the warfare period and its aftermath. Especially in comparison with global reconstructions the analysis for the decades around 1950 was of special interest for this thesis, since many important land change processes started around that time (e.g. afforestation) and many global reconstructions are, due to decreasing data availability, more relying on highly simplified model assumptions, thus inducing uncertainty in the reconstruction results. We further developed the reconstruction method by feeding the reconstruction method with extensive regional and national historic land cover/use data before 1950. This resulted in a second model version described in chapter 3 and 4. This second version of the historic reconstruction method covered the whole last century from 1900 to 2010 while keeping the basic features (classes, temporal and spatial resolution) of the first version. It allowed to study main land change processes throughout the last 110 years and analyse its dynamics in time, especially by comparing the period before 1950 and after 1950. The approach harmonized many different observation data and processed them to a ‘bigger picture‘ at continental scale. In that respect our approach did not only bridge and combine spatial scales but also combined reconstruction approaches relying on historical data and those based on models that rely on simplified relations between land use and population data. Although the objective was to produce ‘accurate’ reconstructions the accuracy could only partly be assessed due to the lack of independent validation data. For this objective we focused with the available data on the model calibration, rather than validation. This resulted in sparse data that were left for accuracy assessments.

6.1.2 Research question B

How can regional historic knowledge, like statistics from encyclopaedias and old topographic maps, be used in large scale reconstructions?

This research question was addressed in chapter 3. By the use of historic data sources, such as encyclopaedias and maps, at large scales we extended our data-driven reconstruction period back to 1900 and covered in total more than a century. In this study we showed that the concept of a data driven reconstruction for historic land cover/use improved the modelling accuracy in comparison to a traditional model-based reconstruction approach that more strongly relies on assumptions and proxy variables for the spatial allocation and land change trends. It was shown that historic reconstruction models can make use of historic statistics when statistics are corrected for changing country borders. By implementation of historic forest maps the modelling error of forest/non-forest areas was reduced by about 16.5%.

The two modelling results presented in chapter 3 showed that historic maps do not only improve the reconstruction of the quantity and location of forest/non-forest areas, but also the structure and shape of these landscape elements. The reconstruction approach without the use of historic maps tended to allocate forest as large continuous areas preferably in mountainous regions as a result of the assumed strong influence of terrain factors (e.g. slope and altitude) on the allocation. As a result, the allocation approach without historic maps ignored the spatial structure of landscapes (e.g. patch sizes, shapes or number of patches). It was seen as an artefact of the reconstruction approach if no historic maps were used.

The major benefit of the approach described in chapter 3, as compared to earlier reconstructions at continental level, was that the more historic data were used the less interpolations and assumptions were required to create the land cover/use reconstruction. In many publications about historic land reconstructions data scarcity before 1950 was mentioned as a main reason for using proxy variables and model assumptions. The need for a more data driven approach was, however, frequently indicated (Gaillard *et al.*, 2010; Klein Goldewijk and Verburg, 2013). With our European study we showed that it was possible to produce large scale data driven historic reconstructions. Multiple data sources were used for verification and each implemented data set could potentially correct for biased assumptions used during the interpolation of data between years and areas. Our method was applied on existing data for Europe for the year 1900, but the method is applicable for other regions in the world with similar data availability as well, thus improving global-scale reconstructions.

The current trend of open data policy should be seen as a chance to close data gaps and benefit reconstructions of historic land cover/use. The open access of archives offers a unique opportunity to look back in Europe's land cover/use history, over large areas and with maps from the early industrialization era. Many archives show potential for usage of land cover/use data in reconstructions for other regions in the world.

6.1.3 Research question C

To what extent do historic land cover/use reconstructions underestimate land cover/use changes in Europe for the 1900–2010 period by accounting for net changes only and how does that affect the European carbon fluxes?

This research question was addressed in chapter 4 and 5 by implementing and analysing a reconstruction approach that accounts for gross land change dynamics. In chapter 4 we found for Europe that the consideration of gross change led to almost double the amount of change over the 110 years considered. The dynamics of change per grid cell increased in comparison to net changes when extrapolated to long periods (1900-2010). This resulted in higher amounts of land changes for all land categories compared to existing global reconstructions that adopt a net change approach. The LUH model estimated 28.1% changes between 1900-2000 and our net change reconstruction estimated 27.6%. However, our gross change reconstruction yielded 49.8% of changes, showing that the difference in estimated land changes between gross and net changes has serious consequences for the quantity of overall change in land cover/use.

The gross/net ratios for the different land classes derived from different data products to inform the reconstruction approach were sensitive to errors in the original products (e.g. misclassifications), like the data of the UNFCCC, Corine land cover, FAO-RSS, HGN and BioPress. In spite of these possible errors we could underpin our gross change reconstruction with empirical evidence, which was not yet done in the gross change analysis presented by Hurtt *et al.* (2006, 2011).

In chapter 5 we found that overall for Europe the differentiation between gross and net land changes led to roughly 7% differences in carbon fluxes. This overall difference reached up to 11% per decade. Fluxes for gross land change data were systematically higher as compared to net land change data. For areas that were in both reconstructions subject to land changes (35% of total area) the differences in carbon fluxes were about 68%, and highest over forested areas. Our results therefore contrast previous findings, e.g. of Schulze *et al.* (2010), Stocker *et al.* (2014) and Wilkenskjeld *et al.* (2014), who found no major difference in carbon fluxes for Europe. Based on our findings it is likely that on global level the impact of the full dynamics of gross land changes might still be significantly underestimated as current assessments only capture part of the full amount of differences between gross and net change in land cover. For integrated assessments, such as in climate change research that are capable to implement gross land change transitions as well as in the upcoming Coupled Model Intercomparison Phase 6 (CMIP 6) model runs, this underestimation of changes and carbon fluxes might have implications at global level.

6.2 Added value to existing reconstruction methods

The added value of the reconstruction methods used in the thesis can be demonstrated in comparison to the two reconstruction approaches at different scales (local/regional/national and global) presented in the introduction of this thesis (chapter 1.2).

Compared to national or regional studies our reconstruction of Europe kept similar levels of detail (spatial, thematic and temporal) as many regional and national studies. However, with the approaches developed in this thesis it was possible to study cross-border changes at large scales. The harmonization method allowed to compare large areas with one another in a consistent way independent of country borders, since definitions of land categories were given on a similar level. This enabled to merge data, which were formerly used in different regional studies, to one consistent continental ‘bigger picture’. This means that data that were often exclusively available for the investigated region could be incorporated in the reconstruction approach to narrow down uncertainties in estimates.

However, innovative aspects in comparison to global reconstructions can be highlighted as well. Up to now most large-scale reconstructions had to be processed on coarse scales (usually 0.5 degree) with fractional land cover/use representations per pixel due to a lack of sufficient available input data for the reconstruction models. For the analysis of land change dynamics the coarse fractional approaches with sub-grid processes reach here their limits. Approaches with fractional land cover/use classes are not able to account for path dependencies and land cover/use history per grid-cell. This can be solved by using distinct land cover/use classes. The HYDE 3.1 model (Klein Goldewijk *et al.*, 2010, 2011) is currently the only global model using a distinct land cover/use representation at roughly 8 km spatial resolution.

Due to the high spatial resolution input data (e.g. the base map for the year 2000) and amount of data for calibration (e.g. statistics and maps) our reconstruction approach is able to circumvent these limitations at large scales allowing to process at 1 km spatial resolution with distinct land cover classes. The complete coverage of the land area with land cover/use classes together with the high-resolution modelling approach allows to study the persistence of land cover/use and the dynamics of land cover/use change at large scales on higher levels of detail than before, while keeping the specific land cover/use history of each grid-cell.

For the first time empirical data were used to retrieve gross change parameters that represent the full gross change dynamics (chapter 4). They were implemented in our historic reconstruction model to reconstruct gross changes in Europe back to 1900. As a result of this study it was shown that the amount of land changes was seriously underestimated without the consideration of gross land changes in reconstructions.

The reconstruction model shown in this thesis based its processing for every EU27CH country on a time-series of 110 years with measurements of land cover/use from various data sources. For many periods multiple independent data sources were available to calibrate and verify land cover/use change trends. The amount of land cover/use data used for the reconstruction enabled to derive consistent area estimates and supported allocation even back to 1900. Up to now, other large scale reconstructions of historic land cover/use change had not such a comparable strong focus on a data-driven approach as our historic reconstruction, although also global reconstructions use extensive databases, but not specifically land cover/use measurements.

By using measurements of land cover/use and their change instead of assumptions the need for scenarios for reconstructions becomes obsolete. Although each of the measurements may be questioned concerning their correctness, they do not require being tested under different conditions like for assumptions. This data driven approach narrows down uncertainties in reconstructions. While assumptions are universally valid, and therefore prone to affect the whole reconstruction period, measurements are only valid for the area and period they cover. Thus, a combination of different input data sources prevents large uncertainties.

6.3 Limitations of the applied research methods

A major limitation of the historic reconstruction methods is the current spatial coverage of only EU27CH countries. The chosen spatial coverage initially arose from the requirements of the project GHG-Europe (Grant No. 244122, http://www.ghg-europe.eu/) in which the model was developed. However, ideally the reconstruction approach needs to be applied at global scale, or at least on wider areas than EU27CH, in order to demonstrate and prove the feasibility of its methods at scales where other large-scale reconstructions got stuck due to various constraints (e.g. data availability, data harmonization, spatial resolution).

The preparation of the various input data sources (e.g. harmonization and digitization) for the reconstruction approach used in this thesis is in the current state very time consuming. With respect to global level reconstructions this may lead to larger expenditure of human labour or time investments than for other global reconstructions.

For a lot of subsequent analysis, for example as input in Dynamic Global Vegetation Models (DGVM), a longer time span of the reconstruction period is needed. DGVMs work with potential vegetation and require at the start of the modelling period a ‘spin-up’ phase for vegetation from bare ground until they reach equilibrium. The ‘spin-up’ phase easily takes several decades and thus reduces actual modelling time if our reconstruction is used as data input.

The reconstruction approach used probability maps to allocate historic land cover/use areas. In the first version (chapter 2) these probability maps consisted of supposed to be explanatory environmental and socio-economic factors, like soil parameters, climate variables, terrain features or the accessibility of the terrain. In chapter 2 we showed deviations in the allocation compared to observations from our validation material. The reconstructed maps were improved by the implementation of historic land cover/use maps from around 1900 (see chapter 3). Historic maps were applied to the probability maps for about 40% of the study area to test the implications of using historic maps as decision support for land cover/use allocation in historic reconstructions. As shown in chapter 3, there are currently more historic maps of Europe for the year 1900 available than used in our assessment. Uncertainties in the allocation method of the reconstruction approach could be further decreased if especially historic maps for countries and regions, which are currently not covered, would be implemented. Potential historic maps of the year around 1900 exist for Spain (Centro National de Information Geografica, 2013), UK (National Libary of Scotland, 2013), France (Geoportail, 2013b) and Sweden (University of Stockholm, 2013a, 2013b).

More recent large scale historic maps, like topographic maps of the 1950's from aerial images (Mapster, 2014; National Libary of Scotland, 2013; University of Texas Libraries, 2014; Vlasenko, 2008) or remote sensing products from the 1980's (Potapov *et al.*, 2014) would provide the possibility to implement dynamic probability maps, where the reconstruction model could make use of historic maps around the date that is processed by the model. Flexible probability maps would further automatize and improve the allocation algorithm.

6.4 Societal impact - Europe's land changes in a nutshell

Besides the need for improved historic land cover/use change reconstructions, especially as data input in environmental assessments such as climate change research, the general public also has an interest in learning about past land cover/use changes. Media coverage and its attention is one aspect to recognize this societal interest. The reconstruction approaches presented in this thesis synthesised the knowledge of historic land changes and contributed to an illustration of the 'bigger picture' for Europe.

In December 2014 the results of the historic reconstruction were picked up by various newspapers in Europe and the United States (e.g. Washington Post, Der Spiegel, Sueddeutsche Zeitung, Gazetta Wyborcza, NRC Nederland, Vice Magazine Netherlands, Ouest France, etc.) (Bojanowski and Fuchs, 2014; Filser and Fuchs, 2014; Nijland and Fuchs, 2014; Noack and Fuchs, 2014; Olivier and Fuchs, 2014; Raspe and Fuchs, 2014; Roes and Fuchs, 2014; Smal and Fuchs, 2014; Wachnicki and Fuchs, 2014; Zaharia and Fuchs, 2014). Subsequently, the reasons for the amount of land changes and the specific change processes throughout the last century in Europe were intensively debated in many different fora and on social media platforms, giving an indication about the societal interest in historic land changes.

This section is a synthesis of the given interviews and puts known important historic land change periods into a spatial context. Major land change processes are discussed and complemented with local/regional examples and highlighted in the context of political and socio-economic changes that went on in parallel with major change processes of the historic reconstruction. Figure 6.1 shows the reconstruction for the historic land cover/use in 1900 and 2010. An animated high-resolution image for every decade of the historic reconstruction is provided under the following shortURL: www.hilda-animation.wur.nl

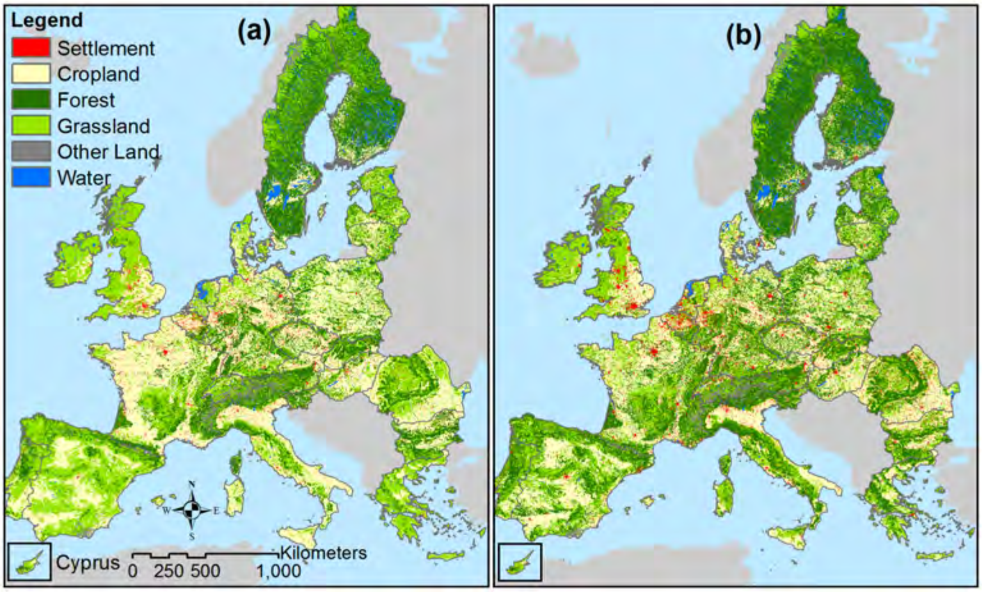

Figure 6.1: Historic land cover/use reconstruction for year (a) 1900 and (b) 2010.

6.4.1 General changes and processes

In our gross change reconstruction half of the size of Europe has changed during the last 110 years and often specific areas changed multiple times (see www.hilda-animation.wur.nl). The forest areas have increased by 1/3 since 1900 until 2010 and settlement areas have doubled since then. At the same time cropland area has decreased roughly by 14%. The main land change processes in the reconstruction were afforestation and cropland/grassland dynamics, but also deforestation and urbanization.

These major land change trends often happened in parallel and varied in intensity throughout time (Fig. 4.8). Overall, in our reconstruction Europe got *greener* in the last 110 years, mainly because of afforestation actions and land abandonment. Higher yields could be achieved on less area than in 1900 due to technological innovations in the agricultural sector (mechanization, synthetic fertilizers, drainage and irrigation) (Jepsen *et al.*, 2015). At the same time the globalization *outsourced* the production of many resources to other parts of the world (e.g. vegetable oil, fodder and bioenergy products), which required less cropland area in Europe (Chemnitz and Weigelt, 2015).

6.4.2 Afforestation in Europe

Our reconstruction showed afforestation as one of the major land changes over the course of the last 110 years. Afforestation was relatively stable in the first four decades.

Since 1940 afforestation was experiencing a sudden increase that continued and reached its climax in 1980. From then onwards the afforestation intensity was declining (Fig. 4.8). In parallel it can be seen in our reconstruction that afforestation appeared throughout whole Europe, however with varying intensity for the different countries. Mostly marginal land (e.g. in mountain areas at medium altitudes) and grassland areas were subject to afforestation (see www.hilda-animation.wur.nl).

Timber was always an elemental product of Europe's economy and ensured its growth and development (FAO, 1947, 1948). At the beginning of the 20th century timber was the basis for almost everything: as fuel wood, for metal production, furniture, house construction, electricity poles, as pit props in mines, for railways, in wars for trenches and in ship construction. Many of the products were a direct result of Europe’s industrialisation, such as the pit props for coal mines, electricity poles or as railroad sleeper for railroads.

As a consequence of the rationing of fossil fuels during the Second World War firewood vehicles became common practice in Europe (Fig. 6.2). At the end of the Second World War roughly 750.000 wood fuel cars drove in Europe (Decker, 2010).

Since the Middle Ages, Europe's forest was consecutively deforested for timber and for accessing new settlement and production areas. This led to the fact that around 1900 large amounts of natural forest areas were gone in Europe with often serious negative consequences for human population and nature (Fig. 6.3). Many European countries recognized that timber resources are limited and are essential for sustainable economic growth (FAO, 1948). Especially after the Second World War many countries started massive afforestation programs, which are still running today. Many abandoned former marginal croplands, e.g. in lower mountain ranges, were afforested again. This temporal change in the afforestation process as a result of the reconstruction can be nicely seen in Fig. 4.8.

Figure 6.2: One out of more than 750.000 wood gas vehicles in Europe at the end of the Second World War that used fuelwood due to rationing of fossil fuels (Anonymous, 1946).

Figure 6.3: Region Vaucluse (France) in 1889 (left) and 2004 (right) showing the massive afforestation efforts in Europe during the last century (Poivert, 2004).

Due to the general timber demand in the 20th century, this trend occurred for almost every country. Especially after the Second World War timber was considered as elemental to ensure economic growth. Countries that had sufficient timber for their own needs exported timber to other countries (e.g. from Scandinavia to the UK, France and Germany) (FAO, 1947, 1948) (see www.hilda-animation.wur.nl).

Many afforestation programs that started after the end of the Second World War were designed for roughly 30-40 years (FAO, 1947, 1948). A decrease in afforestation speed from 1980 onwards can be seen as well in our reconstruction (Fig. 4.8). Besides all the different afforestation actions deforestation still remained an important process in Europe (Fig. 4.8).

Countries with extensive timber use, like the UK, increased their forest area in our reconstruction from ca. 4% in 1900 to 12% in 2010. In Eastern Europe a lot of forest regrew after the Fall of the Iron Curtain. Many former cropland areas were not competitive anymore in the global market and therefore abandoned, especially marginal land (Jepsen *et al.*, 2015; Mueller *et al.*, 2009). This abandonment led often after a few years to shrublands and later on to new forest areas. This trend was evident in our reconstruction for Romania, Poland and the Baltic States (see www.hilda-animation.wur.nl).

A similar development can also be seen in Italy, Spain, Greece and Portugal. Former cropland was abandoned because of market competition, urbanization and emigration (Antrop, 1993). In Mediterranean countries traditional farming like agro-forestry was substituted by high-production agriculture. Former agro-forestry areas grew wild again. Today, in Italy major parts of the Apennine Mountains are dominated by grasslands, shrublands and forests again (see www.hilda-animation.wur.nl).

In the region of Vaucluse in southern France whole mountain ranges were deforested around 1900. Today they are afforested again (Fig. 6.3) (Poivert, 2004). A lot of afforestation took also place in the Scandinavian countries, which expanded their timber exports to supply the demand (FAO, 1948).

6.4.3 The consecutive re-organization of cropland and grassland

The cropland area has decreased in our reconstruction by ca. 14% since 1900. Cropland to grassland conversions had a sudden peak between the 50's and 70's, dropped back to its lowest intensity in the 80's and experienced a second peak from the 90's onwards. A similar development was seen for grassland to cropland conversion, but with a lower magnitude (Fig. 4.8). Cropland disappeared mostly in areas with marginal land and extended its area in flat and easy accessible plains. Grassland areas instead were substituted in plain areas by cropland and replaced croplands in marginal land. Often grassland areas converted after a while into forest areas (see www.hilda-animation.wur.nl)

Due to technological innovations (synthetic fertilizer, mechanization, drainage and irrigation) during the last century the cropland area experienced a continuous decrease in required man-power and an increase in crop yields. Higher yields could be harvested on less area than before. Many people migrated from rural areas to urban areas or even overseas (Jepsen *et al.,* 2015).

Especially after the introduction of the Common Agricultural Policy and the Fall of the Iron Curtain in the 1990's it can be seen in our reconstruction that agriculture concentrated on high-production areas, whereas marginal land was given up (Fig. 2.11). Fields got continuously larger to better manage and maintain them with machines. In Mediterranean countries like Spain and Portugal more than 50% of the agricultural land is owned by companies that manage areas larger than 100 hectare (Chemnitz and Weigelt, 2015; Eurostats, 2014).

After the fall of the communism, most state owned agricultural land in Eastern Europe was privatized again. Often the later generations of former owners moved away, died, did not know anymore how to maintain and manage the land or did not want to invest large amounts of money in order to be competitive on the market (e.g. by investing in new machines) (Jepsen *et al.*, 2015; Sambuchi, 2012). A lot of agricultural land was therefore abandoned, especially in marginal areas (e.g. medium mountain ranges). This trend was seen as well in our reconstruction.

In parallel also larger agro-companies (often big international agro-companies) bought a lot of the high-productive cropland areas and started to intensify the land use again, especially in Eastern European countries with a large fraction of subsistence farmers (e.g. Poland and Romania). Often abandoned cropland areas were found right next to cropland intensification. This trend was seen lately especially in Romania (Sambuchi, 2012) (Fig. 6.4). Within 10 years the value of agricultural land in Romania has increased by more than 1800% (Chemnitz and Weigelt, 2015; Savills, 2014).

Figure 6.4: Cropland intensification next to abandoned cropland areas in the Danube Plain, Romania (Flickr, 2006).

6.4.4 The interplay of socio-economic/political changes and land cover/use changes

A lot of land cover/use changes in our reconstruction happened in parallel with technological, socioeconomic or political innovations, events or shocks, like land reforms, warfare, mechanization or the introduction of synthetic fertilizers. Major land change periods can be attributed to two World Wars, the Cold War, the Fall of the Iron Curtain but also the Common Agricultural Policy (CAP) (Fig. 4.8). Land changes happened either in parallel or with a short time lag to those political or socio-economic events.

Two World Wars suspended or stopped economic growth and prevented political progress and developments in land management in Europe. This stasis kept Europe's land change dynamics stable for almost the first half of the 20th century (Fig. 4.8 until 1940). However, in the shadow of both World Wars, the Haber-Bosch process was developed to not only produce explosives for warfare but also synthetic fertilizers (Encyclopaedia Britannica, 2014). In a similar fashion the industrial production of automobiles in assembly lines came from the U.S. to Europe (Ward's Communications Inc., 2007). During the Second World War automobiles were still reserved for the upper class, but the mass production in Europe started right after the end of the war. This lead to a mechanisation in many sectors, including the agricultural sector (Jepsen *et al.*, 2015).

To overcome the famine after the Second World War, both the mechanisation and synthetic fertilization experienced a sudden boom in the agricultural sector leading to an intensification process for croplands (Jepsen *et al.*, 2015). This intensification process was also reflected in our reconstruction between the 50’s and 70’s (Fig. 4.8). In parallel a number of afforestation programs started throughout Europe to fight Europe’s timber shortage (Fig. 4.8 from 1940 onwards). Early agricultural subsidy systems of the European Union tried to counter migration from rural to urban centres aiming at the large rural population in the 50’s and 60’s (Farmsubsidy.org, 2014). However, the agricultural subsidy systems could not stop the migration to cities. As a result, urbanisation became a major process in Europe. Instead of former small-holders large high productivity agro-businesses started to reform the agricultural land area in the 60’s by intensifying the land use. In Eastern Europe, large scale farming was practiced by kolkhozes of communist and socialistic systems (Jepsen *et al.*, 2015).

In 1990 the CAP came into effect in parallel with the Fall of the Iron Curtain. The early farm subsidy system of the European Union was renewed with a focus on land area and production. Today the subsidy system of the CAP makes 55 billion EUR per year, which is 45% of the yearly EU budget (Chemnitz and Weigelt, 2015; Farmsubsidy.org, 2014). Especially large-scale agro-businesses benefited from these subsidy systems, which caused a further concentration of large-scale agriculture on high-production areas, while rural and marginal land with lower productivity was given up (Fig. 2.11, Fig. 4.8 for 1990 onwards and Fig. 6.4) (Farmsubsidy.org, 2014). The effects of the implementation of the CAP could be seen mainly in the Mediterranean and Eastern European states (see www.hilda-animation.wur.nl). Many agriculture areas in Eastern Europe experienced a sudden shock in land changes due to the Fall of the Iron Curtain and the entry into the EU where the CAP was in effect.

As a result of globalisation Europe is currently the region that is most dependent on land area for production outside of EU territory (Chemnitz and Weigelt, 2015; Fader *et al.*, 2013). The land-footprint of the EU is estimated to be more than 640 million hectare per year, which is 1.5 times the area of the EU itself (Chemnitz and Weigelt, 2015; Fader *et al.*, 2013). The globalisation can be seen as one of the main reasons for the continuous decreasing cropland and pasture land in Europe throughout the last decades.

6.5 Data requirements of the climate research community

On 17th-19th February 2014, a working group on land management, consisting of climate modellers and earth observation experts, were meeting at the International Space Science Institute (ISSI) in Bern, Switzerland (Wang, 2014). The goal was to identify land data requirements of the climate research community, both for current and future developments. This comprised input data for climate models but also data for evaluation.

A questionnaire was prepared and sent out in May 2014 to all major modelling communities in order to assess their current data requirements and those for the next few year (up to 5+ yrs). In total ca. 15 Earth System Model (ESM), 5 Land Surface Model (LSM) and 5 Integrated Assessment Model (IAM) groups were contacted, of which 15 replied to the questionnaire.

Besides questions about features and data requirements of the different models on land management, greenhouse gases and ecological parameters, the questionnaire was inquiring about the implementation and consideration of land changes in the different models.

Two questions were relevant with respect to land change implementations:

Does the model consider sub-grid transitions, like gross land changes?
and
What are the most important data requirements, now and in the coming 5 years?

Concerning the first question, sixteen modelling groups gave an answer whether they are currently capable to consider gross land changes in their models or not. Up to now 37.5% of the models are able to consider gross land changes. However, in the next 1-4 years ca. 72% of the modelling groups want to have gross land changes implemented in their models. This demonstrates the increasing need for gross land change data. But it also shows that the different modelling communities are well aware of the importance of the full dynamics of land change processes and their relevance for climate change related questions.

It is hard to say if the availability of land change data in the end triggered the modelling community to implement gross land changes or if it was the other way around, but before the Coupled Model Intercomparison Project Phase 5 (CMIP5) gross changes were hardly implemented in ESMs. However, since a couple of years up to 33% of the models implemented gross changes. For the upcoming CMIP6, so in the next 1-4 years, the demand for gross change data will further increase.

While question one was explicitly asking for the willingness/capabilities to implement gross land changes, question two was meant to be an open question, where climate modellers could fill in any type of required data. In total 60% of the modelling groups mentioned 'better land cover/use data' and another 40% required 'land change data with gross land change transitions' (Figure 6.5). Gross land cover/use change data was the most frequent answer of all the data requirements.

Currently, only the LUH data set (Hurtt *et al.*, 2011) is used as data input in ESMs, LSMs and IAMs. However, our reconstruction presented in this thesis can make a valuable contribution as independent data set for evaluation. Furthermore, global ESMs, LSMs and IAMs still operate on a very coarse spatial resolution of around 0.5 degree. Land changes still have to be allocated in sub-grid processes by hierarchical assumption-based rules which determine which land cover/use class changes into which other class. Often these transition rules are quite blunt and pragmatic. For instance, some models converted cropland areas always first into forest, while other models picked grassland to be the primary change. These assumptions have implications for the carbon and GHG assessments since land conversions determine the duration of legacy effects. Our high-resolution data can be used to provide an empirical land conversion matrix as presented in chapter 4 (table 4.3) for case studies like Europe. Alternatively, our data can be used to provide land conversion rules for every 0.5 degree pixel separately, making allocation rules obsolete.

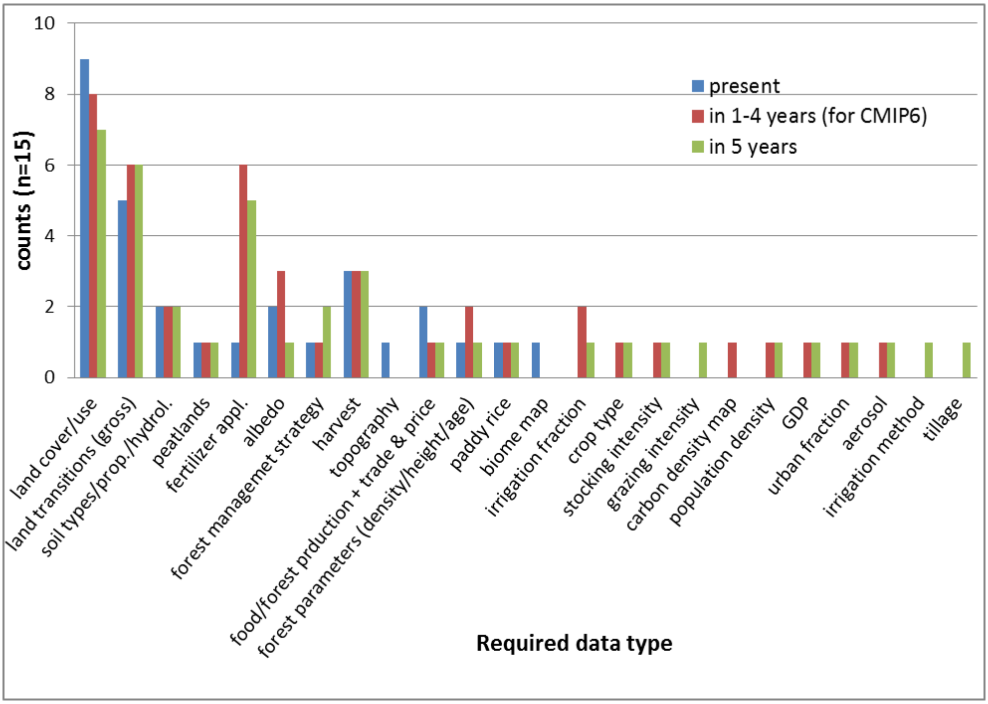

Figure 6.5: Data requirements for global ESMs, LSMs and IAMs, separated for three different periods (present, in 1-4 years and in 5 years).

6.6 Outlook

Land cover/use change research in general is expected to become more important in the near future, since land cover/use changes are one of the main contributors that drive global greenhouse-gas emissions and climate. Land cover/use change, especially in its historic context, is also a valuable input data source for many related environmental, ecological and biogeochemical assessments. So far, land change dynamics and historic legacy effects of land cover/use changes on the biogeochemical cycles are still not well understood. The Fifth Assessment Report (AR5) of the IPCC (IPCC, 2013) highlighted the need for better quantification methods such as land cover/use change methods (e.g. gross change transitions) in historic reconstructions. The climate modelling groups start to see the need and value of a better representation of land change dynamics in their models as well (chapter 6.5).

This thesis makes an important contribution with new reconstruction methods for historic land cover/use changes that allow studying the full dynamics of land changes in their historical context and in the scope of ongoing climate change research. Furthermore, it also demonstrates the potential to achieve higher spatial, temporal and thematic detail in historic reconstructions and to reduce uncertainties in land cover/use change estimates and in land cover/use change allocation, due to a data-driven approach.

The results of the land cover/use reconstruction presented in this thesis can serve as input data to allocate spatially-explicit transitions in European historic land management practices and drivers of land cover/use change. Work, such as presented in Jepsen *et al.* (2015) had to work with narratives, lacking a spatial component, but our historic reconstruction can serve as base layer to allocate management practices spatially consistently explicit over longer time spans.

In order to apply the developed methods and concepts of this thesis to even larger spatial and temporal scales our reconstruction approach needs to be extended to other regions in the world and new time horizons. It might be challenging to find sufficient land cover/use data of the past on global level as we had available for Europe. However, accessible data sources from other regions exist and could be implemented in the reconstruction approach allowing to decrease uncertainties.

In the shadow of military conflicts or natural resource interests the European countries produced a vast amount of data sets. But also colonization, the Cold War and proxy wars (Korea, Vietnam, Afghanistan, Middle East, etcetera) expanded the mapping and statistical activities of industrialized countries to many other regions in the world (Bibliographisches Institut, 1909; Chisholm and Phillips, 1911; Mapster, 2014; Nyssen and Petrie, 2013; Rumsey, 2014; University of Texas Libraries, 2014; Vlasenko, 2008). For some areas, especially in Continental Europe, data sets from the 18th century onwards exist allowing to extent the data-driven approach to longer spans (Centro National de Information Geografica, 2013; Geoportail, 2013a, 2013b; Koningklijke Bibliotheek van België, 2014; Mapster, 2014; Rumsey, 2014).

Several land cover/use products based on remote sensing for multiple time steps exist for deriving gross changes for other parts of the world. FAO-RSS data are globally available for every one-degree Lat/Lon intersection (JRC and FAO, 2012). UNFCCC data are available for Continental Europe, USA, Australia, Canada, Japan, Kazakhstan, New Zealand and Russia (United Nations Framework Convention on Climate Change, 2013).

With the amount of available remote sensing data sets, the current trend of open data policy of (historic) land cover/use archives and the uncertainties in assumption-based reconstruction methods (Gaillard *et al.*, 2010; Klein Goldewijk and Verburg, 2013) data-driven reconstruction approaches (e.g. like the reconstruction approach presented in this thesis) have good chances to become state of the art methods in the coming years for reconstructing historic land cover/use changes.

As suggested in the thesis of Klein Goldewijk (2012) a good effort would be the start of a 'Global land cover/use data base portal' allowing to upload historic land cover/use data or data sets of historic reconstructions in order to concentrate efforts and avoid redundancies. Preferably these data sets could follow a common harmonization scheme to make these data comparable. Under the umbrella of the Intergovernmental Geosphere-Biosphere Program (IGBP) such a data base could be promoted not only to the land change community but also to the climate modelling community.

The preparation of available historic data sources might be labour intensive and time consuming, but profitable in terms of change process understanding and data harmonization. Especially in the data harmonization of existing land cover/use data sources and in the study of land change dynamics, such as gross land changes, lies a huge potential for land cover/use change research. Only since a few years research and society start to unveil and understand the large-scale to global consequences of land use, its long-term pathways and dynamics of change processes. Even more crucial in the future will be to understand and link historic and ongoing land change processes with:

- Impacts of technological innovations on land changes,
- The spatial decoupling of production and trade flows of land-based products, and
- Implications of policies or political events/shocks for the dynamics of land changes.

With respect to future policy it would be valuable to show not only more sophisticated reconstruction methods of historic land cover/use change and their implications on environmental, ecological or biogeochemical assessments for a given time and area, but to disentangle and narrow down spatially and temporally explicit the GHG footprint or climate footprint per land change process or even single political decision or technological innovation.

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Summary

The population in Europe almost has doubled within just a little more than 100 years. The related need for food, fibre, water, and shelter led to a tremendous reorganization of the European landscape and its use. These land cover/use changes have far-reaching consequences for many ecosystem processes that directly or indirectly drive the climate on continental and global scale. Different types of land changes lead to different changes in carbon pools. Examples are rapid carbon pool changes due to deforestation or a delayed carbon pool change from long-term uptake of carbon in re-/afforested areas. This time lag of greenhouse gas fluxes requires the consideration of present and past land use change dynamics. To assess the fluxes of present and past land use change dynamics data or model-based reconstructions of historic land cover/use are needed. Historic land cover/use data as input for historic land reconstructions are fragmented, hard to obtain (copyright, secrecy statuses, accessibility, language barriers), difficult to harmonize and to compare. This lack of available data limits historic land change assessments, especially on large scales. Many continental to global historic land cover/use reconstructions provide little detail of change dynamics, have a rather coarse spatial resolution and reconstruct only a few land cover/use classes. Furthermore, most of them consider only the net area difference between two time steps (net changes) instead of accounting for all area gains and losses (gross changes), which leads to serious underestimation of the amount of area subject to change.

This research aimed to reconstruct historic European land cover/use and its changes for the period from 1900 to 2010 addressing some of the shortcomings of previous studies. The main objective of this thesis was to explore new reconstruction methods that improve the spatial and temporal detail and reduce the uncertainty in the estimates at continental level by better using available data sources. The use of available historic data sets as input data for the reconstruction was evaluated. The main objective was achieved by providing a full representation of gross land changes at continental scale in order to capture all major land change processes and their dynamics for Europe throughout the last century. The thesis also explored the implications of those change dynamics on environmental and biogeochemical research, such as climate change research.

In chapter 2 the combination of different data sources, more detailed modelling techniques and the integration of land conversion types was investigated to create accurate, high resolution historic land change data for Europe suited for the needs of greenhouse gas and climate assessments. A method was presented to process historic net land changes consistently on a 1 km spatial resolution for five IPCC land categories (settlement, cropland, grassland, forest and other land) back to the year

1950 for the EU27 plus Switzerland. Existing harmonized land cover/use change data from census data and from remote sensing were intensively used to feed into the reconstruction.

Chapter 3 analysed how historic statistics of encyclopaedias and old topographic maps can improve the accuracy and representation of land cover/use and its changes in historic reconstructions. This study made use of historic statistics and old topographic maps to demonstrate the added value for model-based reconstructions of historic land cover/use for Central Europe back to 1900. The added value was evaluated by performing a reconstruction with and without the historic information. The study showed that a data driven reconstruction for historic land cover/use improved the modelling accuracy in comparison to a traditional model-based reconstruction approach that more strongly relies on assumptions and proxy variables for the spatial allocation and land change trends.

Chapter 4 explored to what extent historic land cover/use reconstructions underestimate land cover/use changes in Europe for the 1900–2010 period by accounting for net changes only. Available historic land-change data were empirically analysed for differences in quantities between gross and net changes. The empirical results of gross change quantities were applied in a spatially explicit reconstruction of historic land change to reconstruct gross changes for Europe back to 1900. Besides, a land-change reconstruction that only accounted for net changes for comparison was created. The two model outputs were compared with five commonly used global reconstructions for the same period and area. The gross change reconstruction led in total to twice the area change of net changes. All global reconstructions used for comparison estimated fewer changes than the gross change reconstruction.

Chapter 5 investigated to what extent historic gross land changes lead to differences in continental carbon flux estimations compared to net land changes. Historic changes of carbon in soils and vegetation in Europe for the period 1950 to 2010 were assessed, while accounting for legacy effects and gross change dynamics with decadal time steps at 1 km spatial resolution. A net land change assessment was performed for comparison to analyse the implications using gross land change data. For areas that were in both reconstructions subject to land changes (35% of total area) the differences in carbon fluxes were about 68%, and highest over forested areas. Overall for Europe the difference between accounting for either gross or net land changes led to 7% difference (up to 11% per decade) in carbon fluxes and systematically higher fluxes for gross land change data as compared to net land change data.

The research conducted in this thesis contributes to the improvement on historic land cover/use reconstructions and gives a harmonized, consistent ‘bigger picture’ of Europe’s land history with high spatial resolution.

Samenvatting

De bevolking in Europa is bijna verdubbeld in iets meer dan 100 jaar. De bijbehorende behoefte aan voedsel, kleding, drinkwater en onderdak heeft geleid tot een enorme reorganisatie van het Europese landschap en het gebruik ervan. Deze veranderingen in landbedekking en -gebruik hebben verstrekkende gevolgen voor vele ecosysteemprocessen die direct of indirect het klimaat aansturen op continentale en mondiale schaal. Verschillende vormen van veranderingen in landgebruik leiden tot verschillende veranderingen in de koolstofvoorraad. Voorbeelden zijn snelle veranderingen in koolstofvoorraad als gevolg van ontbossing of een vertraagde verandering in koolstofvoorraad als gevolg van een lange termijn opname van koolstof in (her)beboste gebieden. Deze vertraging van broeikasgasfluxen vereist het bepalen van veranderingen in landgebruik nu en in het verleden. Om de fluxen ten gevolge van huidige en vroegere veranderingen in landgebruik vast te stellen, zijn gegevens of modelmatige reconstructies van historische landbedekking en -gebruik nodig. Historische landbedekking en -gebruik gegevens als input voor historische landreconstructies zijn versnipperd, moeilijk te verkrijgen (copyright, geheimhoudingsstatus, toegankelijkheid, taalbarrières), moeilijk te harmoniseren en moeilijk te vergelijken. Dit gebrek aan beschikbare gegevens beperkt evaluaties van historische landveranderingen, vooral op een grote schaal. Veel reconstructies van continentale tot mondiale historische landbedekking en -gebruik bieden weinig detail in dynamiek van veranderingen, hebben een nogal grove ruimtelijke resolutie en reconstrueren slechts een paar klassen in landbedekking en -gebruik. Bovendien beschouwen de meeste reconstructies alleen de netto verschillen in oppervlakte tussen twee tijdstippen (netto veranderingen) in plaats van rekening te houden met alle toenames en afnames in oppervlakte (bruto veranderingen), hetgeen leidt tot een ernstige onderschatting van de oppervlakte die aan verandering onderhevig is geweest.

Dit onderzoek richtte zich op het reconstrueren van historische Europese landbedekking en -gebruik en de veranderingen over de periode 1900-2010, waarbij een aantal van de tekortkomingen van eerdere onderzoeken werden aangepakt. De belangrijkste doelstelling van dit proefschrift was om nieuwe reconstructiemethoden te verkennen die het ruimtelijke en temporele detail verbeteren en de onzekerheid in de ramingen op continentaal niveau verminderen door beter gebruik te maken van beschikbare gegevensbronnen. Het gebruik van beschikbare historische gegevens als invoer voor de reconstructie is geëvalueerd. Het voornaamste doel werd bereikt door een volledige weergave van de bruto landveranderingen op continentale schaal te geven, om zodoende alle belangrijke landveranderingsprocessen en hun dynamiek in Europa gedurende de afgelopen eeuw vast te leggen. In dit proefschrift werden ook de gevolgen van de dynamiek in die veranderingen op het milieu en op biogeochemisch onderzoek, zoals onderzoek naar klimaatverandering, onderzocht.

In hoofdstuk 2 is de combinatie van verschillende gegevensbronnen, meer gedetailleerde modelleringstechnieken en de integratie van verschillende soorten landconversie onderzocht om nauwkeurige, hoge resolutie historische gegevens over landveranderingen voor Europa te creëren geschikt voor de behoeften van broeikasgas- en klimaatschattingen. Een methode is gepresenteerd om historische netto landveranderingen op consistente wijze voor 1 km ruimtelijke resolutie voor vijf IPCC landcategorieën (bebouwing, akkerland, grasland, bos en overig land) te verwerken terug tot het jaar 1950 voor de EU27 plus Zwitserland. Bestaande geharmoniseerde landbedekking en -gebruik gegevens uit statistieken en remote sensing zijn intensief gebruikt om de reconstructie te voeden.

Hoofdstuk 3 analyseerde hoe historische statistieken uit encyclopedieën en oude topografische kaarten de nauwkeurigheid en de weergave van landbedekking en -gebruik en de veranderingen daarvan kan verbeteren in historische reconstructies. Deze studie maakte gebruik van historische statistieken en oude topografische kaarten om de toegevoegde waarde voor modelgebaseerde reconstructies van historische landbedekking en -gebruik aan te tonen voor Centraal Europa terug tot 1900. De toegevoegde waarde is geëvalueerd door het uitvoeren van een reconstructie met en zonder de historische informatie. De studie toonde aan dat een gegevens-gestuurde reconstructie van historische landbedekking en -gebruik de modelnauwkeurigheid verbeterde in vergelijking met een traditionele model-gebaseerde reconstructie die meer is gebaseerd op veronderstellingen en proxy-variabelen voor de ruimtelijke toedeling en trends in landverandering.

Hoofdstuk 4 onderzocht in hoeverre de historische landbedekking en -gebruik reconstructies de veranderingen in landbedekking en -gebruik in Europa in de periode 1900-2010 onderschatten door alleen met de netto veranderingen rekening te houden. Beschikbare historische gegevens over landveranderingen zijn empirisch geanalyseerd op verschillen tussen bruto en netto veranderingen. De empirische resultaten voor bruto veranderingen werden in een ruimtelijk expliciete reconstructie van historische landveranderingen toegepast om bruto veranderingen voor Europa terug tot 1900 te reconstrueren. Ter vergelijk is een reconstructie van landveranderingen gemaakt die alleen met netto veranderingen rekening hield. De twee modelresultaten werden vergeleken met vijf veelgebruikte mondiale reconstructies voor dezelfde periode en hetzelfde gebied. De reconstructie van bruto veranderingen leidde in totaal tot tweemaal de oppervlakte aan veranderingen in vergelijking met die van netto veranderingen. Alle in deze vergelijking gebruikte mondiale reconstructies gaven minder veranderingen te zien dan de reconstructie met bruto veranderingen.

Hoofdstuk 5 onderzocht in hoeverre de historische bruto landveranderingen tot verschillen in schattingen van de continentale koolstofflux leiden ten opzichte van netto landveranderingen. Historische veranderingen van koolstof in de bodem en in de vegetatie in Europa gedurende de periode 1950-2010 zijn bepaald, terwijl rekening gehouden is met effecten van een erfenis uit het verleden en met de dynamiek van bruto veranderingen, voor tijdstappen van een decade en een ruimtelijke resolutie van 1 km. Een bepaling van netto landveranderingen is uitgevoerd ter vergelijking om de implicaties van het gebruik van gegevens over bruto landveranderingen te analyseren. Voor gebieden die in beide reconstructies landveranderingen ondergingen (35% van de totale oppervlakte) waren de verschillen in koolstoffluxen ongeveer 68%, waarbij ze het hoogst waren in beboste gebieden. Over het algemeen leidde het verschil tussen het rekenen met bruto of netto landveranderingen tot 7% verschil (tot 11% per decade) in koolstoffluxen voor Europa. De fluxen waren systematisch hoger voor gegevens met bruto landveranderingen dan met netto landveranderingen.

Het onderzoek dat in dit proefschrift is uitgevoerd draagt bij aan de verbetering van reconstructies van historische landbedekking en -gebruik en geeft een geharmoniseerd, consistent 'groter plaatje' van de geschiedenis van Europa’s landbedekking met een hoge ruimtelijke resolutie.

Zusammenfassung

In etwas mehr als 100 Jahren hat sich die Bevölkerung in Europa beinahe verdoppelt. Die damit verbundenen Bedürfnisse nach Essen, Kleidung, Trinkwasser und Zuflucht haben zu einer gewaltigen Neuordnung der Europäischen Landschaft und ihrer Nutzung geführt. Diese Landbedeckungs- und Landnutzungsveränderungen haben weitreichende Konsequenzen für viele Ökosystemprozesse, welche direkt oder indirekt das Klima auf kontinentaler und globaler Ebene beeinflussen. Unterschiedliche Arten von Landveränderungen führen zu unterschiedlichen Veränderungen in Kohlenstoffspeichern. Abholzung, zum Beispiel, führt zur schlagartigen Veränderung der Kohlenstoffspeicherung eines Waldes, während Wiederaufforstung zu einer langsamen Aufnahme von Kohlenstoff über lange Zeiträume führt. Diese Zeitverzögerung von Treibhausgasflüssen verlangt eine Berücksichtigung der vergangenen und gegenwärtigen Landveränderungsdynamiken. Um die vergangenen und gegenwärtigen Landveränderungsdynamiken zu untersuchen, werden modellbasierte Rekonstruktionen der historischen Landnutzung und Landbedeckung benötigt. Historische Daten die als Input für historische Landrekonstruktionen dienen sind weitverstreut, schwierig zu beschaffen (z.B. wegen Urheberrechten, Geheimhaltung der Daten, Zugänglichkeit oder Sprachbarrieren), schwer zu harmonisieren und zu vergleichen. Dieses Nichtvorhandensein von verfügbaren Daten schränken historische Landveränderungsstudien stark ein, insbesondere Untersuchungen auf globaler Ebene. Viele kontinentale bis globale historische Landnutzungs- und Landbedeckungsrekonstruktionen bieten daher nur eine begrenzte Darstellung der Landveränderungsdynamiken, haben nur eine grobe räumliche Auflösung und rekonstruieren nur einige wenige Landnutzungs- und Landbedeckungsklassen. Des Weiteren berücksichtigen viele dieser Rekonstruktionen nur die Nettoveränderung zwischen zwei Zeitschnitten (Netto-Landveränderung), anstatt alle Flächenzugewinne und –verluste (Brutto-Landveränderung) mit einzubeziehen. Das führt zur ernsthaften Unterschätzung der Menge an Landfläche, die sich in der Vergangenheit verändert hat.

Die vorliegende Forschungsarbeit hatte zum Ziel die historische Landnutzung und Landbedeckung Europas für den Zeitraum von 1900 bis 2010 zu rekonstruieren und dabei die Defizite bisheriger Studien auszugleichen. Das Hauptanliegen dieser Doktorarbeit war es, neue Rekonstruktionsmethoden zu erforschen, welche den räumlichen und zeitlichen Detailgrad, sowie die Genauigkeit der Schätzungen auf kontinentaler Ebene verbessern, bei gleichzeitiger verbesserter Verwendung von verfügbaren Datenquellen. Die Verwendung von verfügbaren historischen Datensätzen, welche als Inputdaten für die historische Rekonstruktion dienten,

wurden evaluiert. Das Hauptanliegen dieser Doktorarbeit war eine vollständige Repräsentation der Brutto-Landveränderung auf kontinentaler Ebene, welche alle Hauptprozesse der Landveränderung und deren Dynamiken für Europa während des letzten Jahrhunderts abbildet. Die Doktorarbeit erforschte zudem die Implikationen der Landveränderungsprozesse und Dynamiken für Forschungen im Umwelt- und Biogeochemiebereich, wie etwa Forschungen zum Klimawandel.

In Kapitel 2 wurde die Kombination von verschiedenen Datenquellen, einer verbesserten Modellierungstechnik und die Integration von Landveränderungstypen untersucht, um eine akkurate, hochauflösende historische Rekonstruktion der Landveränderung von Europa zu erstellen, welche den Bedürfnissen laufender Treibhausgas- und Klimastudien entspricht. Es wurde eine Methode präsentiert, die es erlaubt die historische Netto-Landveränderung konsistent mit 1km räumlicher Auflösung für fünf IPCC Landveränderungskategorien (Siedlung, Ackerland, Grasland, Wald und anderes Land) die EU27 Staaten und die Schweiz bis in das Jahr 1950 zurück zu modellieren. Dabei wurden bestehende, harmonisierte Landveränderungsdaten von Volkszählungen, Landnutzungsstatistiken und Fernerkundungsdaten intensiv in das Rekonstruktionsmodell eingepflegt.

Kapitel 3 hat untersucht, wie historische Landnutzungsstatistiken von alten Enzyklopädien und topografischen Karten die Genauigkeit und Repräsentation von Landbedeckung und Landnutzung und deren Veränderung in historischen Landrekonstruktionsmodellen verbessern. Die Studie machte Gebrauch von diesen historischen Quellen, um deren Potenzial für die modellbasierte Rekonstruktion historischer Landveränderung am Beispiel Zentraleuropas für das Jahr 1900 zu demonstrieren. Der Mehrwert wurde evaluiert, indem eine Rekonstruktion mit und eine ohne historische Informationen durchgeführt wurde. Die Untersuchung konnte zeigen, dass eine datengetriebene Rekonstruktion die Modellgenauigkeit im Vergleich zu traditionellen modellbasierten Rekonstruktionsmethoden verbessert, welche stärker auf Annahmen und Näherungsvariablen für die räumliche Allokation und der Landveränderungstrends angewiesen sind.

Kapitel 4 hat erforscht in welchem Umfang bisherige historische Rekonstruktionen Landveränderung in Europa für die Periode 1900 bis 2010 unterschätzen, wenn sie nur Netto-Landveränderungen in Betracht ziehen. Verfügbare historische Landveränderungsdaten wurden auf ihre Unterschiede zwischen Netto- und Brutto-Landveränderungen hin empirisch analysiert. Die empirischen Ergebnisse der Brutto-Landveränderungen wurden dann in einer räumlich expliziten historischen Landnutzungsrekonstruktion angewandt, um die Brutto-Landveränderungen für Europa bis 1900 zurück zu berechnen. Zum Vergleich wurde eine Landrekonstruktion mit Netto-Landveränderung erstellt. Die zwei Modellergebnisse wurden mit fünf allgemein verwendeten globalen Landnutzungsrekonstruktionen für denselben Zeitraum und Fläche verglichen. Die Brutto-Landveränderungsrekonstruktion führte zu doppelt so viel

Flächenveränderung als die Nettorekonstruktion. Alle globalen Rekonstruktionen die zum Vergleich genommen wurden, schätzten weniger Veränderungen als die Bruttorekonstruktion.

Kapitel 5 untersuchte inwieweit sich historische Brutto-Landveränderung in ihrem Ausmaß auf den kontinentalen Kohlenstofffluss unterscheidet, verglichen mit Netto-Landveränderung. Historische Veränderungen von Kohlenstoff in Böden und Vegetation in Europa wurden für die Periode 1950 bis 2010 untersucht, wobei Langzeithinterlassenschaften von Kohlenstoff und Brutto-Landveränderungen in 10 Jahres Intervallen bei 1km räumlicher Auflösung berücksichtigt wurden. Eine Analyse zur Netto-Landveränderung wurde zum Vergleich angefertigt, um die Implikationen der Brutto-Landveränderungen zu bestimmen. Für Flächen, welche in beiden Rekonstruktionen Landveränderungen unterlagen (35% der Gesamtfläche) haben die Unterschiede in den Kohlenstoffflüssen 68% betragen, wobei jene auf Forstflächen am größten waren. Insgesamt machte der Unterschied für gesamt Europa rund 7% aus (bis zu 11% pro Jahrzehnt) und die Kohlenstoffflüsse waren systematisch höher für Brutto-Landveränderungen.

Die Forschung dieser Doktorarbeit trägt zur Verbesserung der historischen Landnutzungsrekonstruktion bei und gibt ein harmonisiertes, konsistentes Gesamtbild für Europas Landnutzungsgeschichte in einer hohen räumlichen Auflösung.

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Richard
Wageningen, 30-08-2015

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Short biography

Richard Fuchs was born in Weimar, Germany, on August 11th, 1982. He followed primary and secondary school in Weimar. His high school he finished with medium grades in geography, although he liked this subject a lot. Media systems was his first study at the Bauhaus University, Weimar. For a very long time Richard believed that his personal future would be within media and arts/design. However, after two years of study Richard realized that this study was not his passion and that he couldn't see any perspective for him within that field of work.

Richard started a second try, this time a bachelor in geography at the Friedrich Schiller University, Jena (Germany). Richard gained experience throughout several work visits at the German Aerospace Center (DLR), Oberpfaffenhofen where he worked as remote sensing specialist. His bachelor thesis was about "Analysis of the spatial, spectral and temporal variability with SPOT 5 and IRS-LISS-III Data in Khorezm, Uzbekistan" which he passed at the German Aerospace Centre (DLR), Oberpfaffenhofen (Germany).

His bachelor was followed by a master study in Geoinformatics and Remote Sensing at the Friedrich Schiller University, Jena (Germany). Richard spent some time of his master study as visiting scientist at the University of Leicester under supervision of Heiko Balzter in Leicester (United Kingdom). There he processed radar time series to monitor the regrowth of vegetation after disturbance in peatlands of Indonesia. His master thesis under supervision of Martin Herold was entitled: "Detecting European-wide land-use changes from AVHRR GIMMS data using spatial-temporal trend analysis and seasonal extraction of phenologic parameters – a feasibility study"

In 2010 Richard joined the Laboratory of Geo-information Science and Remote sensing of Wageningen University to do his PhD entitled: "A data-driven reconstruction of historic land cover/use change of Europe for the period 1900 to 2010"for which he developed the reconstruction model HILDA. His PhD was funded by the FP7 project Greenhouse Gas-Europe (Grant No. 244122) (http://www.ghg-europe.eu/). Throughout his PhD Richard published four peer reviewed articles, gave plenty presentations at international workshops, conferences and symposia. In December 2014 his work was picked up by international newspapers and debated on various social media platforms.

Richard's research interests are related to historic land cover/use modelling, with emphasis on dynamics and pathways of land changes. This includes socio-economic, political and climatic reasons and impacts of land changes. His research is also strongly connected to many environmental, biogeochemical and ecology topics, such as climate change

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the 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 (6 ECTS)

- Monitoring and estimation of land use changes associated with greenhouse gas emissions for Europe from 1900-2010

Writing of project proposal (4.5 ECTS)

- Monitoring and estimation of land use changes associated with greenhouse gas emissions for Europe from 1900-2010

Post-graduate courses (3.6 ECTS)

- Summer school DeGlind: greenhouse gas emissions from rural activities; SENSE, Wageningen en Klimaat voor ruimte (2010)
- IALE Summer school: changing European landscapes; IALE Europe, Manchester, UK (2013)
- Entrepreneurship in and outside science; Start Centre of Entrepreneurship, Wageningen , NL (2014)

Invited review of (unpublished) journal manuscript (3 ECTS)

- International Journal of Geographical Information Science: simple and effective: using basic GIS analysis tools for revealing complex spatial temporal changes of particular (2014)
- Applied Geography: transformation of landscape structure in the view of analysis of land cover changes: case study (2015)
- Land Use Policy: Transitions in European land management regimes between 1800 and 2010

Competence strengthening / skills courses (1.5 ECTS)

- Scientific writing course; GHG-Europe, Braunschweig, DE 92011)
- IALE Summer school: paper writing sessions; IAL Europe, Manchester, UK (2013)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)

- PE&RC PhD Weekend (2011)
- PE&RC Day (2011)

Discussion groups / local seminars / other scientific meetings (9.5 ECTS)

- Climate change & soil-water-atmosphere interactions; CSI, Wageningen, NL (2010-2014)
- Doc-Kolloq; Jena, DE (2010-2014)
- Workshop: forest management intensities; Ede, NL (2014)
- Workshop: integrating earth observation data and the description of land management practices into global carbon cycle models; International Space Science Institute, Bern, CH (2014, 2015)

International symposia, workshops and conferences (14.2 ECTS)

- Annual meetings of GHG Europe project; Orvieto, IT (2010-2013)
- COCOS; Braunschweig, DE (2011)
- EGU; Vienna, AT (2013)
- IMECS; Amsterdam, NL (2013)
- Global land cover meeting; Berlin, DE (2014)
- EARSel; NASA meeting, Berlin, DE (2014)

Lecturing / supervision of practical's / tutorials (2.4 ECTS)

- GIS For society: story maps (2014)
- RS & GIS Integration course (2014)
- Story maps: communicating and promoting GIS information (2014, 2015)

Supervision of MSc student

- Harmonization, validation and evaluation of land use products