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Exploring long-term trends in land use change and aboveground human appropriation of net primary production in nine European countries

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ABSTRACT

Profound changes in land use occurred during the last century in Europe, driven by growing population, changes in affluence, and technological innovation. To capture and understand these changes, we compiled a consistent dataset on the distribution of land-use types and biomass extraction for nine European countries (Albania, Austria, Denmark, Germany, Italy, the Netherlands, Romania, Sweden, and the United Kingdom) since the late 19th to early 20th century, when national statistical publications became available. We then calculated a range of indicators within the "human appropriation of net primary production" (HANPP) framework for the nine countries and for the sum of all countries on a yearly basis from 1902 to 2003. We find that cropland and grazing land contracted in all countries except Albania in the observed period, while forestland increased. Crop yields increased in all countries, most strongly during the second half of the 20th century. In some countries, biomass extraction on grazing lands increased to a similar extent. Overall, HANPP was high but declined slightly from 63% of the net primary production of potential vegetation in 1902 to 55% in 2003. This is the result of increasing crop yields on shrinking cropland and grazing land, which was only partly offset by increasing biomass extraction on expanding forests and by expanding settlement areas. HANPP trends on croplands were mostly uniform across countries, but differed substantially on grazing lands. While political differences, *e.g.*, between communist and capitalist countries, did not directly affect HANPP dynamics, economic and population growth were related to increases in biomass extraction for long periods of time in much of the sample, and only in recent decades did the collapse of the Eastern Block's Comecon market, EU agricultural policy, and world market developments coincide with a stagnation of biomass extraction.

1. Introduction

Land use has changed profoundly in the past centuries. Among other factors, growing world population and rising demand for biomass have led to both land-cover change and intensification of land use (Foley et al., 2005; Lambin et al., 2001). The decline of biodiversity and degradation of ecosystem services are among the most pervasive consequences of these developments (Millennium Ecosystem Assessment, 2005). Temporal trends of land-use change have been empirically and conceptually described dominantly by focussing on changes in the area extent of particular land-use types. The "forest transition" (Mather, 1992; Meyfroidt and Lambin, 2011; Rudel et al., 2005) has become a prominent concept based on the empirical observation that forest areas expand in many parts of the world, particularly in industrialized regions. Similarly, studies on

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changes in area extent have shown how croplands expanded globally over the last centuries and retracted recently in some world regions (Klein Goldewijk, 2001; Ramankutty and Foley, 1999). While the area extent of particular land-use types is rather straightforward to assess, the question how land-use intensity changed in the past centuries is more difficult to address. The idea of a "land-use transition" (*e.g.*, DeFries et al., 2004; Foley et al., 2005) considers land-use intensification as part of long-term land-use change. However, long-term changes in land-use intensity remain hard to operationalize, as no clear-cut consensus on the definition of land-use intensity has been reached and several definitions focusing on various aspects of land-use intensity coexist (Erb et al., 2013; Kuemmerle et al., 2013). A sound understanding of changes in land-use intensity is however a prerequisite for policy toward sustainable land use (Rounsevell et al., 2012).

One approach to analyzing the effects of land-use change on ecosystems in an integrated way is the methodological framework of "Human appropriation of net primary production" (HANPP, Haberl et al., 2014; Vitousek et al., 1986; Wright, 1990). By measuring the combined effect of land conversion and land-based production (*i.e.*, harvest) on the net primary productivity (NPP) of ecosystems, HANPP assesses the total impact of human activity on trophic energy flows in ecosystems (Haberl et al., 2014; Vitousek et al., 1986; Wright, 1990). The framework, thus, combines information on (1) extent of particular land-use types (*e.g.*, cropland, grazing land, forests), (2) intensity of biomass extraction from ecosystems, and (3) human-induced changes in systemic ecosystem characteristics (or "system-level intensity", see Erb et al., (2013)). HANPP is an integrated socio-ecological indicator (Haberl et al., 2014), and has been shown to correlate negatively with biodiversity (Haberl et al., 2005). As any indicator set, the HANPP framework does not encompass all aspects of environmental change. For example, the environmental impacts induced by highly intensive agriculture (*e.g.*, the excessive application of mineral fertilizer, the plantation of genetically modified organisms, or cultivation in greenhouses) are not captured directly in HANPP accounts, which focus on biomass flows only.

Empirical studies have operationalized the HANPP framework at various temporal and spatial scales. At the global scale, HANPP currently amounts to c. 24% of net primary production (NPP) (Haberl et al., 2007; Imhoff et al., 2004), and has doubled since the early 20th century (Krausmann et al., 2013). Strong regional variations exist, both in terms of current HANPP patterns (Erb et al., 2007) and historical trends. Europe is one of the world regions with a particularly long and well-documented history of land use (Jepsen et al., 2015 under review), characterized by relatively high HANPP values, as a number of national HANPP case studies document (*e.g.*, Austria (Krausmann, 2001), the United Kingdom (Musel, 2009), Spain (Schwarzlmüller, 2009), Hungary (Kohlheb and Krausmann, 2009), the Czech Republic (Vačkář and Orlitová, 2011), Italy (Niedertscheider and Erb, 2014) and Germany (Niedertscheider et al., 2014)). While important efforts have been made in recent years to harmonize the methodology, differences in terms of both accounting methods and analytical system boundaries of HANPP accounts still exist (Haberl et al., 2014, 2007), hampering comparability between studies. Previous comparisons of historical HANPP trends between countries were, due to these limitations, restricted to descriptive analyses (Krausmann et al., 2012).

The study presented here aims at overcoming this constraint by introducing a consistent data set of long-term trends in aboveground HANPP (*i.e.*, HANPP related to aboveground processes, disregarding *e.g.*, soil dynamics) in nine European countries based on long-term national statistical records: Albania, Austria, Denmark, Germany, Italy, the Netherlands, Romania, Sweden, and the United Kingdom. Making use of some previously-published HANPP data sets (Krausmann, 2001; Musel, 2009; Niedertscheider et al., 2014; Niedertscheider and Erb, 2014), we follow the same methodological approach for all case studies.

Because of its consistency, the here presented data set allows for systematic comparison of long-term trends in land use change. The sample size provides a basis for exploring the degree of variation in land use patterns and trends between countries, which is operationalized in a formalized analytical investigation. In an index decomposition analysis, we disentangle the HANPP-effects of changes in extent of land-use types on the one hand and land-use intensification on the other hand, in the course of the past century. Such decomposition analyses are often used in research on long-term changes in energy use or CO_2-emissions to identify the importance of different drivers of temporal change or regional differences (Ang and Zhang, 2000; Xu and Ang, 2013). Decomposition analyses have also been applied to investigate drivers of land-use change (*e.g.*, Kastner et al., 2012). However, decomposition analyses have, to our knowledge, never been used in connection with HANPP. Encompassing a time frame of up to 180 years, the study aims at contributing to an advancement of our understanding of long-term land-use changes and their underlying drivers in the context of long-term socio-ecological research (LTSER; (Haberl et al., 2006; Singh et al., 2013)).

While Europe is the world region in which most HANPP studies have been performed in the past, we argue that it is also a particularly interesting region to study for two reasons. (1) European HANPP levels are high in comparison to the global average (Haberl et al., 2007; Krausmann et al., 2013), hence, deserving a better understanding of their emergence and current trends, and (2) exceptionally good data exist for European land-use history in the form of national land-use statistics, allowing a long-term investigation covering not just recent decades, but one to two centuries. This enables us to trace the effects of megatrends, such as industrialization on the land-use system at the national scale and in a comparative approach. Based on the data sample of nine European countries, the paper empirically and analytically addresses the following research questions: (1) Which land-use changes can we observe in the course of the past two centuries, and how do these affect changes in HANPP? (2) Which underlying processes determine changes in HANPP: changes in extent of land-use types, changes in biomass extraction, or dynamics of land-use efficiency? We discuss our findings in view of the different biogeographic and socio-economic conditions of the different countries.

2. Data and methods

2.1. Country sample

The sample of nine European countries (Fig. 1) was chosen based on data availability in the network of co-workers with the aim at representing a North–South transect through Central Europe (from Sweden to Italy), and a good gradient from Western to Eastern Europe (from the United Kingdom to Romania). Fig. 1 presents a map of the country sample providing information on the first year of data availability.

The dataset includes several (social) market economies and two formerly communist countries (Romania and Albania) and covers wide ecological and socio-economic gradients within Europe (Table 1): In terms of population totals, the largest country (Germany) exceeded the smallest country (Albania) by a factor larger than 20 in the year 2005. In terms of area extent, the range is slightly smaller, with the smallest country (again Albania) making up for less than 7% of the area of the largest country (Sweden). Population density was highest in the Netherlands in the early 21st century (392 cap/km^2) and lowest in Sweden (20 cap/km^2), the only country in the sample with population density below