Global Environmental Change 28 (2014) 98–108

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Exploring the effects of drastic institutional and socio-economic changes on land system dynamics in Germany between 1883 and 2007

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ARTICLE INFO

Article history:
Received 20 January 2014
Received in revised form 23 May 2014
Accepted 18 June 2014
Available online 16 July 2014

Keywords:
Germany
Land use change
Institutional change
Political change
HANPP
Land-use intensification

ABSTRACT

Long-term studies of land system change can help providing insights into the relative importance of underlying drivers of change. Here, we analyze land system change in Germany for the period 1883–2007 to trace the effect of drastic socio-economic and institutional changes on land system dynamics. Germany is an especially interesting case study due to fundamentally changing economic and institutional conditions: the two World Wars, the separation into East and West Germany, the accession to the European Union, and Germany's reunification. We employed the Human Appropriation of Net Primary Production (HANPP) framework to comprehensively study long-term land system dynamics in the context of these events. HANPP quantifies biomass harvests and land-use-related changes in ecosystem productivity. By comparing these flows to the potential productivity of ecosystems, HANPP allows to consistently assess land cover changes as well as changes in land use intensity. Our results show that biomass harvest steadily increased while productivity losses declined from 1883 to 2007, leading to a decline in HANPP from around 75%–65% of the potential productivity. At the same time, decreasing agricultural areas allowed for forest regrowth. Overall, land system change in Germany was surprisingly gradual, indicating high resilience to the drastic socio-economic and institutional shifts that occurred during the last 125 years. We found strikingly similar land system trajectories in East and West Germany during the time of separation (1945–1989), despite the contrasting institutional settings and economic paradigms. Conversely, the German reunification sparked a fundamental and rapid shift in former East Germany's land system, leading to altered levels of production, land use intensity and land use efficiency. Gradual and continuous land use intensification, a result of industrialization and economic optimization of land use, was the dominant trend throughout the observed period, apparently overruling socio-economic framework conditions and land use policies.

1. Introduction

Land use has emerged as a major driver of global environmental change, with far-reaching effects on ecosystems, the services they provide, and biodiversity (Tilman, 1999; Bouwman et al., 2011; Matson et al., 1997). Transitioning to sustainable land systems that satisfy growing demands while avoiding the detrimental environmental and social outcomes of land use is one of the main challenges humankind faces in the coming decades (Foley et al., 2011). Meeting this challenge requires a better understanding of how and why land systems change.

A substantive body of literature suggests that land system change results from the collective impact of individuals' land use decisions. These decisions depend on a range of factors which operate and interact at different spatial and temporal scales (Lambin et al., 2001; McConnell and Keys, 2005; Geist et al., 2006; Lambin and Meyfroidt, 2011). The relative importance of these underlying drivers, however, is often unclear. A major reason for this is that drivers in complex systems are often intrinsically interlinked and tend to change in parallel, making attribution difficult (Lambin et al., 2001).

Much can be learned about land system dynamics from a historic perspective, particularly regarding the role of underlying drivers, which are often hard to quantify when focusing on short time periods (i.e., years to decades; Willis & Birks, 2006; Gaillard et al., 2010; Singh et al., 2013; Krausmann et al., 2013). Long-term studies are particularly powerful in assessing the relative

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http://dx.doi.org/10.1016/j.gloenvcha.2014.06.006
0959-3780/

importance of socio-economic, institutional and political drivers for land system change (Liu et al., 2007; Turner et al., 2007). Especially rapid socio-economic change, induced by technological innovations, institutional shifts, economic crisis, as well as by shock events such as wars, can prompt major reorganization of land systems (Lepers et al., 2005; Hecht & Saatchi, 2007; Kuemmerle et al., 2009; Hostert et al., 2011). Most studies assessing the impacts of such events, however, have focused on land conversions (e.g., deforestation) and short time periods (i.e., decades), mainly because reliable and more comprehensive long-term historic datasets of land system change and its underlying drivers are missing for most parts of the world (Singh et al., 2013). This results in an incomplete picture of land change, because land use intensification has played a key role in the past (Lambin and Meyfroidt, 2011; Ellis et al., 2011). Intensification of land use allowed for a decoupling between biomass production and agricultural expansion and thus contributed to reducing conversion of natural areas into croplands (FAO, 2013). Sustainable intensification is also expected to play an important role in the future (Foley et al., 2011). However, large knowledge gaps persist with regard to intensification pathways and their drivers, and long-term studies of land system dynamics that assess the drivers of both area changes in broad land uses and intensity changes within these categories remain scarce (Erb et al., 2013; Kuemmerle et al., 2013).

The 'Human Appropriation of Net Primary Production' (HANPP, Haberl et al., 2007; Martinez-Alier, 2004) is excellently suited for analyzing long term changes in land systems, and to explore the relative importance of land cover change versus land use intensification (Erb et al., 2013; Kuemmerle et al., 2013; Krausmann et al., 2013). HANPP quantifies the share of Net Primary Production (NPP) appropriated through the three main processes of human land use: (1) productivity changes associated with land conversions (e.g., conversion of forests to croplands), (2) productivity changes through changes in management intensity (e.g., fertilization and irrigation) or through land degradation, and (3) direct harvests through agriculture, forestry and livestock grazing. NPP refers to the annual amount of biomass produced by photosynthetic organisms and serves as a benchmark for ecosystem productivity (Roy et al., 2001). HANPP addresses both socio-economic as well as ecological aspects of land change, because it explicitly allows for quantifying societal biomass consumption patterns and management interventions, while measuring the amount of productivity remaining in ecosystems after land use. In comparing potential NPP to current NPP flows, HANPP controls for bioclimatic and environmental disparities when comparing land system change across heterogeneous areas, which renders it a suitable indictor for analyzing drivers of land system change (Erb et al., 2009). Finally, a central feature of HANPP is its usefulness as an integrated indicator of land use intensification, because HANPP combines information on output intensification (i.e., yields) with system-level outcomes of land use (e.g., changes in productivity, Erb et al., 2013; Kuemmerle et al., 2013).

Here, we apply the HANPP framework to analyze land system change in Germany over the past 125 years. Germany provides an interesting example of a country in which drastic political and institutional changes affected land systems. Germany experienced several episodes of rapid reorganization of its institutional and socio-economic setup, encompassing the transition from the German Empire to the Weimar Republic after World War I, the rise and fall of the German Reich, the separation into West Germany and East Germany after World War II, the establishment of the European Economic Community (EEC) in 1957 with West Germany as a founding member, the accession to the European Union, and finally the reunification in 1990. The political separation from 1949 to 1990 into socialist East Germany with a centralized planning economy and West Germany with a capitalistic, market-oriented economy is particularly interesting in this context. Because history, culture, and environmental conditions in both countries are relatively homogenous, the Germany separation can be interpreted as a unique natural experiment for studying the influence of two starkly contrasting political ideologies, economic paradigms, and institutional setups on land system change. Yet, to our knowledge, no study has so far comprehensively assessed long-term land system change in Germany to understand how rapid institutional and socio-economic changes, and specifically the separation and reunification of Germany, affected land system dynamics.

Our overarching goal was to analyze long-term land system dynamics, including both land use conversions and intensity changes, in Germany with the HANPP framework. We used our results to assess the impact of Germany's separation and reunification on land change and to explore the relative importance of institutional and socio-economic factors versus other factors of land system change. Specifically, we ask three main research questions:

1. How did land systems change in Germany during the last 125 years in terms of land cover, land use intensity and HANPP?
2. What was the impact of the drastic institutional and socio-economic changes on land system change since 1883?
3. How did the contrasting institutional and socio-economic setup during the separation into East and West Germany and the reunification affect land system dynamics?

2. Materials and methods

2.1. Data

We gathered statistical data on land cover and land use for the time period 1883–2007. Datasets were collected at sub-national level before World War II (e.g., in the German Empire) and between 1991 and 2007. In addition, we gathered data at national level between 1950 and 1989, allowing us to aggregate datasets to the current (2013) territorial boundaries and thus accounting for political border changes that occurred during our study period. Between 1950 and 1989 (German separation), we collected data separately for East and West Germany. All primary data were taken from the official German national statistics (Kaiserliches Statistisches Amt, 1884–1917; StRA, 1918–1948; Destatis 1950–2013; SZS, 1950–1989) and were collected in 5-year intervals. Some historical statistics were available from secondary literature, such as forestry harvest before 1938 (Hoffmann et al., 1965), cereal production, forestry harvest, land cover (Franzmann, 2012a, 2012b; Franzmann, 2013), as well as population and labor statistics between 1950 and 1989 (Fritz, 2001; Sensch, 2004a, 2004b). We did not consider the period 1936–1950 (World War II and aftermath) and 1990–1991 due to data deficiencies.

The four main datasets to derive consistent time series of land system change and biomass flows can be summarized as follows (Table 1; all primary data sources and definitions of individual sub-categories are reported in the text and Figs. S1–S3 of the Supporting Information).

1. Data on land use change for five land use categories (cropland, forestland, grassland, settlement areas, other land), expressed in km^2. The category "other land" includes inland water bodies, wetlands, permanent snow and ice, permanent rocks, and other unused land.
2. The amount of biomass harvest on all land use classes. Primary crop and forestry harvest was available in the national statistics,

Table 1
Data sets used in this study including categories and main data sources.

Data set	Categories	Data source and methods
1. Land use	Cropland, Grassland, Forest land, Settlement areas, Other land	Data from national statistics; supplemented with data from the literature (Franzmann, 2013; Hoffmann et al., 1965; Schöne, 2005)
2. Biomass harvest	Cropland: harvest of primary crops Grassland: harvest through foraging and grazing Forest land: wood harvest Settlement areas: harvest through gardening, etc.	Data from national statistics; supplemented with data from the literature (Hoffmann et al., 1965; Franzmann, 2012a; 2012b), and model assumptions (for grazed biomass and harvest on settlement areas)
4. Potential productivity (NPP_{pot})	NPP which would prevail without human land use, e.g. natural productivity for all land cover classes	Derived from outputs of the LPJ (Sitch et al., 2003)
5. Indicators of land system change	Input intensity: Nitrogen use/cropland/year, agricultural workforce/ agricultural land/year, Output intensity: cereal yields, $HANPP_{harv}$/km^2/year System level: HANPP % NPP_{pot}, HANPP/cap/year Integrated indicators: Nitrogen productivity (cropland harvest/kg nitrogen/ year), agricultural labor productivity ($HANPP_{harv}$/agricultural worker/year), HANPP efficiency ($HANPP_{harv}$/HANPP/year)	Derived from national statistics, secondary literature (Fritz, 2001; Sensch, 2004a, 2004b) and own calculations

while harvest on grassland (mowing or grazing by ruminant livestock) was modeled through a grazing gap approach (Krausmann et al., 2008, 2013; refer to Section 2.2). For settlement areas, harvest was assumed to be 50% of actual productivity (Haberl et al., 2007).

3. Potential NPP (NPP_{pot}) was derived from the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model, a process-based ecosystem model (Sitch et al., 2003). Based on gridded climate data, the LPJ approximates NPP levels of natural vegetation in gC/m^2/year considering no land use (Krausmann et al., 2013). Driven mainly by climate dynamics, the NPP_{pot} ranged between 286 and 368 gC/m^2/year during the observed period on the German territory. We used a share of 60% aboveground NPP to total NPP (Roy et al., 2001).
4. Indicators of land management were calculated by combining metrics of (a) input intensity, (b) output intensity and (c) system-level changes (Erb et al., 2013). Input intensity encompasses metrics for production inputs such as nitrogen consumption per cropland area and agricultural workforce per unit of agricultural land. Output intensity comprises cereal yields and harvested NPP per km^2. System-level metrics include HANPP as percentage of NPP_{pot} and HANPP per capita and year. The ratio between inputs and system level changes provides measures for the efficiency and intensity of land use. We approximate nitrogen productivity with the amount of cropland harvest per unit of nitrogen applied (Franzmann, 2013) to assess the efficiency of nitrogen application. We quantify labor productivity with the $HANPP_{harv}$ per agricultural worker to measure the efficiency of labor input per unit of harvested output. Finally, HANPP efficiency is measured as $HANPP_{harv}$ per unit of HANPP and it refers to the share of HANPP that is of direct societal use. High levels of HANPP efficiency indicate a large fraction of harvested HANPP, corresponding to low productivity losses associated with land use.

2.2. HANPP calculation

We calculated all HANPP indicators separately for the five land use categories described above. HANPP is calculated as the sum of (a) $HANPP_{harv}$, which consists of primary crop harvest and crop-residues and (b) indirect NPP changes through land conversion and land use change ($HANPP_{luc}$) (Fig. 1). A high HANPP indicates low NPP_{eco}, which is defined as the fraction of potential productivity left within ecosystems after land use. Hence, NPP_{eco} is the sole energy basis for all other heterotroph organisms (Haberl et al., 2007). As a consequence, high HANPP levels signal a high pressure on ecosystems.

$HANPP_{harv}$ not only includes primary harvest flows, which are typically reported in statistical inventories, but also secondary harvest flows (e.g., used and unused crop residues or wood felling losses). Cropland harvest reported in the statistics was converted into carbon units through biomass-specific water content ratios (Table S1) and by assuming a dry-matter carbon content of 50% (Haberl et al., 2007). The amount of crop residues of total plant biomass was calculated by multiplying primary crop harvest with crop specific harvest factors (Table S1), which were assumed to decrease during the 20th century owing to technological improvements. Wood biomass was converted into tons carbon by applying a wood density factor of 0.46 (tons dry-matter per m^3, Krausmann et al., 2008, 2013). To account for felling losses, we considered a recovery rate of 0.8 as well as a bark factor of 90% (ratio of below-bark to above-bark biomass, Krausmann et al., 2008, 2013). Harvest on grasslands consists of mowed biomass taken from the national statistical data sources as well as of grazed biomass. The latter was calculated as the difference between annual feed supply (market feed, forage production and used crop residues) and the sum of annual feed demand of all livestock species. Livestock statistics (animal

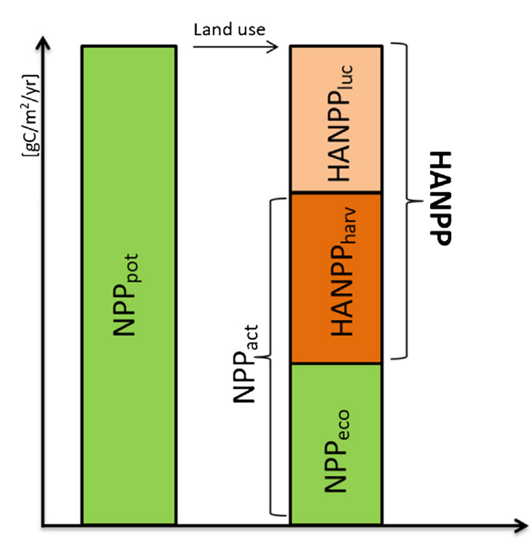

Fig. 1. Definition of HANPP. Through human land use potential productivity of natural ecosystems (NPP_{pot}) is converted into actual productivity. HANPP is defined the sum of indirect NPP losses associated with land use change ($HANPP_{luc}$ = difference between NPP_{pot} and NPP_{act}) and human harvest ($HANPP_{harv}$), or as the difference between potential NPP (NPP_{pot}) and the amount of NPP that remains in ecosystems after human harvest (NPP_{eco}).

numbers, meat, egg and milk production and forage amount) were taken from the national statistics, while animal-specific feed demand was calculated based on input/output efficiency factors (see Supporting Information for a detailed description).

NPP_{act} is defined as the sum of NPP_{eco} and $HANPP_{harv}$. NPP_{act} on croplands was extrapolated from biomass harvest using pre-harvest loss factors in order to account for biomass, which was destroyed during plant growth. These factors were assumed to decrease from 1.25 in 1900 to 1.14 in 2007 due to technological improvements (Krausmann et al., 2013). For grasslands, NPP_{act} was considered to correspond to 80% of NPP_{pot}, in years when modeled forage demand did not exceed NPP_{act} levels. For all other years, NPP_{act} was extrapolated from grassland harvest (mainly after WWI due to grassland intensification). On forest land, NPP_{act} was assumed to equal NPP_{pot}. For infrastructure areas, NPP_{act} was calculated as 1/3 of NPP_{pot}, assuming that 2/3 of these areas are sealed and the rest is covered by potential vegetation (Haberl et al., 2007).

$HANPP_{luc}$ was calculated as the difference between model-derived NPP_{pot} and NPP_{act}. Following this definition, land use intensification results in concomitant increases of $HANPP_{harv}$ and NPP_{act} (e.g., boosted productivity due to fertilizer application) and thus in an overall decline of HANPP (Erb et al., 2009; Krausmann et al., 2013).

2.3. Data quality

Issues of data availability and quality are a concern of any long term land-system change assessment (e.g. Erb et al., 2008, 2009). In our case, an exceptionally rich database was available that allowed to trace land use back close to the foundation of the German nation state in 1871. The abundance of statistical data improved throughout the observed period, in particular with regard to spatial and thematic resolution. Between 1883 and 2007, only minor data gaps in agricultural and forestry statistics prevail. For instance, for the period before WW II only national data were available for categories such as for forestry harvests (before 1945) or for the extent of fallow land and grasslands extent (before 1930). In such cases, national-level data for the German Empire were disaggregated to the current territorial boundaries according to area shares. Furthermore, the sum of fallow land and all crop areas reported in the statistics was lower than total arable land before 1927, indicating an under-reporting of cropland areas in the historical statistics (between 15% and 20% in the 1883–1940 period). In order to account for harvest on these croplands we applied the average yields of all documented crops to these areas.

In general terms, the robustness of land use and biomass harvest data from the statistical handbooks has been described as relatively high, due to the close links of biophysical data and economic, fiscal and strategic interests (Fischer-Kowalski et al., 2011). A general concern, however, relates to the reliability of data for East Germany during the socialist period 1945–1989 (Filer and Hanousek, 2002). These concerns mainly relate to trade data, whereas production data (e.g., agricultural production and land cover) is generally assumed to be of higher quality and relatively robust (Von der Lippe, 1996; Donda, 2000). According to Donda (2000), major data flaws are not to be expected because the central economic committee of former East Germany build the development of five-year plans on statistical data on agricultural production.

Data uncertainty may pertain nevertheless, in particular to land uses that are economically of minor importance. The calculation procedures which we follow here, however, have been developed to limit such uncertainties and to generate datasets that are comprehensive and free of double-counting (Erb et al., 2007, 2009). We achieve this, for instance, by providing closed-budget land accounts (full accounts that address 100% of the land surface) and consistent biomass flow accounts that integrate ecological (e.g. NPP) and socioeconomic (e.g. agricultural yields) flows in a manner that is consistent with the widely accepted Material Flow Accounting framework (MFA; Weisz et al., 2007). These procedures have been shown to allow for the identification of data gaps and the minimization of inconsistencies and so help to reduce data uncertainty (Krausmann et al., 2008). A particular uncertainty relates to the model-derived NPP_{pot}, due to the large knowledge gaps associated with the CO_2 fertilization effect (Krausmann et al., 2013). A sensitivity analysis of global HANPP trends, however, suggests that the HANPP accounting framework allows to generate robust time series results despite this uncertainty (Krausmann et al., 2013). Because our analyses used the best available data and these systematic consistency checks, we are confident that the overall results are robust, although minor uncertainties may remain for single elements of our assessment.

3. Results

3.1. Area changes in broad land use and land cover categories

Land use and land cover in Germany changed substantially, albeit gradually, over the last 125 years (Fig. 2a). Agricultural areas (the sum of cropland and grassland) decreased from 69% of the total territory of Germany in its current boundaries (245,000 km^2) in 1883 to 47% (168,000 km^2) in 2007. The extent of cropland and grassland dropped by 27% and 39%, respectively. A considerable share of former agricultural areas were converted to settlement areas, which grew more than fourfold during the study period from 3% or 11,000 km^2 in 1883 to 14% or 49,000 km^2 in 2007. Forest cover expanded from 27 to 30% and occupied 107,000 km^2 in 2007. "Other land" also increased markedly, from 7% to 12%, mainly due to agricultural abandonment (Fig. 2a).

In 1950, cropland accounted for 35% of the total land area in West Germany (Fig. 2b) and for 50% in East Germany (Fig. 2c). The reduction of cropland and grassland as well as the increase of urban areas and forest land was slightly more pronounced in West Germany where forest land increased by 9% between 1950 and 2007 compared to 6% in East Germany. However, the overall trends in land use and land cover between 1950 and 1989 in East and West Germany were very similar with pronounced decreases of agricultural land on either side of the Iron Curtain (Fig. 2b and c).

3.2. Changes in harvest and in HANPP

The total amount of harvested aboveground NPP in Germany almost doubled between 1883 and 2007 (Fig. 3a). Remarkably, biomass harvests increased continuously throughout this period, except for a small decline after World War II and after the reunification in 1990, respectively. Harvest on croplands was the largest contributor to total harvest, and the share of cropland harvest to total harvest increased from 43% in 1883 to 64% in 2007. Harvest on grasslands, the second largest contributor to HANPP, showed a peak between the mid-1970s and 1990 but was relatively constant otherwise. Wood harvest, in contrast, increased from ∼10 Mio tons carbon per year (tC/year) to ∼20 Mio tC/year within the study period. Generally, more biomass was harvested in West Germany than in East Germany (Fig. 3b and c) for all land use types, and in particular for grasslands, before the reunification. In contrast to steadily increasing harvests in West Germany until the reunification, harvests in East Germany stagnated until 1970, followed by a steep increase until 1985. Harvests declined starkly after reunification and dropped to the 1960 level, mainly due to declining harvests on grassland and cropland. Harvest levels

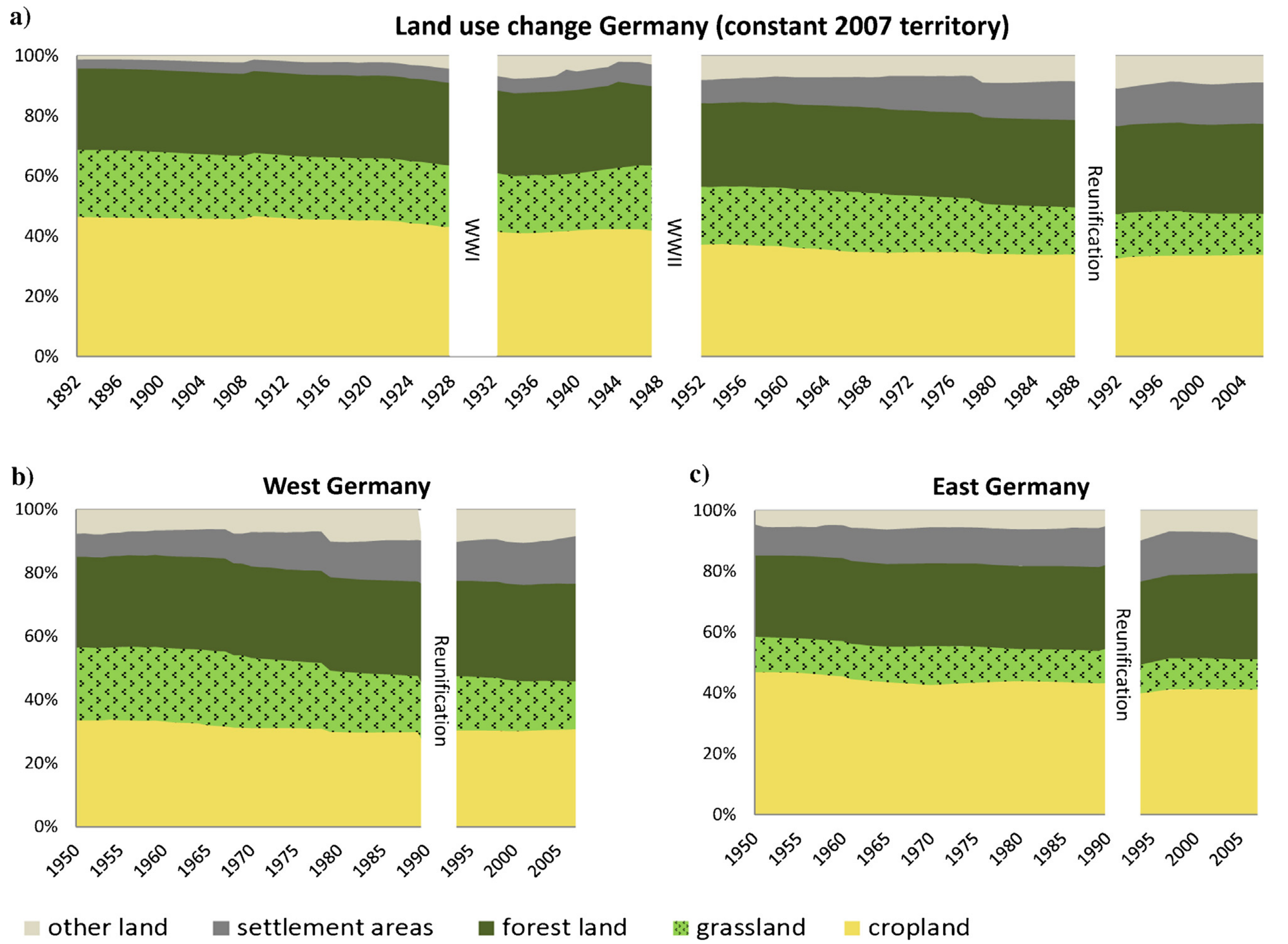

Fig. 2. Land use change as percentage of total territory (a) Germany in its 2007 borders, (b) West Germany in 1950-borders and (c) East Germany in 1950 borders.

subsequently recovered, but were still almost 20% below the level of the late 1980s in East Germany (Fig. 3c).

Land use and productivity changes had little effect on the absolute HANPP levels, which remained rather constant throughout the study period (HANPP in 1883 and in 2007 was close to 80 Mio tC/year, Fig. 4a). The highest HANPP occurred in 1908 (84 Mio tC/year) and the lowest in 1991 (64 Mio tC/year), following a sudden drop by 16% between 1989 and 1990. HANPP on cropland declined particularly during the inter-war period and remained constant after World War II. HANPP was stable on grassland until WW II but declined by more than 14% in the post-war years. One key difference between East and West Germany was the strong dominance of HANPP from cropland in East Germany (Fig. 4c), while HANPP on grassland and forests contributed a much larger share to total HANPP in West Germany (Fig. 4b). Decreases of grassland-induced HANPP in the West were compensated by increases in the contribution of settlement areas and forestry. The peaks of HANPP in East Germany at around 25 Mio tC/year in 1979 and again in 1986 are associated with high levels of NPP_{pot} (Fig. S1), because NPP_{act} did not show a similar increase. High NPP_{pot} translated into higher levels of productivity losses ($HANPP_{luc}$, i.e., the difference between NPP_{act} and NPP_{pot}) and therefore higher HANPP. Thus, these HANPP peaks were induced naturally as a result of changing suitability of biophysical conditions rather than due to land use changes.

Relative to NPP_{pot} and in per capita terms, HANPP declined gradually over the study period, with the most rapid decrease between World War I and 1950 (Fig. 5). HANPP per capita decreased by 60% from 1883 until the 1950s (i.e., from 2.3 tC/capita/year to around 0.9 tC/capita/year, Fig. 5), then stagnated until the reunification, which prompted a marked and sudden decrease (by 10%), after which the level quickly recovered to the post-WW II levels. HANPP efficiency (i.e., harvested NPP per unit of HANPP) continuously increased from 1883 to the mid-1970s, particularly following World War I. After 1970, HANPP efficiency became more volatile (Fig. 5). In 1883, one unit of HANPP was associated with 0.7 units of harvest, whereas this ratio increased to around 1.4 by 2005–2007. This increase was due to the reductions of productivity losses induced by land use intensification.

3.3. *Comparing trends in land use intensity changes between East and West Germany*

Most land use intensity indicators followed similar trajectories in East and West Germany from 1950 to 1989 (Fig. 6). Input, output and system level indicators were almost identical in terms of level and trends in both countries. This holds true in particular for $HANPP_{harv}/km^2$, cereal yields and HANPP in % of NPP_{pot}, with the exception of HANPP per capita. Input intensity diverged in the last decade before the reunification when nitrogen application rates in East Germany fell below and agricultural workforce input per unit land above the levels of West Germany (Fig. 6a and d). As a result, nitrogen productivity in West Germany was higher than in East Germany over almost the entire study period. Nitrogen productivity constantly declined since 1950 until reunification in West Germany but in East Germany the decline only commenced by

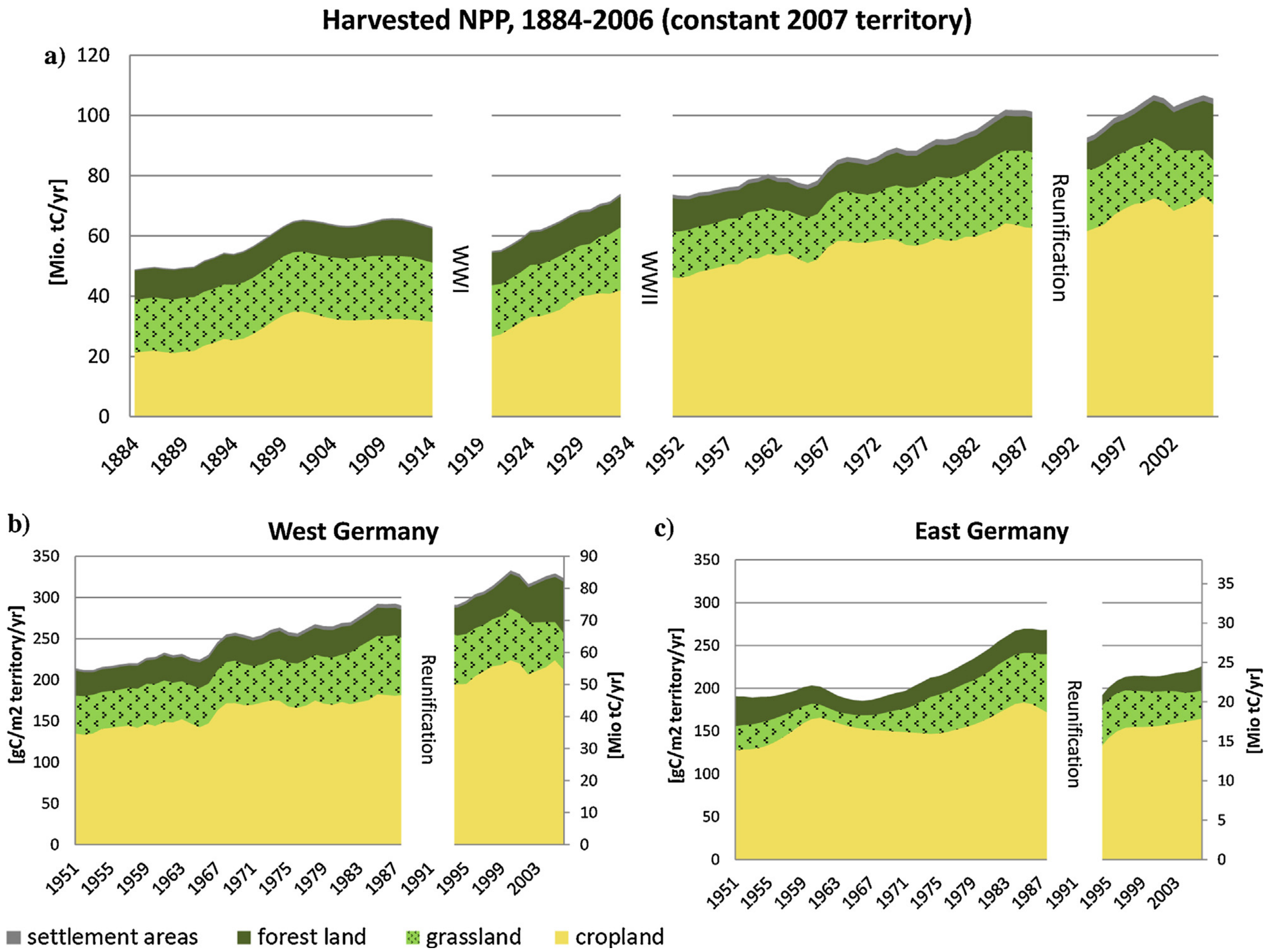

Fig. 3. $HANPP_{harv}$ per year [Mio tC/year] for each land use class in 3-year moving averages. (a) Germany in its 2007 borders, (b) West Germany in 1950-borders and (c) East Germany in 1950 borders; for reasons of comparability (b) and (c) are area corrected (tons carbon on each land use class divided by total territory); the right axis shows total values in Mio tons carbon per year.

the late-1960s. Likewise, agricultural labor productivity was substantially lower in East Germany compared to West Germany after the mid-1970s (Fig. 6h). Interestingly, HANPP was very similar in both parts of Germany throughout the study period but HANPP per capita was considerably and consistently lower in West Germany (Fig. 6c and f). Due to higher agricultural harvest per area, HANPP efficiency was higher in West Germany throughout the entire time period. (Fig. 6i).

The reunification brought about substantial changes and remarkably diverging trends between East and West Germany. Input intensity, e.g., nitrogen application, dropped to West German levels and output intensity, measured as cereal yields, declined below Western levels. As a result, nitrogen productivity was lower in the East (Fig. 6). A substantial part of the agricultural workforce was laid off after the collapse of the socialist system, resulting in a rapid increase of agricultural labor productivity ($HANPP_{harv}$ per unit of agricultural workforce, Fig. 6h) in East Germany, approaching West German levels in the 1990s (Fig. 6h). Finally, HANPP efficiency differed substantially, with increasing efficiency in West and decreasing efficiency in East Germany, reflecting decreasing biomass harvests in East Germany and increasing area efficiency in West Germany.

4. Discussion

Land use decisions and thus land use change are driven by a wide range of underlying causes. Yet, their relative importance often remains unclear as these drivers tend to change gradually when observed over shorter time periods, making attribution difficult. Here, we used Germany as an example to explore the effects of fundamental and often rapid shifts in institutional settings and socio-economic framework conditions on land system dynamics. During the observed period, Germany experienced two World Wars, a 4-decades long period of political separation, the reunification, and the accession to the European Union. Our results showed that land systems changed markedly in Germany between 1883 and 2007, yet these changes mainly occurred in gradual fashion. Agricultural productivity increased substantially while marginal lands were progressively abandoned. Forests cover increased and infrastructure areas gradually expanded. Technological advancements and structural changes in agriculture since the 19th century were likely the main drivers behind these trends (Bender et al., 2005). However, although Germany witnessed major institutional and socio-economic changes during the time period studied, our results suggest that land systems changed surprisingly gradually. Specifically, the separation of Germany appeared to have little effect on overall trends in land cover and agricultural output, possibly because, despite starkly contrasting institutional and socio-economic paradigms, both countries shared the common goal of increasing agricultural production after WW II. Both countries also underwent similar socio-economic transformations, such as urbanization and a restructuring of the economy. These similarities are particularly reflected in indicator trends; in absolute levels, stronger differences prevail.

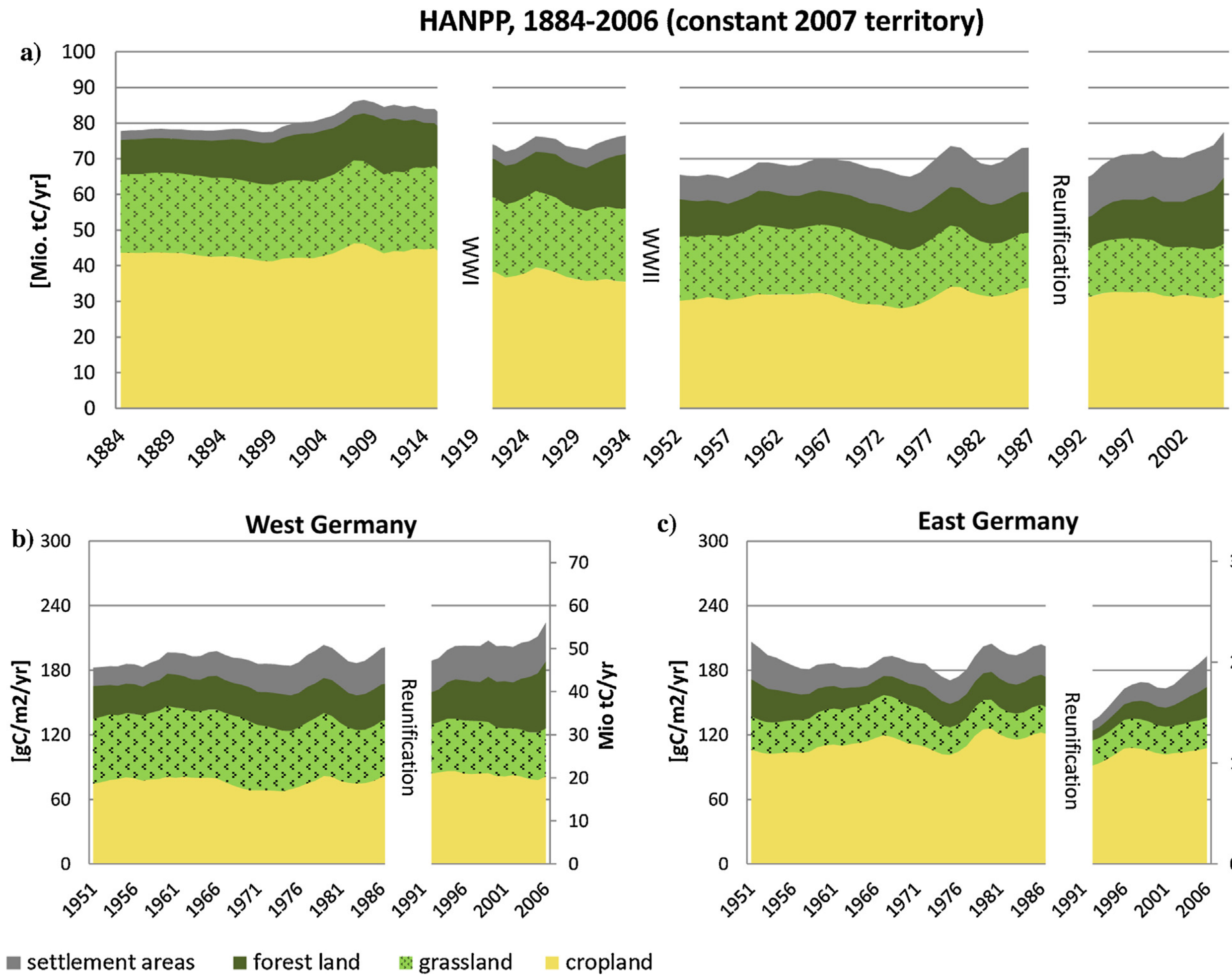

Fig. 4. HANPP per year [Mio tC/year], for each land use class in 3-year moving averages. (a) Germany in its 2007 borders, (b) West Germany in 1950-borders and (c) East Germany in 1950 borders; for reasons of comparability (b) and (c) are area corrected (tons carbon on each land use class divided by total territory); the right axis shows total values in Mio tons carbon per years.

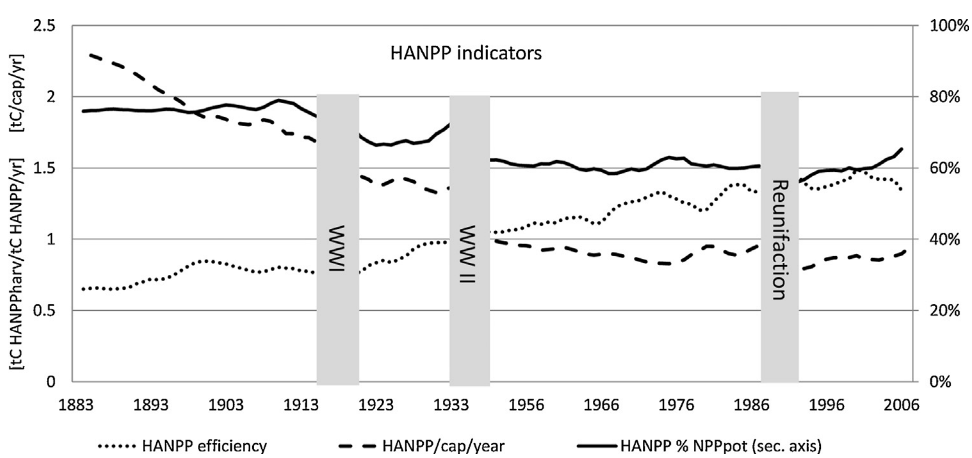

Fig. 5. Indicators of HANPP for Germany in its 2007 borders: HANPP per capita and year (HANPP/cap/year); HANPP efficiency is HANPP harvested per fraction of HANPP in tons carbon of HANPP per tons carbon of harvested NPP per year; HANPP as percentage of potential NPP (NPP_{pot}) is on right axis. Values are shown in 3-year moving averages.

The collapse of the socialist government following the German reunification was a shock event that brought about a drastic change in the land system in East Germany. This shift was characterized by rapidly declining levels of harvest and HANPP, but increasing labor productivity in the East leading to a convergence between East and West Germany.

4.1. Long-term land system dynamics in Germany from 1883 to 2007

In the late 19th century, German land systems were already in the midst of a first wave of agricultural intensification. Forest cover was expanding throughout the study period, suggesting that the forest transition occurred earlier, likely because agricultural land

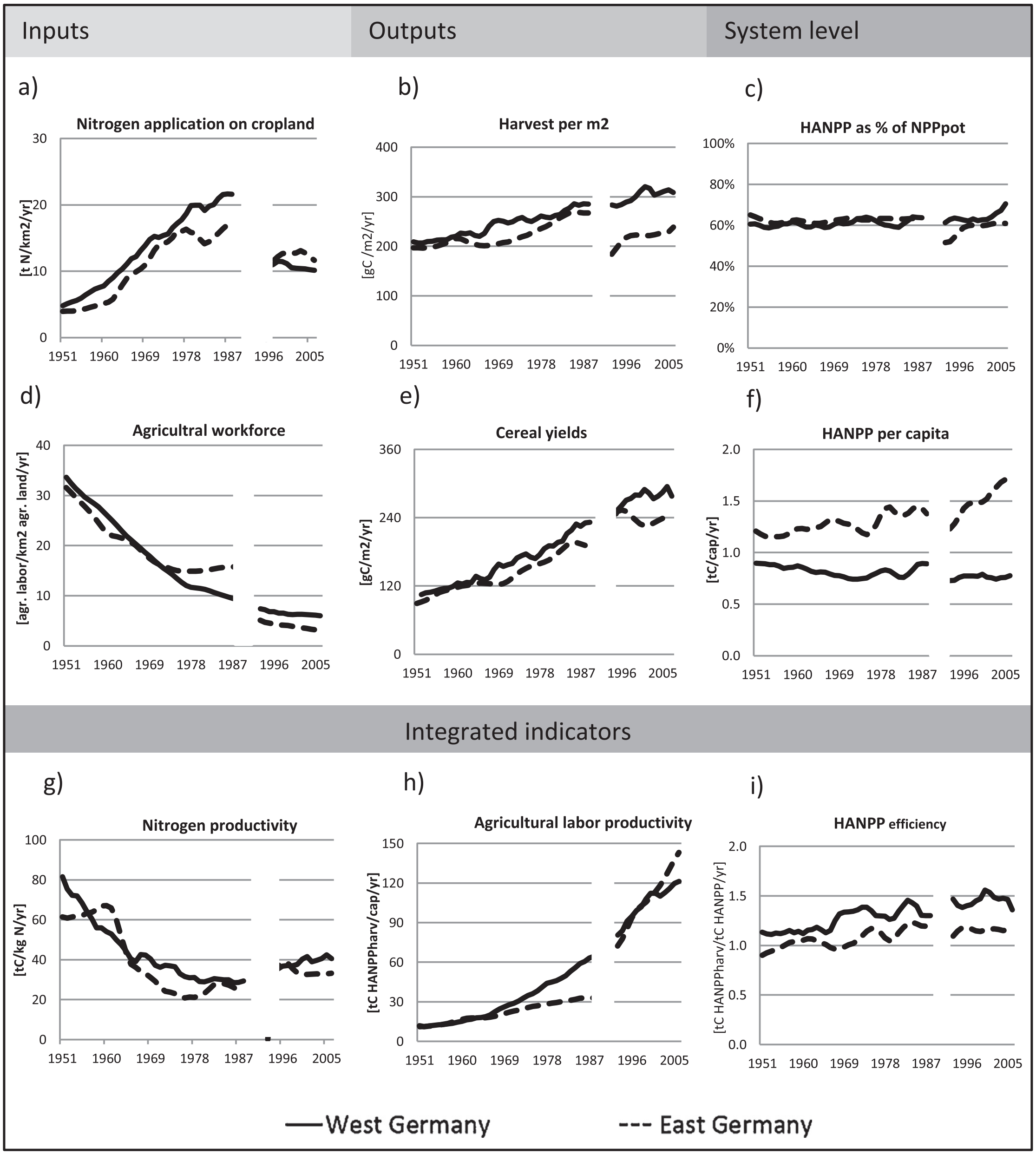

Fig. 6. Indicators of land system change in West and East Germany; input indicators: (a) Nitrogen application in tons per km^2 of cropland; (d) Agricultural labor per unit of agricultural land. Output indicators: (b) Harvest (HANPP$_{harv}$) per m^2 of territory; (d) Cereal yields [g carbon per m^2 of land planted to cereals]. System level indicators: (c) HANPP as percentage of potential productivity (NPPpot) [%/year], (f) HANPP per capita [tC/cap/year]. Integrated indicators denote the combination of land use intensity dimensions (input, output and system level parameters): (g) Nitrogen productivity, i.e. cropland harvest per unit of ied [tC/kgN/year], (h) Agricultural labor productivity (tons harvest per agricultural worker), (i) HANPP efficiency (harvest per unit of HANPP; dimensionless).

had already started to decline before 1883 (Fig. 1a, Kandler, 1992). Forest regrowth on declining agricultural areas affected particularly marginal mountainous areas (Bender et al., 2005) and was facilitated by the concentration of land use as well as the transition from biomass-based to fossil energy sources in the 19th century (Erb et al., 2008, refer to Fig. S2).

Although the German population grew by almost 50% between 1883 and World War I (Sensch, 2004a,b), the shift to fossil energy sources prevented rising fuelwood consumption. Industrialization led to increasing employment in the industrial sector, pulling labor off farms, particularly on marginal agricultural land. Nevertheless, biomass harvests increased, due to improved nutrient availability from rising livestock numbers and mineral sources, mechanization, advances in cropping techniques such as intercropping with clover and in plant breeding (Hoffmann et al., 1965; Grant, 2008). Indeed, our results show that crop yields continuously increased over the last 125 years (Fig. S3). A shift from grazing to forage production on cropland combined with rising numbers of cattle and pigs but declining sheep and goat numbers point to livestock intensification (Fig. S4a and b).

The inter-war period was characterized by a considerable acceleration of land use intensification and biomass production, combined with policy mechanisms aimed at decreasing import dependency (tariffs and price supports, Gessner, 2006). Particularly, the industrial nitrogen production with the commercialization of the Haber-Bosch technology in 1913 (Smil, 1999) was a technological milestone that enabled cereal yields to rise by more than 50% between 1918 and 1938. Hence HANPP$_{harv}$ (Fig. 3) on croplands increased while cropland areas contracted. Through the gradual concentration of agriculture on productive land, forest recovery on marginal land continued (Fig. 4). In consequence of all these trajectories, HANPP efficiency (i.e., the amount of harvest per HANPP unit, Fig. 5) increased and HANPP as percentage of the potential productivity declined considerably (Fig. 5).

After World War II, the German territory was separated into a socialist East and a capitalist West entailing contrasting institutional set-ups and policy frameworks. Nevertheless, both nations shared the common goal of increasing agricultural production through the rapid modernization and industrialization of land use to avoid the food shortages experienced after World War II (Bauerkämper, 2004). Thus, in both East and West Germany, policies aimed at intensifying land use and raising agricultural production. Moreover, growing industrialization in other sectors and urbanization raised wage rates and contributed to declining labor intensity in agricultural production (Patel, 2009; Dannenberg, 2010).

Land systems in West Germany came under the influence of the Common Agricultural Policy (CAP) from 1962 onwards, which initially aimed at increasing production through subsidies. This allowed farmers to increase the level of mechanization and the use of intermediate inputs such as fertilizers and pesticides, and led to the establishment of modern infrastructure and improved market access for farmers (Patel, 2009; Küster, 2010). Farming became oriented toward larger and more specialized production units, in particular in the North, where large farms had a longer tradition than in the South (Bauerkämper, 2004; Dannenberg, 2010). As a result, harvests continuously increased and West Germany became a net exporter of biomass in the mid-1970s (Fig. S5).

In contrast to market integration in West Germany, the policy paradigm in East Germany was national self-sufficiency and independence from the West. The biomass production system, previously prone to many structural problems (e.g., small farm sizes, lack of agricultural assets after the 1945–1949 land reform), was quickly reformed in the 1950s and 1960s (Schöne, 2005). Until the 1960s, agricultural land was almost entirely expropriated and collectivized into large state-owned farms (*Volkseigene Güter*) and collective farms (*Landwirtschaftliche Produktionsgenossenschaften*, LPGs) with the aim to fully industrialize land use (Bauerkämper, 2004). The resulting agricultural holdings in East Germany were much larger than farm sizes in West Germany. Average farm size increased from 10.5 ha in 1938 to 1231 ha in 1989 in East Germany, while it increased from 5.9 ha to 18.2 ha in the same period in West Germany (Koester, 1999). Nevertheless, both countries experienced strikingly similar pathways in terms of land use change and biomass flows between 1950 and 1980, characterized by declining agricultural area and rising $HANPP_{harv}$, while HANPP remained fairly constant (Fig. 4b and c, Fig. 6b and c).

The massive agricultural intensification wave during the 1950s and 1960s also caused growing negative environmental externalities such as soil and water pollution in both East and West Germany (Thoss, 1988; Töpfer, 1990; Meißner et al., 1994; Bauerkämper, 2004). Surges in nitrogen application were associated with declining nitrogen productivity, i.e. N-application was growing stronger than harvest volumes. In response, European policies started to promote programs to set-aside land and incentivize the decrease of land use intensity (Küster, 2010), which contributed to the stagnation of harvests by the late 1980s in West Germany (Fig. 3b). In East Germany, land use was increasingly constrained by growing environmental problems caused by the high degree of industrialization (Bauerkämper, 2004) combined with a weak economy that was unable to supply sufficient amounts of agricultural assets (e.g., capital and machinery). Hence, biomass harvests also declined in East Germany by the late 1980s and the overall target of biomass self-sufficiency was not reached (Fig. S5).

The collapse of the socialist system triggered wide-ranging reforms. As in many former Socialist countries, it resulted in an initially drastic decline in harvested areas, crop yields and livestock numbers (Fig. 3, Fig. S6, see also Kuskova et al., 2008; Kohlheb and Krausmann, 2009; Rozelle and Swinnen, 2004; Swinnen et al., 2010). After the reunification, East German agriculture was rapidly integrated into the Western policy framework. As a result, former East Germany experienced rapid structural change in the 1990s, leading to a massive decline in agricultural workforce and higher labor productivity (Fig. 6h, Plieninger et al., 2006). However, the former collectivized enterprises were not transformed into farming systems based on family enterprises as in the West, but the large, highly specialized farming units were frequently taken over by private cooperatives or shareholder companies (Swinnen et al., 1997; Plieninger et al., 2006).

The 1990s were also characterized by the establishment of the European Union (EU) and the formulation of policies to incentive more environmentally-friendly land use, including the abolition of slaughter premiums and declining export subsidies for beef. This resulted in declining cattle numbers (Gurrath, 2009; Dannenberg, 2010), decreasing $HANPP_{harv}$ on grasslands (Fig. 4a), a stagnation in cereal yields (Fig. 6e) and a strong decline in nitrogen usage (Fig. 6a) triggered by the EU-nitrate directive of 1991 (European Commission, 2010). After 2000, HANPP increased again in West Germany, mainly due to increasing significance of renewable energy, indicated by drastically rising wood harvest (Fig. 3b).

4.2. Lessons learned from 125 years of land system change in Germany

Germany provides an excellent opportunity to study the effect of drastic institutional and socio-economic changes on land systems and the period of Germany's political separation provides an interesting natural experiment for assessing the importance of starkly contrasting institutional and socio-economic setups for land system change. In this context, four major insights emerge from our study.

First, our study shows that land systems can be surprisingly resilient to institutional and socio-economic change. Two World Wars, the accession of Germany to the European Union, and the political separation of Germany after WW II did not lead to fundamental shifts in land systems. Instead, our results demonstrate that land systems changed gradually in terms of land cover and management intensity. This was certainly surprising, particularly considering that other research has pointed out the significant role of socio-economic disruption as a driver of rapid land system change (Lambin et al., 2003; Dearing et al., 2010; Hostert et al., 2011). Possible explanations for this relative resilience include the importance of underlying drivers that did not change abruptly (e.g., demographic change, urbanization, structural change of the economy). Identifying the ultimate causes of the relative resilience of land systems requires further analyses though, and our article is a starting point for this.

Second, different institutional set-ups and socio-economic frameworks do not necessarily lead to diverging trajectories of land use/cover change and biomass flows. Apparently, the overarching goal to intensify and industrialize land use in order to reach biomass self-sufficiency and to satisfy increasing consumption was equally important in both East and West Germany after WW II and overruled institutional and socio-economic differences and their influence on land system changes. Hence, by studying the example of East and West Germany, we could identify the intensification of biomass production, based on the ubiquitous availability of new agricultural technologies, as the dominating trend of land system change. This is in line with other research highlighting that land use intensification was the overarching land system trajectory in the 20th century in diverse policy, institutional and natural environments (Krausmann, 2001; Kuskova et al., 2008; Schwarzlmuller, 2009; Musel, 2009; Kohlheb and Krausmann, 2009; Kastner, 2009).

Third, even though contrasting institutions and socio-economic set-ups did not result in differing land cover change and HANPP trajectories in East and West Germany, they played out in the trends of several integrated indicators of land use intensification. Most importantly, we found differences between East and West Germany in terms of input/output efficiency, particularly the amount of crop harvest per unit of nitrogen inputs (i.e., nitrogen productivity, Fig. 6g) or the amount of harvest per agricultural worker (agricultural labor efficiency, Fig. 6h). This shows that institutions and socio-economic paradigms play an important role in influencing the strategies leading to land use intensification, and these strategies were more input intensive in terms of fertilizer and labor in East Germany than in the West. Furthermore, differences in HANPP efficiency highlight that West Germany succeeded in harvesting higher shares of biomass in relation to HANPP than East Germany. Interestingly, these discrepancies in terms of input–output efficiency and HANPP efficiency did not lead to different levels of HANPP as % of NPP_{pot}, which is indicated by similar levels of ecosystem disturbance in the two countries. However, as it was beyond the scope of this study to assess the impacts of high intermediate inputs on soil, water, and air quality, we lack full understanding about potential environmental trade-offs, particularly at the field level.

Fourth, considering the relative stability of German land system trajectories over the past 125 years, the effects of the collapse of the socialist system in East Germany was remarkable and triggered a shift to a new trajectory in East Germany's land systems. After 1989, most land system parameters changed markedly, in particular the different indicators of land use efficiency. This change corresponds to a shift away from the focus of socialist land use policies on maximizing output in order to gain self-sufficiency, at the expense of high labor and the supports by state subsidies. After 1990, the agricultural labor force declined drastically, wages rose and labor productivity became even with than in West Germany. However, this structural change in agriculture did not result in simultaneous improvements in other forms of land use efficiency in former East Germany such as HANPP efficiency or nitrogen productivity. Hence, the emerging post-socialist land system was neither a direct continuation of past trends nor a mere alignment of land system characteristics in the West and former East Germany.

Understanding the political, institutional and economic conditions under which land systems remained stable, changed gradually or swiftly transitioned to new states in the past, can help to better anticipating future land change. As intensification pathways become dominant globally, new, sustainable modes of intensification are urgently needed. Long-term studies of land system dynamics can help providing insights into the patterns and the complex drivers of gradual and rapid land system change. The HANPP framework allows for the systematic analysis of drivers of land system change and it can make the interplay of land use expansion and contraction, intensification and efficiency explicit. This may reveal insights that are counterintuitive at first glance, such as the gradual land system change and high resilience of land systems to institutional and socio-economic changes in the case of Germany as well as the similarities in land change trajectories in spite of stark institutional and socio-economic differences in East and West Germany. Long-term studies are powerful to help better understanding both the individual roles and the complex interplay of underlying drivers of land system change. As such, long-term studies allow disentangling the responses of land systems to demographic and technological change, changes in demand, and the ongoing megatrends such as globalization or urbanization.

Acknowledgements

We gratefully acknowledge support by the European Commission (Project VOLANTE FP7-ENV-2010-265104), the European Research Council (ERC-2010-Stg-263522 LUISE), the Einstein Foundation Berlin, Germany and the Austrian Science Fund (Project P20812-G11). We also thank Tobias Plieninger, Dagmar Haase, Martin Rudbeck Jepsen, and Peter Dannenberg for helpful discussions and comments on earlier manuscript drafts, and Christoph Israel and Friederike Wirth for assistance in the data collection.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.06.006.

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