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

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A B S T R A C T

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.

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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
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 (Schwarzmüller, 2009), Hungary (Rohiheb and Krausmann, 2009), the Czech Republic (Vačkář and Orličná, 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 CO₂-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/km²) and lowest in Sweden (20 cap/km²), the only country in the sample with population density below
the global average of 50 cap/km². Population dynamics in the 20th century were also different between countries. Population more than quadrupled in Albania in the 20th century, more than tripled in the Netherlands and Romania, and was relatively stable in Austria and the United Kingdom (increasing by factors around 1.4 between 1900 and 2005). Ecological differences between the countries exist as well. The net primary productivity of potential vegetation (NPPpot) is around or slightly above the global average in most of our case study countries. In Sweden, the country with the lowest value, NPPpot was 14% below the global average in 2005, while in Austria, where NPPpot is highest, the value exceeds the global average by 38%. In socio-economic terms, most countries in

![Map of country sample indicating the starting year of our data set for each country. AT – Austria, UK – United Kingdom, DK – Denmark, RO – Romania, DE – Germany, IT – Italy, SE – Sweden, NL – the Netherlands, AL – Albania.](image)

Table 1

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Albania</td>
<td>28,750</td>
<td>0.74⁴</td>
<td>3.14</td>
<td>109</td>
<td>4,117</td>
<td>332</td>
</tr>
<tr>
<td>Austria</td>
<td>83,858</td>
<td>5.97</td>
<td>8.22</td>
<td>98</td>
<td>22,583</td>
<td>362</td>
</tr>
<tr>
<td>Denmark</td>
<td>43,998</td>
<td>2.45</td>
<td>5.41</td>
<td>126</td>
<td>24,017</td>
<td>320</td>
</tr>
<tr>
<td>Germany</td>
<td>357,127</td>
<td>42.37</td>
<td>82.43</td>
<td>231</td>
<td>19,597</td>
<td>318</td>
</tr>
<tr>
<td>Italy</td>
<td>301,328</td>
<td>32.27</td>
<td>58.67</td>
<td>195</td>
<td>19,296</td>
<td>287</td>
</tr>
<tr>
<td>Netherlands</td>
<td>33,743</td>
<td>5.14</td>
<td>16.30</td>
<td>392</td>
<td>23,114</td>
<td>261</td>
</tr>
<tr>
<td>Romania</td>
<td>238,391</td>
<td>6.04</td>
<td>21.66</td>
<td>91</td>
<td>8,529</td>
<td>348</td>
</tr>
<tr>
<td>Sweden</td>
<td>450,300</td>
<td>5.13</td>
<td>9.05</td>
<td>20</td>
<td>23,627</td>
<td>238</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>239,910</td>
<td>41.15</td>
<td>60.53</td>
<td>248</td>
<td>23,157</td>
<td>265</td>
</tr>
<tr>
<td>Sample total/average</td>
<td>1,776,506</td>
<td>141.23</td>
<td>264.72</td>
<td>149</td>
<td>19,783</td>
<td>321</td>
</tr>
<tr>
<td>Europe total/average</td>
<td>4,722,110</td>
<td>343.58</td>
<td>518.43</td>
<td>110</td>
<td>17,352</td>
<td>295</td>
</tr>
<tr>
<td>World total/average</td>
<td>129,966,210</td>
<td>1,753.45</td>
<td>6,500.79</td>
<td>50</td>
<td>6,780</td>
<td>276</td>
</tr>
</tbody>
</table>

⁴ National data derived from national statistical records, see SOM.
⁵ National data derived from the global economy database: http://www.conference-board.org/data/economydatabase/; values refer to international Geary–Khamis dollars (GKS) indicating constant purchasing power parity of 1990.
⁶ National data derived from estimations on basis of the LPJ-Dynamic Global Vegetation Model (Sitch et al., 2003).
⁷ Albanian population data refer to 1912.
⁸ All numbers for “Europe total” and “World total” are based on data set presented in Krausmann et al. (2013). “Europe total” refers to the sum of the regions “Western Europe” and “Southern and South-Eastern Europe”. This region excludes Turkey and the countries of the former Soviet Union.
⁹ Value refers to 1910.
the sample can be considered industrialized, with the exceptions of Romania and Albania, the two countries in the sample which were under communist rule for several decades of the 20th century, displaying income levels of below 50% of the other countries in 2005, see Table 1.

The sample total represents roughly 38% of the European land area (excluding Turkey and the countries of the former Soviet Union) and 51% of the European population, see Table 1. Using this definition of Europe, the countries in the sample not only display higher population density than the European average, they are also characterized by higher income (14%) and slightly higher net primary productivity (9%). This is due to the fact that our sample includes several high-income, highly ecologically productive countries of Central Europe, while Mediterranean (Southern), boreal (Northern) and continental (Eastern European) countries are underrepresented in the sample.

2.2. HANPP calculations

For all nine countries, a common methodology was applied to establish accounts of the extent of individual land-use types, biomass extraction and aboveground HANPP, based on national statistical data sources. The data sets of Albania, Denmark, the Netherlands, Romania and Sweden are presented here for the first time, while the datasets for Austria, Germany, Italy and the United Kingdom draw from previous research (Kraussmann, 2001; Musel, 2009; Niedertscheider et al., 2014; Niedertscheider and Erb, 2014). The existing datasets on these countries were extended, aggregated and partly reassessed in order to meet the desired level of methodological consistency. For instance, the studies for Austria (Kraussmann, 2001) and the United Kingdom (Musel, 2009) were based on different HANPP definitions and required a complete re-assessment in order to warrant comparability. In consequence, the HANPP results reported here for these countries differ slightly from those of previous publications. For Italy (Niedertscheider and Erb, 2014) and Germany (Niedertscheider et al., 2014), the methodology in previous work are identical with the approach followed here, except for slight differences in the aggregation schemes used for grazing land and the allocation of grazed biomass.

Fig. 2 schematically represents the HANPP framework, discerning various different NPP flows, and introducing the abbreviations we will use throughout the text: NPPpot denotes the NPP of potential vegetation, NPPeco the NPP of vegetation after harvest, HANPPharv the NPP removed and destroyed during harvest, and HANPPloc refers to NPP lost through land conversion. NPPact is the NPP of actually surviving ecosystems before harvest.

The national statistical records used to generate this data set provide information on land use, livestock and agricultural and forest production for each year in the country total. These data were complemented by data compilations in literature and – in cases of data gaps – some international statistical sources such as the FAO database (for a detailed list of data sources and literature used, see SOM). We adopted a common protocol of data aggregation, conversion and estimation procedures which was applied to all countries. Starting point for the assessment of HANPP is a standardized land-use data set. Land-use data were aggregated to the broader land-use types “cropland”, “grazing land” (including all grassland and “other lands”, i.e., land under use, but not for cropping, forestry or infrastructure (Haberl et al., 2007)), “forests”, and “settlement areas”. It is important to note that changes in the extent of a land-use type refer to net-changes of these land-use types at the national scale, and not to gross changes, which can exceed net changes by a factor of up to four (Fuchs et al., 2015). An assessment of gross land-use changes would have been a major empirical challenge, requiring a spatially-explicit perspective (e.g., based on historical maps and current spatially-explicit land-use data sets) which was not adopted in this study.

C-flows relevant for HANPP were assessed for the different land-use types separately. For a complete assessment of HANPP, knowledge of three out of the five HANPP components (Fig. 1) is required. We individually assessed HANPPharv, NPPact, and NPPpot, each in tons carbon per year (tC/yr) for each land-use type and year. HANPPloc and NPPeco are calculated from these flows as indicated in the equations in Fig. 2. We applied 5-year moving averages to all NPP flows in order to identify medium- and long-term trends and to increase readability of graphs. As in previous national HANPP accounts, our analysis was restricted to above-ground HANPP, omitting belowground C-flows (with the exception of harvested belowground biomass such as roots and tubers) for reasons of data availability and reliability.

For the assessment of biomass extraction (HANPPharv), we combined the information on biomass harvest provided in the primary sources with modeling assumptions for non-reported flows of residues and grazed biomass. Annual NPPpot values are based on LPJ-DGVM model runs (Sitch et al., 2003) with an improved representation of hydrology (Gerten et al., 2004). NPPact was assessed differently on cropland (based on biomass production), forests and settlement areas (based on NPPpot) and grazing land (a combination of both, depending on harvest intensity). The major processing steps are presented in Table 2, and a detailed description of the factors used and underlying assumptions applied is provided in the SOM. Generally, we complied with the methodology developed for national-scale analyses presented in Haberl et al. (2007), Kraussmann et al. (2008) and Kraussmann et al. (2013). A sensitivity analysis was carried out to challenge the reliability of our results by changing the assumptions underlying the assessment of grazed biomass, as described in the SOM.

Fig. 2. Net primary production flows considered in the framework of human appropriation of net primary production (HANPP).
The established data set allows for tracing long-term national trends of land-use change and HANPP, but data robustness decreases in many countries as we go back in time. The earliest year of the time series in our dataset reaches from 1830 (Austria, United Kingdom) to 1938 (Albania). Fig. 1. According to the specificities of national data reporting and data gaps, some specific data estimations, aggregations and interpolations were performed in specific countries, which are described in detail in the SOM. While some countries covered virtually the same territory throughout the entire period (Albania, Denmark, Italy, the Netherlands and Sweden), others experienced changes in area extent and even geographic position. For Austria and Germany, the datasets established in previous research allowed to cover the respective country in its current boundaries (for details see Krausmann, 2001; Niedertscheider et al., 2014). Major regional distortions occurred also in the United Kingdom with the separation of the Republic of Ireland in 1923, somewhat affecting the composition of land-use types and general land-use patterns (Musel, 2009). The case of Romania was particularly challenging since its territory changed dramatically after World War I, when Romania’s size more than doubled from 130,000 km² to almost 300,000 km², and again during World War II, after which the country shrank to its current boundaries with an area of 240,000 km². Temporal trends in Romania therefore need to be interpreted with particular care. Due to these changes in absolute area extent of some of the countries, we focus our long-term analyses on relative values (e.g., area of land-use type per total land area, biomass extraction per area, HANPP as % of $\text{NPP}_\text{pot}$), rather than absolute values.

### 2.3. Disentangling changes in land-use extent from intensity changes

The human appropriation of net primary production (HANPP) measures the combined effect of land conversion and biomass extraction on the availability of trophic energy in ecosystems. One of the aims of this study is to disentangle the two effects. To achieve this goal we employ an index decomposition analysis. Before describing the technical details of this analysis, it is important to understand how the different HANPP components behave during typical land-use change processes.

Fig. 3 displays typical land-use change processes and their effects on HANPP on a hypothetical land area. While HANPP components are presented in tC/yr, overall HANPP is presented as % of $\text{NPP}_\text{pot}$ (secondary axis). This unit warrants comparability of system-level land-use intensity across the different countries. In Fig. 2 we distinguish changes in the extent of land-use types (Fig. 3a and b) from changes in intensity (Fig. 3c and d) and ecosystem productivity (i.e., due to climate change, or CO₂ fertilization; Fig. 3e). The numbers underlying the figure correspond roughly to typical productivities of the different land-use types and reflect the accounting principles applied in the study, but do not represent an actual empirical case. It is important to emphasize that

#### Table 2

Major calculation procedures performed to derive HANPP indicators from primary sources. For more detailed methodological descriptions see SOM.

<table>
<thead>
<tr>
<th>Land use HANPP&lt;sub&gt;harv&lt;/sub&gt;</th>
<th>Information used&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Calculation procedures</th>
<th>Data quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use (PS)</td>
<td>Production of primary products from cropland, permanent cultures, meadows and forests (PS)</td>
<td>Aggregation</td>
<td>Generally high, but decreasing back in time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aggregation, conversion</td>
<td>Data quality of primary sources generally high, but decreasing back in time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HANPP&lt;sub&gt;harv&lt;/sub&gt; = primary crop harvest + used residues + unused residues</td>
<td>The assessment of residues is based on general factors (accounting consistency was prioritized over detailed accuracy).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residues assessed by applying scale factors to primary crop harvest (see SOM)</td>
<td>Data on market feed intake generally lack in the period before 1961 (starting year of FAO database); thus numbers on feed intake and composition before this point rely on assumptions (see SOM).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feed balance calculation. Grazing assumed to fill the gap between feed supply and demand. Grazing allocated to grassland and non-specified other land (grazing land”).</td>
<td>Low due to the very general assumption.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HANPP&lt;sub&gt;harv&lt;/sub&gt; = $\text{NPP}_\text{pot}$ × 0.5</td>
<td>The assessment of NPP&lt;sub&gt;pot&lt;/sub&gt; is based on rough assumption and combines model output data with data from statistical publications. It is therefore less robust than HANPP&lt;sub&gt;harv&lt;/sub&gt;.</td>
</tr>
<tr>
<td>NPP&lt;sub&gt;act&lt;/sub&gt;</td>
<td>Cropland: HANPP&lt;sub&gt;harv&lt;/sub&gt;</td>
<td>NPP&lt;sub&gt;act&lt;/sub&gt; = HANPP&lt;sub&gt;harv&lt;/sub&gt; × loss expansion factor loss expansion factor × 1 accounts for biomass lost during plant growth (see SOM)</td>
<td>Temporal trends in the difference between HANPP&lt;sub&gt;harv&lt;/sub&gt; and NPP&lt;sub&gt;act&lt;/sub&gt; on croplands are solely the result of the conversion factors applied.</td>
</tr>
<tr>
<td></td>
<td>Grazing land: NPP&lt;sub&gt;pot&lt;/sub&gt; or HANPP&lt;sub&gt;harv&lt;/sub&gt;</td>
<td>If HANPP&lt;sub&gt;harv&lt;/sub&gt; &lt; NPP&lt;sub&gt;pot&lt;/sub&gt; × 0.8, then NPP&lt;sub&gt;act&lt;/sub&gt; = NPP&lt;sub&gt;pot&lt;/sub&gt; × 0.8</td>
<td>Data from LPJ DGVM provide NPP&lt;sub&gt;pot&lt;/sub&gt; values for aboveground plus belowground vegetation (4NPP&lt;sub&gt;pot&lt;/sub&gt; + NBP&lt;sub&gt;pot&lt;/sub&gt;) in the period 1900–2010. We assume aboveground NPP&lt;sub&gt;pot&lt;/sub&gt; to account for 60% of the total (Roy et al., 2001). Prior to 1900, we use the 1900 NPP&lt;sub&gt;pot&lt;/sub&gt;-values. Historic changes in national territories are reflected by applying the contemporary per-area values to the respective territory. NPP&lt;sub&gt;act&lt;/sub&gt; data from LPJ DGVM increase over time. Peaks in NPP&lt;sub&gt;pot&lt;/sub&gt; do not necessarily coincide with peaks in HANPP&lt;sub&gt;harv&lt;/sub&gt;.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If HANPP&lt;sub&gt;harv&lt;/sub&gt; &gt; NPP&lt;sub&gt;pot&lt;/sub&gt; × 0.8, then NPP&lt;sub&gt;act&lt;/sub&gt; = HANPP&lt;sub&gt;harv&lt;/sub&gt; × loss expansion factors (see SOM)</td>
<td></td>
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<td></td>
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<td>NPP&lt;sub&gt;act&lt;/sub&gt; = NPP&lt;sub&gt;pot&lt;/sub&gt;</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>NPP&lt;sub&gt;act&lt;/sub&gt; = NPP&lt;sub&gt;pot&lt;/sub&gt; × 1/3</td>
<td></td>
</tr>
<tr>
<td>NPP&lt;sub&gt;pot&lt;/sub&gt;</td>
<td>LPJ DGVM</td>
<td>NPP&lt;sub&gt;pot&lt;/sub&gt; = (&lt;S&gt;4NPP&lt;sub&gt;pot&lt;/sub&gt; + NBP&lt;sub&gt;pot&lt;/sub&gt;&lt;/S&gt;) × 0.6</td>
<td></td>
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</tbody>
</table>

<sup>a</sup> PS: primary (statistical) sources.
Fig. 3. Typical HANPP effects of individual, isolated land use changes on a hypothetical land area. We distinguish two land use types (agricultural and forest), and two processes of land-use change (expansion and intensification). The “initial state” assumes a territory covered by agriculture and forests in equal amounts with agricultural harvest exceeding forest harvest by a factor 3. Expansion and intensification refer to a 33% increase of area or harvest in agriculture and forests, respectively; ecosystem productivity increase refers to a 33% rise in potential NPP. In the “initial state”, HANPP_{harv} on agricultural land amounts to 70% of NPP_{pot}, HANPP_{luc} is 16% of NPP_{pot}, and NPP_{eco}, thus, makes up the remaining 14%. On forests, the “initial state” describes HANPP_{harv} at 30% of NPP_{pot}, HANPP_{luc} is zero by definition on forests, thus, NPP_{eco} equals 70% of NPP_{pot}. 

The dynamics displayed in Fig. 3 refer to isolated changes of e.g., intensity or extent, under ceteris paribus conditions, which are not occurring in such forms in the actual land use dynamics of a country. Since agricultural areas tend to have higher HANPP levels than forests, agricultural expansion increases HANPP (Fig. 3a), while forest expansion at the expense of agricultural land leads to declining overall HANPP (Fig. 3b). Agricultural intensification (i.e., higher
HANPP$_{harv}$ per unit land) translates into higher NPP$_{act}$ and allows for higher biomass extraction per unit HANPP (Fig. 3c). HANPP even declines slightly in the course of agricultural intensification, because in our accounting procedure for cropland HANPP (Table 2), rising HANPP$_{harv}$ translates into increasing NPP$_{act}$ and higher NPP$_{pot}$. Forestry intensification on the other hand increases HANPP, as the increase in HANPP$_{harv}$ is assumed to directly translate into declining NPP$_{pot}$ (Fig. 3d). Finally, ecosystem productivity increase (i.e., increasing absolute NPP$_{pot}$) may decline the level of HANPP as share of NPP$_{pot}$ despite constant HANPP$_{harv}$ (Fig. 3e).

In order to separate the effects of intensification and changes in extent of land-use types in the temporal trends of HANPP, we perform a log mean division index (LMDI) decomposition analysis (Ang, 2005). We employ the decomposition for the period 1902 and 2003, the first and latest year for which the required data (5-year averages of all data) are available for all countries. The only exception is Albania, where data availability allows for investigating only the time period between 1938 and 2003. Based on the considerations depicted in Fig. 2 we chose the following identity to decompose changes in HANPP in this time period:

\[
\text{HANPP} \times \text{Area} \times \text{time} = \text{HANPP} \times \text{Area} \times \text{time}
\]

HANPP denotes the share of NPP appropriated through human activities in a given year, measured in percent of NPP$_{pot}$. Area represents the area of the respective land use type in that year (measured in km$^2$), and HANPP$_{harv}$ refers to the total amount of biomass extracted and destroyed during harvest on the respective land use category per year (in tons carbon per year). We carry out the decomposition analysis along two dimensions: (1) we investigate changes in the effects on the different land-use types for the total sample, (2) we investigate overall changes in the individual countries. In addition, dynamics of cropland and grazing lands, known to be particularly relevant for HANPP trajectories (Erb et al., 2009; Haberl et al., 2014), are also analyzed at the country-level.

We employ this identity to quantify changes in the four land-use types related to three separate effects: (1) The term Area of equation 1 (“area effect”) covers the effect of changes in the extent of land-use types on changes in HANPP, assuming constant output intensity (i.e., HANPP$_{harv}$ per unit land). (2) The term HANPP$_{harv}$ per area (“harvest intensity effect”) describes changes in the amount of HANPP$_{harv}$ per unit land. (3) The term HANPP per HANPP$_{harv}$ (“HANPP efficiency effect”) can be understood as a measure of land-use efficiency. Formally, it describes how much HANPP is induced per unit harvest, thus representing the inverse of “HANPP efficiency” as proposed by Kohleb and Krausmann (2009) and Niedertscheider and Erb (2014), i.e., the fraction of annual HANPP in a region used for socio-economic processes. Note that the way the identity is formulated in equation (1), increasing efficiency produces a negative signal. The formulae used to calculate the importance of the different effects are presented in the SOM.

Our analysis thus focuses on the effects of different patterns and trends in land use on HANPP rather than the importance of socio-economic factors such as population, income, or foreign trade. We employ the additive version of the LMDI approach (Ang, 2005), thus, the sum of the three effects always adds up to the changes in national level HANPP during the studied period (in our case 1902–2003, except for Albania). While the comparison between the first and last years of a 100-year time period obscures temporal trends which took place during this period, it allows for identifying the most important processes determining long-term changes in HANPP between the two time points.

### 3. Results

The data set empirically substantiates the notion of a forest transition in Europe (Meyfroidt and Lambin, 2011): with the exception of Albania, forest areas increased in all countries between the starting point and the end point of our time series (Fig. 4c and d), the time series starting after the turning point. In Albania, in contrast, forest areas show a steep decline after 1950 and a stagnation in later decades. At the same time, the results suggest that agricultural expansion had not fully ceased at the beginning of statistical reporting: specific countries such as Denmark and Italy (and Romania, with the caveat of limited data quality) reported strong increases in cropland in the late 19th century. Overall, we see that in the sum of all countries in our sample, cropland and grazing land decreased in the second half of the 20th century (the declining trend started earlier on grazing lands than on cropland), and forest areas and settlement areas increased. The only exception to this general pattern is Albania, where agricultural expansion persisted well into the second half of the 20th century.

The different countries vary widely with regard to their land-use profile. The Northern and Alpine countries Sweden and Austria are dominated by forests at c. 40% of land area and more, while the more oceanic countries (the United Kingdom and the Netherlands) are dominated by grassland areas which here cover >40% of the land area. Denmark is the country with the highest share of cropland (above 50%), followed by Italy and Romania (Fig. 4a and b).

The amount of biomass harvested per unit of area (including used and unused residues, according to our definition of HANPP$_{harv}$) varied greatly between countries, time periods and land use categories (Fig. 5). The most significant increase in biomass yields took place on cropland (Fig. 5a). In many countries of our sample, typical HANPP$_{harv}$ values for cropland in the late 19th century were below 100 g C/m$^2$/yr, while in the early 21st century, HANPP$_{harv}$ per area cropland grew well above 500 g C/m$^2$/yr. Most of the increase in HANPP$_{harv}$ on cropland took place in the decades after World War II. In most countries (Eastern and Western), cropland productivity leveled off or even decreased toward the end of the 20th century.

Trends of harvest dynamics on grazing land and forests are much more variable and more difficult to interpret than those on cropland (Fig. 5b and c). Only in the Netherlands, values and trends of HANPP$_{harv}$ on grazing land show a similar development as on cropland. In all other countries, the level was about half of that of cropland in recent decades. Similarly to cropland trends, also on grazing land a certain leveling-off can be observed in the more recent decades. In forests (Fig. 5c), per-area yields also varied greatly, but were generally well below the values of grazing land or cropland. Fig. 5d reveals that the overall HANPP$_{harv}$ trend in the nine countries was dominated by trends in cropland production. Despite stagnating and even declining cropland areas, the absolute amount of HANPP$_{harv}$ on croplands increased steadily throughout the 20th century, leveling off only toward the end of the millennium. While in the late 19th century, HANPP$_{harv}$ on cropland accounted for roughly one third of total HANPP$_{harv}$ in the sum of our sample, the share of cropland HANPP$_{harv}$ increased to well above 50% at the turn of the millennium.

HANPP, depicting the aggregate effect of land conversion and biomass harvest, ranged between 40 and 80% of NPP$_{pot}$ in most countries of the sample during most of the time period (Fig. 6a). The only exception is Sweden, where, HANPP was below 30% throughout the 20th century. No clear temporal trends in HANPP can be identified on the country level. Only in the late 20th century, in almost all countries HANPP leveled off or declined. In the earlier periods, we observe diverging trends: while in Austria and the United Kingdom, HANPP values are stable from the beginning of the time series in the early 19th century, HANPP increased in Romania, Italy, and Denmark in the late 19th century.
The changes in HANPP are the result of the combination of varying underlying trends in the different national case studies. In Fig. 6 we summed up all national cases in the period 1902–2003 and found that at this aggregate scale, HANPP decreased from around 63% of NPP$_{pot}$ in the early 1900s to around 55% at the turn of the 21st century. Most of this decrease took place after World War II. Also the composition of HANPP changed in this period: HANPP$_{harv}$ increased from around 120 gC/m$^2$/yr in 1902 to above 180 gC/m$^2$/yr in 2003, that is an increase of around 50% in 100 years. HANPP$_{lux}$ declined from approximately 52 gC/m$^2$/yr in 1902 to ~12 gC/m$^2$/yr in 2003. This means that while land conversion led to a decline in NPP in the early 20th century relative to potential vegetation, land conversion actually increased NPP in the early 21st century by up to ~5%. The increase in NPP was accomplished due to those countries where agricultural intensification was combined with low forest cover, particularly the Netherlands, Denmark, Germany and the United Kingdom. The combination of increasing HANPP$_{harv}$, declining HANPP$_{lux}$ and rising NPP$_{pot}$ led to the overall HANPP decline described above. At this pan-European spatio-temporal scale, agricultural intensification seems to be the process dominating changes in HANPP, with strong increases in HANPP$_{harv}$, slight increases in NPP$_{eco}$ and strong decreases in HANPP$_{lux}$. The decomposition analysis sheds light on the contribution of underlying factors to this overall trend.

Fig. 7 summarizes the results of the decomposition analysis. Fig. 7a analyzes the trajectories in the the sum of all countries, in a break-down of the different land-use types, disentangling changes in area extent (“area effect”), HANPP$_{harv}$ per unit area (“harvest intensity effect”) and HANPP per HANPP$_{harv}$ (“HANPP efficiency effect”). We see that, in the period 1902–2003 and for the total sample, negative trends in HANPP are explained by a combination of a negative area effect and HANPP efficiency gains, which are only partly counterbalanced by a positive harvest intensity effect. Cropland and grazing land contributed to the observed decline in HANPP in equal amounts, but with a much smaller amplitude for grazing land between harvest intensity effect and HANPP efficiency effect. Both these land use types were characterized by declining areas and increasing harvest per unit of land, with less HANPP induced per unit of harvest (higher efficiency).

The expansion of forests and settlement areas positively contributed to HANPP, partly compensating for the effects on cropland and grazing land. Please note that the decomposition analysis refers to the isolated area-effect of a land use type by assuming a constant harvest intensity and HANPP efficiency. Thus, the expansion of forest area has a positive effect on HANPP when isolated from the effect of other land use changes such as (concurring) cropland area reduction.

The harvest intensity effect on forests was found to be negligible, indicating that the current harvest intensity on forests is similar today to that of 100 years ago at the national scale, despite increasing wood extraction in recent decades in the European total (Food and Agriculture Organization of the United Nations, 2010). Settlement areas, despite their small total area extent (7% of total land area in 2003), had a higher effect on HANPP than the large and expanding forest areas in our sample (more than one third of
the total area in 2003), because of the high HANPP values on this particular land use type.

The second dimension of analysis tackles the question which effect dominated HANPP trends in the individual countries across all land-use types (Fig. 7b). All Western countries, i.e., all countries except Romania and Albania, display a more or less pronounced negative area effect, a strongly positive harvest intensity effect, and an even stronger HANPP efficiency effect (more HANPP$_{harv}$ per unit of HANPP). In all Western countries of the sample except for the United Kingdom, HANPP efficiency gains and the “area effect”

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**Fig. 5.** HANPP$_{harv}$ per unit of area on cropland (a), grassland (b), and forests (c) in all nine countries of our sample. (d), total HANPP$_{harv}$ from different land use categories in the sum of all countries. All values are 5-year moving averages. During World Wars I and II, data availability is limited, thus, some interpolations were performed. These time periods are shaded in the graphs.

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**Fig. 6.** Changes in HANPP in the nine countries (a) and in HANPP components of the sum of all countries (b) All values are 5-year moving averages. During World Wars I and II, data availability is limited, thus, some interpolations were performed. These time periods are shaded in the graphs. Note the secondary y-axis in (b) for HANPP [%], that does not cross the x-axis at zero.
more than overcompensated for the increase of harvest intensity, and HANPP decreased in overall terms. Albania and Romania differed from this pattern in two distinct ways: in Romania, all three effects produced negative signals – land use was dis-intensified at all levels. Some of this result may be explained by the collapse of the agricultural sector after the fall of the iron curtain, and the land-use extensification that followed. In Albania, in contrast, HANPP increased, mainly due to a positive area effect. Albania is the only country in our sample (and maybe one of the few such examples in Europe) where large-scale agricultural expansion reached well into the 20th century.

A country-by-country analysis of the different effects on cropland and grazing land is displayed in Fig. 7c and d. This analysis allows discussing the degree of homogeneity or divergence between the different countries on the level of land-use types for the two land-use types with the most pronounced effects on HANPP trends. On cropland, the signal of the different effects (negative area effect, positive harvest intensity effect, HANPP efficiency gains) was the same in all countries, with the only exception of Albania, as discussed above. However, the relative importance of area decline, harvest increase and efficiency gains differed. Most harvest intensity increase and HANPP efficiency gains were achieved in Denmark, the country with the highest share of cropland in our sample (above 50% of the land area), while these effect were lowest in Sweden, where cropland covered only up to 4% of the territory.

On grazing land, the role of the different effects varies much more between the countries: in all countries except the United Kingdom, the total change on grazing land would have reduced HANPP. The area effect was negative in all countries except in Italy and Germany, where, it was absent. However, the combination of harvest intensity and HANPP efficiency was highly diverse. In the Netherlands and the United Kingdom, grazing land was intensified in a similar way as cropland, with concurring harvest intensity increases and HANPP efficiency gains (which in the UK did not fully compensate harvest increases). Germany too saw increasing HANPP efficiency on grazing land. Other countries however, such as Romania or Italy, experienced an extensification of grazing lands, expressed by a negative harvest effect combined with efficiency losses.

4. Discussion

The consistent long-term land-use dataset presented and analyzed in this study allows for drawing a rich picture of regional
patterns and temporal trends in European land-use change. The combination of intensifying but contracting croplands and grazing lands on the one hand, and the expansion of forest areas on the other led to a stagnation and decline of HANPP at a high level in most countries. Aboveground HANPP at the aggregate level of nine countries decreased from 63% of NPP\_pot in 1902 to 55% in 2003. While the trend of declining HANPP indicates declining pressures on domestic ecosystems in terms of trophic energy availability to species other than humans, the value of 55% is still exceptionally high compared to the global average of 29% (Haberl et al., 2007). The reductions of HANPP in the last decades, however, do not necessarily imply a reduction of global environmental pressure related to the European consumption. From trade analysis, it becomes evident that these dynamics are at least partly concuring with shifts away from domestic to international production and imports of biomass to Europe (Kastner et al., 2014). Before discussing the main findings in view of the research questions outlined in the introduction, we briefly review the our results with respect to the conceptual choices made, and regarding the least reliable data and assumptions.

Several definitions of HANPP have been operationalized empirically, and the choice of definition may strongly impact the results (e.g., Haberl et al., 2014; Smil, 2011). We chose the definition proposed in Haberl et al. (2007) for our study aims, because it offers the most inclusive definition, incorporating harvest flows on all land use types (as opposed to only agricultural harvest such as in the low definition of Vitousek et al., 1997), as well as indirect NPP appropriation due to land conversion (which was not accounted for in the medium estimate of Vitousek et al., 1997 and the HANPP assessment of Imhoff et al., 2004). Focusing on aboveground HANPP, as we have done, produces slightly higher HANPP results than HANPP definitions which include also belowground NPP flows. Given that most biomass appropriation takes place aboveground, aboveground HANPP tends to be higher than total HANPP (e.g., 29% as opposed to 24%) on the global scale in the year 2000, see Haberl et al. (2007)). This difference may – together with the different data sources used – explain why our numbers tend to be slightly higher than the respective national results in the data set presented by Krausmann et al. (2013). The robustness of our data is weakest concerning the amount of grazed biomass, particularly in the time period before the availability of data on livestock productivity and feed composition. A sensitivity analysis carried out to challenge data robustness in the period before World War I shows that, while the amount of grazed biomass may have differed substantially from our assessment in some countries as we go back in time, total HANPP trends were not impacted by modified assumptions. Our results thus demonstrate that it is both possible and worthwhile to use national data on land use to generate consistent long-term data sets of HANPP on the national scale.

The most important land-use changes of the past two centuries, observed in most countries of the sample, can be divided into changes in area extent of land-use types and changes in land-use intensity on these land-use types. Concerning changes in the extent of individual land-use types, we observed a stagnation and decline of cropland in the 20th century, for some countries after a (shorter) period of cropland expansion, decreasing grazing areas, and growing settlement as well as forest areas. These findings are well in line with observations described as forest transition (Mather, 1992; Meyfroidt and Lambin, 2011; Rudel et al., 2005).

Concerning changes in biomass extraction, stronger intensification processes took place on cropland. Cropland harvest represents the largest harvest component, and harvest intensity is highest on croplands, in many cases even surpassing the level of NPP\_pot. The increase in HANPP\_\text{harv} per unit of cropland during the decades after World War II was fostered by the industrialization of agriculture, with strong increases in input intensity, such as increases in tractor numbers and mineral fertilizer use (Erb et al., 2008; Krausmann et al., 2012). According to the FAO database (Food and Agriculture Organization of the United Nations Statistics Division; http://faostat3.fao.org/), total fertilizer consumption increased in all countries in the decades after 1961 with highest values reaching levels of c. 150% of 1961 (Netherlands) and c. 1600% (Albania) in the 1980s. Since then, fertilizer consumption declined and, by the year 2000, had reached values similar to those in 1961. The number of tractors also increased by a factor of two in the sum of our sample, with a stagnation since the 1980s. These stagnations in input intensity are mirrored by stagnations and a decline of harvest as well as harvest intensity in the late 20th century.

The quantification of the relative importance of underlying trends in explaining temporal trends of HANPP revealed that land-use intensification and efficiency gains were particularly relevant, while the area effects played a smaller role. In all countries, efficiency gains were larger than increases in biomass extraction, with the only exception of the United Kingdom. Efficiency gains were particularly high in those land-use types and countries, where biomass extraction was high too, i.e., on croplands and – in some countries – on grazing lands, as well as in Denmark, the Netherlands and the United Kingdom, the countries with the highest HANPP levels. The expansion of forests (the least intensively-used land-use type) at the expense of more intensively-used lands (cropland and grazing lands) had, in the overall sample, an effect in a similar dimension as the net-effect of the two counterbalancing effects, HANPP efficiency and harvest intensity. These results provide important insights which complement research on long-term changes in area extent of croplands (Klein Goldewijk, 2001; Ramankutty and Foley, 1999) or forests (Meyfroidt and Lambin, 2011) on the one hand, and on patterns of land-use intensity, which has been studied on croplands mainly (Siebert et al., 2010). With its integrative approach, the HANPP framework sheds light on the relative importance of the different processes occurring on different land-use types. Particularly the finding that grazing areas had an important effect on HANPP declines in Europe due to area decline and intensification is insightful in this respect.

Trends on grazing areas were particularly diverse and inconclusive, showing an overall trend of a reduction of the extent grazing land but concomitant with increases of harvest intensity in certain countries and decreases in others. Part of this heterogeneity in grazing land change and its effect on HANPP owes to the fact that grazing land comprises a very wide range of ecosystems, with a huge range in the degree of land-use intensity. For instance, the Netherlands show grazing land dynamics similar to those of cropland – not surprising when taking into account that in this country more than half of the national consumption of nitrogen fertilizers is applied to grasslands (Lassaletta et al., 2014). In contrast, in many regions of the European South, grazing occurs on land hardly managed at all, such as the Macchia-dominated grazing lands in Italy (Niedertscheider and Erb, 2014). In consequence, the overall trend of shrinking grazing land is reflected in the observed HANPP dynamics, but with regard to harvest intensity as well as changes in efficiency no clear signal in their contribution to the HANPP trajectory was observed. Both effects, however, are of similar magnitude, but show a strong regional variation.

Which environmental or socio-economic drivers were linked to the described changes in land-use and HANPP? The temporal and spatial differences in HANPP we have observed in our sample appear to be the results of complex combinations of political, socio-economic and environmental factors, none of which are exclusive. Environmental factors, such as climate and topology had major effects not only on the levels of HANPP at the country scale, but also on the temporal trends of HANPP and its two components, HANPP\_\text{harv} and HANPP\_\text{frac}. High shares of mountainous areas in a country (e.g., in Austria, Italy, partly Romania) combined with shorter vegetation periods in the more northern, boreal regions
(e.g., Sweden) go hand in hand with high shares of forest land. This results in generally lower levels of HANPP and lower harvest levels. Topological differences also play out in land use dynamics along with the post-WWII agricultural industrialization processes, during which small scale agriculture in predominantly mountainous areas became less profitable (Guidi and Piusi, 1993; Piusi and Pettenella, 2000). Hence forest re-growth combined with agricultural contraction was highly pronounced in Italy and Austria after WWII, leading to overall higher area effects on declining HANPP levels compared to the other case countries.

On the other hand, political and economic drivers also affect HANPP levels and trends. Economic and population growth went along with increasing biomass extraction and HANPP, for most of the countries in our sample during much of the observed period. Interestingly, the stagnation of biomass extraction in the 1980s occurred in Eastern and Western European countries under very different circumstances. In Eastern European countries, it coincided with the collapse of the agricultural sector after the fall of the iron curtain, dynamics described also for other formerly centrally planned economies of Europe, such as Hungary (Kohilheb and Krausmann, 2009), Czechoslovakia (Kuskova et al., 2008) or the German Democratic Republic GDR (Niedertscheider et al., 2014). In Western European countries, such as as the Netherlands and Denmark, other drivers had a similar effect, such as agricultural policy (e.g., set-aside policies), or world market dynamics. Wars were another political driver changing (short-term) HANPP levels. Based on the (admittedly limited) evidence available (data were interpolated for some countries during war years), we conclude that short-term land abandonment and martial destruction may have significantly reduced HANPP levels during and shortly after the World Wars. The extent of individual land-use types, however, does not show a similarly clear trend, which can be, of course, also attributed to the poor data quality in these periods. In general terms, wars seem to be interruptions rather than turning-points toward novel trends.

It is noteworthy to also mention factors which do not directly correspond to HANPP trends or patterns in our sample. For instance, the shift from monarchy to republic which occurred in many countries after the First World War (WWI) does not translate directly into a shift in land systems, at least not those parameters assessed within the HANPP framework. In addition, there seems to be no direct link between HANPP levels and economic structure: capitalistic countries do not display substantially different levels than centrally-planned economies, with the evident exception of the Albanian case. Similar findings are presented in other national long-term case studies, such as Czechia and Germany (e.g., Grešlová Kušková, 2013; Niedertscheider et al., 2014), warranting a future research focus on the political driving forces and their implications for land-use change.

5. Outlook

Based on the empirical findings discussed above, we want to highlight three suggestions for further research in the field of long-term socio-ecological research: (1) Our findings on the diverse national intensity changes on grazing lands merits further emphasis. To improve our understanding of the various types of grazing lands, their management and ecological characteristics, as well as the pertinent databases appears timely. (2) Both, spatially and temporally, consistent analyses on nested scales, from small-scale, local levels to the national and supranational scale, would allow opportunities to gain insights into drivers of land-use change. Local or regional scale case studies would help to better understand processes of intensification versus abandonment which are often leveled off (and thus withdrawn from analysis) on the national scale (Fuchs et al., 2015). These small-scale changes in land use can inform and be informed by national-scale research on socio-economic drivers (Bürgi et al., 2004; Munteanu et al., 2014). Such an endeavor could also profit from shorter-term temporal perspectives on the interrelation of political practices and HANPP trajectories (focussing e.g., on periods coined by the dominance of stabilizing forces, i.e., land use regimes (Jepsen et al., 2015 under review)). (3) The analysis of impacts of HANPP on ecosystem functioning, or the provision of ecosystem services, needs to be further explored, as they represent consequences as well as a drivers of land system change (Erb et al., 2013). Our finding that in many European countries, land use drove actual NPP above levels of potential vegetation raises questions such as: how far could NPP be pushed, and which ecological costs would this entail? Research in this direction would yield important insights for sustainable development.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landusepol.2015.04.027

In addition, data are provided at the website of the Institute of Socio Ecology, http://www.uni-klu.ac.at/socsec/inhalt/1088.htm

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