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Human appropriation of net primary production in the United Kingdom, 1800–2000 Changes in society's impact on ecological energy flows during the agrarian–industrial transition☆

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ABSTRACT

This paper presents an empirical analysis of the United Kingdom's society's long-term intervention into the energy flows of domestic terrestrial ecosystems through the human appropriation of aboveground net primary production (aHANPP) covering the period 1800–2000. The depicted aHANPP trajectory and the historical development of its components are discussed in view of a continuously increasing population and the transition process from an agrarian to an industrial socioecological regime. During the 19th century, aHANPP shows a steady decline from its level of 71% in 1800. While even higher levels were reached during the mid 20th century, the trend during the last forty years of the period under investigation again shows a reduction of aHANPP, which lies at 68% in the year 2000. The high values of aHANPP in the United Kingdom are primarily attributable to the limited amount of forest in comparison to large agricultural areas. At the beginning of the studied period, the relative stabilisation or even decrease in aHANPP in comparison to population development was made possible through the area expansion of and productivity increases on cropland and permanent pastures. Later this was made possible through the outsourcing of biomass harvest, by satisfying local nutritional demands by means of overseas imports, and as from the mid 20th century through huge amounts of fossil fuel based inputs into agriculture (e.g. increased amounts of fertilizers and motorized traction) which allowed increases in biomass harvest to be decoupled from HANPP.

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1. Introduction

Hobsbawm (1969) described the industrial revolution as having been the most thorough upheaval of human existence in world history ever documented in writing. A multitude of studies deal with industrial transformation from a social and classical economic–historical point of view. On the other hand, researchers from the fields of social ecology and environmental history (e.g. Schandl and Schulz, 2002; Krausmann et al., 2003; Sieferle et al., 2006; Schandl and Krausmann, 2007) have analyzed the transition process from agrarian to industrial society in view of its biophysical implications and its effect on society–nature interaction, based on the concept of socieconomic metabolism. According to this approach, society is a system that establishes and maintains a permanent throughput of energy and materials to produce and maintain its material components (see, for example, Fischer-Kowalski et al., 1997; Schandl and Schulz, 2002).Within this context, the core aspect of industrialisation lies within the transformation of the socioeconomic energy system from a solar energy characteristic of agricultural societies (a biomass based, area dependent energy system), to an energy system relying predominantly on area independent energy sources, above all fossil energy (Sieferle, 1982, 2001; Krausmann and Haberl, 2002).

In the United Kingdom, this transition process took place over a period of almost 400 years (Schandl and Krausmann, 2007). By the beginning of the 19th century, coal had replaced wood as a fuel for both industrial and domestic proposes on a large scale, and was gaining increasing importance as a source for power in connection with the development of the steam engine (Sieferle 1982; 2001; Schandl and Krausmann, 2007). Agricultural production however, still remained within the limits of the solar-based energy system up until the 1950s. These and other changes in society–environment interrelations were discussed in a special section of *Ecological Economics* (41: 175–288) on "European Environmental History and Ecological Economics". This special section included a study by Schandl and Schulz (2002) on the United Kingdom's changing socioeconomic metabolism during industrial transformation. This study shares the intention of that special section to develop a historical understanding of socially and economically driven environmental change within the framework of Ecological Economics.

In particular, this study extends on the historical metabolism study of Schandl and Schulz (2002) in that it explores the related impact

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of historical changes in the United Kingdom's socioeconomic metabolism (and hence society's natural relations) on ecosystem processes. More specifically, it empirically analyses the effect of changes in land use and biomass metabolism associated with the United Kingdom's socio-metabolic transition, on ecosystem energy flows using as the measure 'human appropriation of net primary production' (Whittaker and Likens, 1973; Vitousek et al., 1986; Haberl, 1997), abbreviated 'HANPP'. In terrestrial ecosystems, NPP is the amount of energy made available by green plants through the process of photosynthesis over a given time period, less the energy plants require for their own respiration, and constitutes the energetic basis of heterotrophic food chains. This study only considers aboveground NPP which is denoted by the prefix "a" (aNPP, aHANPP, etc.).

HANPP was assessed for the United Kingdom on a national level covering the period 1800–2000, based on national historical statistics, extensive literature reviews and own calculations. In contrast to the recent study of global HANPP by Haberl et al. (2007), which was based on international databases, a grid-based GIS land use data set derived from remote sensing information and vegetation modelling, this study also considers country level data and national statistics, thus allowing a cross-check of results derived from global data sets with national level data.

2. Methodology and materials

2.1. Calculating human appropriation of net primary production

This article is part of a special section that extensively discusses several aspects of HANPP; I therefore give just a short overview of general features of HANPP methods here. More detail can be found in the introductory article (Erb et al., 2009-this issue). The study is confined to the accession of terrestrial aboveground net primary production (aNPP), i.e. not considering the productivity of roots and NPP of aquatic plants. The human appropriation of aboveground NPP (aHANPP) was calculated for the United Kingdom adhering to its definition as the combined effect of harvest and changes in productivity due to land use as given in Haberl et al. (2004, 2007). Variables ascertained within the aHANPP calculation include the aNPP of the potential vegetation ($aNPP_0$), i.e. vegetation that would prevail without human influence (Tüxen, 1956) and the aNPP of the actually prevailing vegetation ($aNPP_{act}$), harvested aNPP ($aNPP_h$) and aNPP remaining in ecosystems after harvest ($aNPP_t$), as well as land use induced productivity changes ($\Delta aNPP_{LC}$). These relate to aHANPP and to each other in the following way:

$$aHANPP = aNPP_0 - aNPP_t \text{ with } aNPP_t = aNPP_{act} - aNPP_h$$

(Haberl, 1997)

and

$$aHANPP = \Delta aNPP_{LC} + aNPP_h \text{ with } \Delta aNPP_{LC} = aNPP_0 - aNPP_{act}$$

(Haberl et al., 2004; 2007).

In order to calculate aHANPP, one therefore needs data on the development of land use and land cover, the aboveground productivity of vegetation units, as well as data on biomass harvest. The unit of measure used to record aNPP flows was tons dry matter biomass per year (t DM/yr). Factors were assessed historically, on a yearly basis, relying on official statistical sources and if these were not available, model assumptions based on an extensive literature review (Table A1 in the Appendix).

2.2. Spatial reference system

During the period 1800 to 2000 covered in this study, there was a change in the United Kingdom's constituent countries. Up to 1922, these included England, Wales, Scotland (i.e. Great Britain) and Ireland. After the separation of the Republic of Ireland in 1923, only Northern Ireland remained part of the Union and the United Kingdom's territory was reduced by 22% (FAO, 2004). While this led primarily to a reduction of permanent pastures, other land use classes show little variation (Table 1). This is similarly true for other indicators such as total population, which was reduced by merely 6%. Agricultural production only shows a noteworthy decline in the production of hay as well as in the decrease of cattle numbers of around 35%.

The advantage of choosing this spatial reference system is that the results refer to the United Kingdom as a political and economic unit and that they can be directly related with previous studies of historical metabolism of the United Kingdom (Schandl and Schulz, 2002; Sieferle et al., 2006; Schandl and Krausmann, 2007). This choice also enabled me to use data from these studies and extend on their research. In the 'results' section, I present relative values (i.e. results per hectare and year (t DM/ha/yr) and per capita and year (t DM/ha/yr)) in order to be able to discuss the development of HANPP over time. For reference purposes a table of absolute values of HANPP and its constituents, from 1800–2000, has been included in the online supporting material (Table S1). The complete data set can be downloaded at http://www.uni-klu.ac.at/socec/inhalt/1088.htm.

2.3. Data sets

2.3.1. Land use and land cover data set

There exists no official land use inventory compiled for the United Kingdom at regular intervals of time (Best, 1981) and individual land use surveys undertaken vary both in approach, time and area scale (e.g., CS, 2000; Best, 1964, 1981). To establish a consistent time series of land use on which to base my aHANPP calculations, I therefore relied above all on agricultural statistics which give continuous historical information on the greater part of the land area in the United Kingdom (e.g., Statistical Abstracts for the United Kingdom; followed by Annual Abstract of Statistics, 1854ff; Mitchell, 1994; Collins, 2000). These derive from the agricultural census returns of Great Britain, Ireland and Northern Ireland undertaken in June of each year. The established data set consists of 24 consistent land use classes, which I have aggregated into the 6 main classes displayed in Table 1.

Cropland includes 13 different classes of predominantly annual as well as permanent crops, rotation grassland for the production of hay/silage or grazing and fallow land, which includes 'set aside' land as from 1992. Abiding to the distinction made within agricultural statistics (Statistical Abstract for the United Kingdom, followed by Annual Abstract of Statistics, 1854ff), permanent pastures were also distinguished according to their predominant use for haymaking or

Table 1
Land use in million hectares and population in millions in the United Kingdom, 1800–2000, for selected years.

Years	Population [millions]	Cropland [Mha]	Permanent pastures [Mha]	Rough grazing [Mha]	Forest and woodland [Mha]	Urban land [Mha]	Other land [Mha]
1800	15.46	6.75	4.64	9.40	1.57	0.25	8.38
1830	23.81	8.64	6.70	8.13	1.22	0.38	5.90
1870	31.26	9.52	9.20	6.94	1.01	0.56	3.74
1900	41.16	7.95	11.43	7.20	1.23	0.85	2.32
1923	44.60	6.37	7.04	6.65	1.14	1.03	1.87
1950	50.57	7.41	5.17	6.92	1.52	1.54	1.52
1960	52.37	7.36	5.18	7.41	1.70	1.68	0.75
1970	55.63	7.26	4.94	6.69	1.91	1.87	1.41
1980	56.33	7.24	4.66	6.33	2.12	2.02	1.71
1990	57.44	6.81	5.32	6.20	2.41	2.21	1.14
2000	58.65	6.61	5.36	5.67	2.79	2.40	1.24

Sources: Population: Mitchell (1994) and Annual Abstract of Statistics (2004). Land use: Own calculations. See text and Table A1 in the Appendix.

grazing, within the original data set. Rough grazing land refers to mountainous and heath land used for grazing, predominantly by sheep (Lazenby, 1981), which bares vegetation of low productivity (Hopkins, 2000a,b).

Forest and woodland includes areas of high forest; that is, forest normally composed of trees of seedling origin, but may also include trees of vegetative reproduction such as poplars, coppices and scrublands (UN, 2000). Urban land comprises residential and industrial areas and associated spaces as well as transport land. Other land represents all remaining land not accounted for in one of the other land use classes and was obtained by subtracting the sum of these classes from the total land area. At the beginning of the period under investigation, the predominant part of this area is agriculturally unproductive mountain moor and heath land, closely resembling rough grazing land. It further contains agricultural land and woodland not included in agricultural returns and censuses of woodland and trees, mining areas and military land, as well as montane, sublitorral and litorral areas and inland rock (Best, 1981; CS, 2000; Sieferle et al., 2006). Except for the change in territory, related to the secession of the Republic of Ireland, constant values were used regarding the total land area of the United Kingdom. Changes that might have occurred along the coastlines or because of inland flooding were considered negligible in relation to the overall calculation. The historical development of the extent of urban land was determined via historical values on urban land provision (ha/1000people) adapted from Best (1981), who has dealt extensively with the development of urban land in Great Britain, and population figures taken from Mitchell (1988) and Annual Abstract of Statistics (2004).

With respect to agricultural and woodland areas, the existing data set builds on records previously established by Schandl and Schulz, different parts of which have been published in Schandl and Schulz (2000) Schandl and Schulz (2001) and Schandl and Schulz (2002), Krausmann et al. (2003) and most recently in Sieferle et al. (2006), and are based chiefly on periodically available data supplied by Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics, 1854ff), Mitchell (1994) and Collins (2000). I comply with model assumptions made by Schandl and Schulz (2002) for years before official statistical documentation, as well as aggregate categories of crops used by them when individual categories were reported inconsistently (Table A1 in the Appendix; Schandl and Schulz, 2001; Sieferle et al., 2006). Figures relating to areas of individual crops and other agricultural land uses were, for the most part, made available by agricultural returns as from the second half of the 19th century. This also applies to data on woodland areas. Sources of area statistics for each of the individual land use categories and their constituents have been summarized in detail in Table A1 (Appendix). This also includes sources of associated harvest and productivity values, which will be referred to in the following sections.

2.3.2. Productivity of potential vegetation ($aNPP_0$)

$aNPP_0$ denotes the productivity of vegetation that would prevail without human influence (Tüxen, 1956). The values used for this paper derive from calculations with the Lund–Potsdam–Jena (LPJ) Dynamic Global Vegetation model (Sitch et al., 2003) with an improved representation of hydrology (Gerten et al., 2004), carried out during the course of a study on global HANPP published by Haberl et al. (2007) and relate to the total land area of the United Kingdom (Erb et al., 2009-this issue).

In the United Kingdom, vegetation that would prevail without human influence would predominantly be temperate deciduous forest and woodland (Ramankutty and Foley, 1999). Grasslands, which are characteristic of the landscape today, are for the most part a result of extensive forest clearance and intensive agricultural management (Hopkins, 2000a,b; Green, 1990; Sala, 2001) and only form the natural climax vegetation were environmental conditions prevent tree growth (Price, 2003 citing Bell and Walker, 1992; Archibold, 1995).

2.3.3. Biomass harvest ($aNPP_h$)

$aNPP_h$ relates to all aboveground biomass harvested in the course of human activities. Besides commercial crop harvest (according to common procedure roots and tubers are included in the aboveground compartment, see Erb et al., 2009-this issue) and wood harvest, this also includes crop residues such as straw (whether used or remaining on the field) and the non-merchantable parts of trees cut for timber, biomass grazed by livestock and harvest in urban areas (e.g. mowing). Biomass destruction through human induced fires, which can also be regarded as part of NPP_h (Haberl et al., 2007), was not included in the calculation. It makes up a negligibly small fraction of appropriated biomass in the United Kingdom (Annual Abstract of Statistics, 1956ff; GBA, 2000).

Agricultural statistics on the production of crops are available for Great Britain as from 1884 and for Ireland as from 1847. Figures for preceding years were extrapolated from yields, recorded by authors such as Thirsk (1985) and Mingay (1989) or modelled based on their development in previous years, and available crop areas. To determine the amount of by-product harvested, I used harvest indices (HIs) for individual crops. These relate the commercial harvest of a crop to its total aboveground biomass (Evans, 1993). Sources of statistics for different crops and HIs have been summarized in Table A1 in the Appendix. The production figures used for individual crops again comply, to a large extent, with those applied by Schandl and Schulz (2002).

While agricultural statistics report fresh weight or standardized water content (e.g., 14% for hay) of biomass harvested, in HANPP calculations biomass flows are expressed either as dry matter or as carbon flow (Schandl et al., 2002). Figures were therefore converted to t DM/yr by using information on the water content of the crops under consideration (Souci, 2000; Löhr, 1993; Watt and Merrill, 1975; Haberl, 1995).

The amount of grazed biomass was ascertained by determining the grazing demand (designated as the "grazing gap") of grazing livestock. This constitutes the difference of feed demand of grazers and the quantity of market feed and non-market feed (including fodder crops and crop residues from local production) available to them after accounting for feed demand of non-grazing livestock. Feed demands were calculated using models developed by Haberl et al. (2007). For the years 1961–2000, data on available market feed was taken from FAO commodity balances (2004). Feed commodities given by FAO include primary crops used as feed, as well as processed feedstuffs (of both plant and animal origin), from local production and imports. For years before 1961, amounts of available commodities were modelled based on information on their historical availability given by authors such as Overton and Campell (1999) and Brassely (2000a,b). Grazing was attributed primarily to fallow land, rotation and permanent pasture for grazing, and rough grazing land, with the constraint, that a maximum of 75%, 75% and 65% of annual biomass increment respectively, could be grazed from these areas (Krausmann and Erb, personal communication 2006). Excess grazing demand between 1800 and 1819 was attributed to 'other land'. Between 1962 and 2000, grazing demand again exceeds the grazing potential. Here I assumed marked feed might have been underestimated due to faulty statistical data, feed demands might be slightly overestimated and excess grazing to be accounted for in harvest from urban areas. These also include isolated dwellings in the countryside (Best, 1981).

Harvest of wood is poorly documented within UK national statistics. Data used was therefore taken from the UNECE TIMBER database (2004), which provides figures on removals (1000 m^3 under bark) of coniferous and non-coniferous round wood and fuel wood, as from 1964. Wood harvest for earlier years was determined based on available data on forest area and assumed values for removal per hectare based on information on the historical development of timber harvest found in literature (Sieferle, 1982). To convert green volumes to t DM, I used wood densities referring to dry matter per cubic metre

green volume, taken from Haberl et al. (2007), namely 0.41 and 0.57 t DM/m^3, for coniferous wood and non-coniferous wood respectively. To determine the total amount of biomass harvested from data on removals, I used factors accounting for bark removed (these are based on information on the percentage of bark that has been removed −11% for both coniferous and non-coniferous wood), and country-specific recovery rates to establish the amount of wood left in forest and destroyed during the process of logging (88% and 74% for coniferous wood and non-coniferous wood respectively, relating to both round- and fuel wood). Both bark factors (i.e., bark as a percentage of total biomass volumes of woody biomass harvest) and recovery rates derive from UN (2000) data, and relate to recent years. Due to missing historical data, these were applied over the entire period under investigation. Harvest from urban areas was held to be 50% of the $aNPP_{act}$ attributed to this land use class, following Haberl et al. (2007).

Recent HANPP studies (e.g., Haberl et al., 2007) report separately appropriated biomass that has no further societal use and is therefore returned back to nature (were it might still supply energy to ecological food webs) as 'backflows to nature'. This includes crop residues from annual crops ploughed in or burnt on the field, wood left in the forest during harvest of timber and on-site backflows of manure from grazing livestock. Within this paper these are presented as percentage of total harvested biomass, also giving an indication of the change in efficiency in the use of harvested biomass. Amounts of used and respectively unused crop residues and wood were determined via recovery rates, which were compiled based on values and information found in the literature (Foot, 1977; Di Blasi et al., 1997; UN, 2000; Stott, 2003; FAO, 2004). With respect to livestock feces I followed the conjecture of Haberl et al. (2007) who, based on Vetter and Steffens (1986) and BMLF (1991), assumed that cattle excrete 35% and all other grazers 25% of dry matter feed intake and that two thirds of this excreted amount is dropped directly on grazing areas, assuming these proportions not to have changed markedly, over time.

2.3.4. Productivity of actually prevailing vegetation ($aNPP_{act}$)

Two approaches were chosen to calculate the $aNPP_{act}$ relating to different land use categories. The $aNPP_{act}$ of individual crops and rotation pasture on cropland as well as permanent pasture was extrapolated from available data on crop and grass harvest. For all other land use areas, I used estimates of $aNPP_{act}$ per unit area in t DM/ha/yr, and modelled these historically, backed by information and values found in the literature. This will be explained in more detail below. Also, a summary of used data sources and model assumptions applied to determine $aNPP_{act}$ historically for each of the land use categories can be found in Table A1 in the Appendix.

The $aNPP_{act}$ of individual crop areas was calculated as the sum of commercial crop harvest, crop residues and unaccounted-for $aNPP_{act}$; that is, $aNPP_{act}$ losses during the growth period, due to herbivory and the aNPP of weeds. Crop residues were extrapolated from crop harvest by means of harvest indices (as previously described for $aNPP_h$), while unaccounted-for $aNPP_{act}$ was extrapolated from $aNPP_h$ using pre-harvest loss factors based on Oerke et al. (1994). Unaccounted-for $aNPP_{act}$ makes up 23% of $aNPP_{act}$ in 1800, 20% in 1850, 17% in 1900 and 14% for the years after 1950. Fallow land I assumed to be invaded by herbaceous vegetation and $aNPP_{act}$ in t DM/ha/yr to be similar to that of less productive permanent pastures.

The $aNPP_{act}$ of rotation pastures and permanent pastures for hay/silage was determined based on available data on harvest of grass from these areas, assuming that the amount of grass harvested in a given year constitutes 75% of total $aNPP_{act}$ (Krausmann, personal communication 2006 and Suttie, 2000). I did not distinguish between the $aNPP_{act}$ t DM/ha/yr of rotation pasture for hay/silage and that of rotation pasture for grazing. I did however make this distinction with respect to permanent pastures used for grazing, assigning to them a lower productivity as compared to permanent pastures for hay/silage. While some permanent pasture swards may still contain high amounts of sown species, i.e. rye grasses, and be located on favourable sites and therefore might be highly productive, the larger part of these pastures — and these are most often used for grazing — are dominated by *Agrostis* spp., *Festuca* spp. and other plants of low productivity (Stapledon and Davies, 1948; Lazenby, 1981) also characteristic of rough grazing land (Stapledon and Davies, 1948; Tansley, 1965; Hopkins, 2000a,b). While I am aware that the agricultural distinction made on the basis of management of permanent pastures does not necessarily adhere to actualities of productivity, I believe the method chosen does allows a fair approximation of the overall aboveground productivity of permanent pastures. Based on the applied methodology, this ranges between 3.9 t DM/ha/yr in 1800 and 7.3 t DM/ha/yr in the year 2000, while the average $aNPP_{act}$ of cropland including rotation pasture and fallow land lies at 5.4 t DM/ha/yr at the beginning and 12.6 t DM/ha/yr at the end of the studied period.

Rough grazing land was allocated an average constant $aNPP_{act}$ value per unit area of 3.5 t DM/ha/yr. This was done based on information on the distribution of dominant plant communities and literature values found on annual herbage production (Stapledon and Davies, 1948; Milne et al., 2002; Hopkins, 2000a,b; Palmer, 1997) of these communities, as well as values found on aNPP of chalk grasslands in the southern English uplands (Williamson and Pitman, 1998). It is difficult to estimate how the average $aNPP_{act}$ of these areas might have varied over the studied period.

The $aNPP_{act}$ of forest and woodland was held to be equal to $aNPP_0$. This category includes high forest areas, areas of coppice, scrub and felled areas. Nevertheless, since the area of high forest makes up by far the greatest part over the entire period under investigation (Forestry Commission, 1987; UN, 2000) and forests and woodlands make up merely a small proportion of the area of the United Kingdom this method seemed permissible.

Concerning the $aNPP_{act}$ of urban land I followed the assumption of Haberl et al. (2007), that one third of the urban area is covered by vegetation, while two thirds are unproductive. Assuming the vegetated area to be covered mainly by cultivated grass (e.g., lawns, golf courses, and road verges) and trees (e.g., parks), this was attributed the yearly averages of $aNPP_{act}$ per unit area of woodland an intensified grassland and lies at 1.6 t DM/ha/yr in 1800 and 2.6 t DM/ha/yr in the year 2000.

As the majority of 'other land' between 1800 and 1850 resembles rough grazing land, this was assigned the same productivity i.e., 3.5 t DM/ha/yr at the beginning of the studied period. A slightly lower value of 3.0 t DM/ha/yr similar to that of urban land was assigned for the year 2000, assuming the majority of the area of 'other land' at this stage to be unproductive. Values for intermediate years are based on linear interpolation.

3. Results

During the 200 years under investigation, human appropriation of aboveground net primary production (aHANPP) in the United Kingdom remains at high levels but shows clear decreasing and increasing trends in distinct periods. While aHANPP steadily declines from the beginning of the studied period up to the late 19th and early 20th century, this is followed by a visible increase in aHANPP up to the late 1950s, after which it declines once again up to the year 2000. This decline at the end of the studied period coincides with a strong decrease in aHANPP due to land use induced productivity changes ($\Delta aNPP_{LC}$), while harvest ($aNPP_h$) and aNPP of actually prevailing vegetation ($aNPP_{act}$) show the reverse trend.

The aNPP of actually prevailing vegetation ($aNPP_{act}$) and harvested aNPP ($aNPP_h$) show an almost corresponding development during the examined timeframe, with the effect that aNPP remaining in ecosystems after harvest ($aNPP_t$) remains relatively stable over the entire

period. While there was a mutual rise in productivity and harvest of biomass up to the mid 19th century, within the subsequent 100 years, both of these constituents show only little variation. This interval of stagnation was followed by steep increases in both $aNPP_{act}$ and $aNPP_h$ between 1950 and 2000. The steep rise in $aNPP_{act}$ was in turn accompanied by a dramatic decline $\Delta aNPP_{LC}$ (Fig. 1). While this had still contributed considerably to total HANPP up to the mid 20th century, as from the mid 1980s HANPP is in sum attributable solely to harvested aNPP and $\Delta aNPP_{LC}$ even becomes negative (Fig. 1).

Related developments in land use (Fig. 2) show that intensively cultivated areas, including cropland and permanent pastures, jointly expanded to around 63% of the total land area up to the early 20th century and then decreased again down to 50% of the total land area towards the end of the studied period. Together with extensively managed rough grazing land the agricultural area in the United Kingdom makes up between 68 and 86% of the United Kingdom's total land area during the observed period, while the share of forest area, even at its greatest expansion in the year 2000, still only makes up 12%. While urban land continuously increases between 1800 and 2000, remaining 'other land' dramatically declines.

When looking at the contribution of individual harvest types to total $aNPP_h$, agricultural harvest is responsible for over 90% of total biomass harvest over the entire period under investigation, while wood harvest never makes up more than 5%. Agricultural harvest includes commercial crop harvest and harvest of by-products (on cropland and also including harvest of hay on permanent pastures) and grazing on other land at the beginning of the studied period, fallow land and rotation pasture included in cropland, permanent pasture and rough grazing land. Backflows of harvested biomass, including on-site backflow of manure on grazing areas, of crop residues to cropland and wood residues to forest and woodland, remain relatively stable up to the end of the observed period, even with the dramatic increase in $aNPP_h$ during the second half of the 20th century (Fig. 3).

While population shows a steep, almost linear, overall increase over the examined period, aHANPP and its related parameters did not

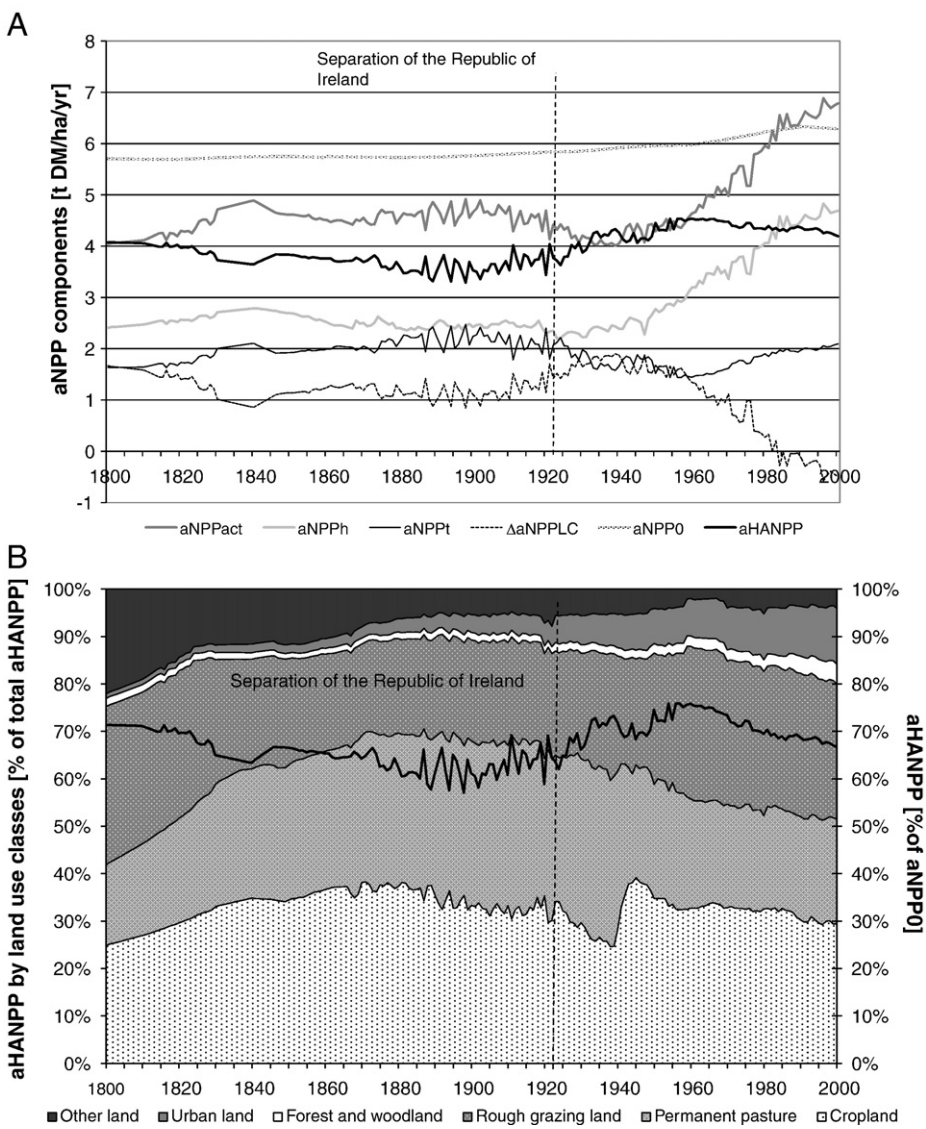

Fig. 1. Human appropriation of aboveground net primary production (aHANPP), in the United Kingdom, 1800–2000. A) Appropriated aNPP (aHANPP), productivity of potential vegetation ($aNPP_0$), productivity of actually prevailing vegetation ($aNPP_{act}$), biomass harvest ($aNPP_h$), aNPP remaining in ecosystems after harvest ($aNPP_t$) and land use induced productivity changes ($\Delta aNPP_{LC}$), in tons dry matter per hectare and year. B) Primary Axis: aHANPP according to individual land use classes. Secondary axis: appropriated aNPP (aHANPP) as percentage of productivity of potential vegetation ($aNPP_0$). Sources: Own calculations. See text.

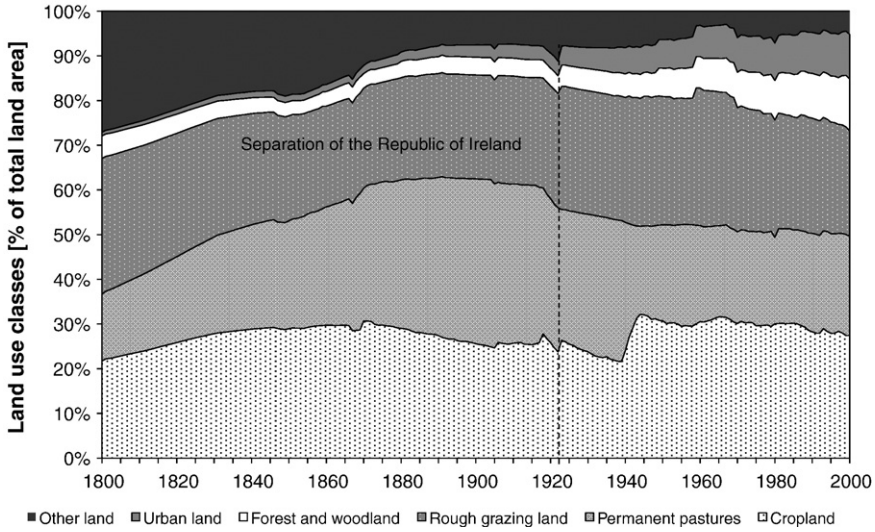

Fig. 2. Aggregated land use classes, as percentage of total land area, in the United Kingdom, 1800–2000. Source: Own calculations. See text.

follow this growth pattern. When looking at per capita developments, values are therefore considerably lower in 2000 than in 1800. Per capita, aHANPP declines most steeply at the beginning of the studied period and seems to stabilize after the secession of Ireland, decreasing again marginally as from the late 1950s, in spite of an increase in per capita biomass harvest during this time (Fig. 4).

Recently, Schandl and Krausmann (2007) have identified three distinct stages in the course of the United Kingdom's socio-metabolic transition towards a fully industrialized country located between the mid 17th and early 19th century, the 1830s and the mid 20th century and the 1950s onwards. Amongst other socioeconomic developments, these stages are characterised by incisive changes within the United Kingdom's agricultural and energy system. Taking a closer look at the development of aHANPP according to the three stages identified by Schandl and Krausmann (2007), one can observe that it shows a decline of almost 10% during the investigated part of the first stage — from 4.1 t DM/ha/yr at the beginning of the 19th century to around 3.7 t DM/ha/yr, in the 1830s. This corresponds to a decline of aHANPP as percentage of $aNPP_0$ from 71% to 65%. $\Delta aNPP_{LC}$ declined from around 1.7 t DM/yr in 1800 to 0.9 t DM/ha/yr in the late 1830s. At the same time, biomass harvest increased from around 2.4 to 2.8 t DM/ha/yr but remained at a level of nearly 60% of $aNPP_{act}$, which increased from roughly 4.1 to 4.9 t DM/ha/yr (Fig. 1). Looking at related land use developments, cropland expanded by around 7% and permanent pastures by almost 10% between 1800 and the 1830s (Fig. 2). This expansion was accompanied by a simultaneous increase in the productivity of these areas. While $aNPP_{act}$ per area of cropland increased by about one quarter, $aNPP_{act}$ per area of permanent pastures increased by about one tenth. Extensive areas of low productivity, namely rough grazing and other land, decreased by around 5 and 10% respectively between 1800 and the 1830s. As the average population growth per annum during this time was around 1.33%, aHANPP per capita declines quite drastically, from 8 t DM/cap/yr down to 4.5 t DM/cap/yr (Fig. 4), in other words by more than 40%.

A different rate of development becomes visible between 1840 and the mid 20th century. Up to the beginning of the 20th century, aHANPP shows a further decline down two around 3.5 t DM/ha/yr (60% of $aNPP_0$). After 1905, aHANPP increases again and reaches a high of 4.5 t DM/ha/yr (76% of $aNPP_0$) in the late 1950s (Fig. 1). The area of cropland grew up to the early 1870s, when it held a share of around 30% of the total land area. By this time, the area of forest and woodland had already been reduced to merely 3% of the total land area, while other land, which had still made up around a quarter of the land area at

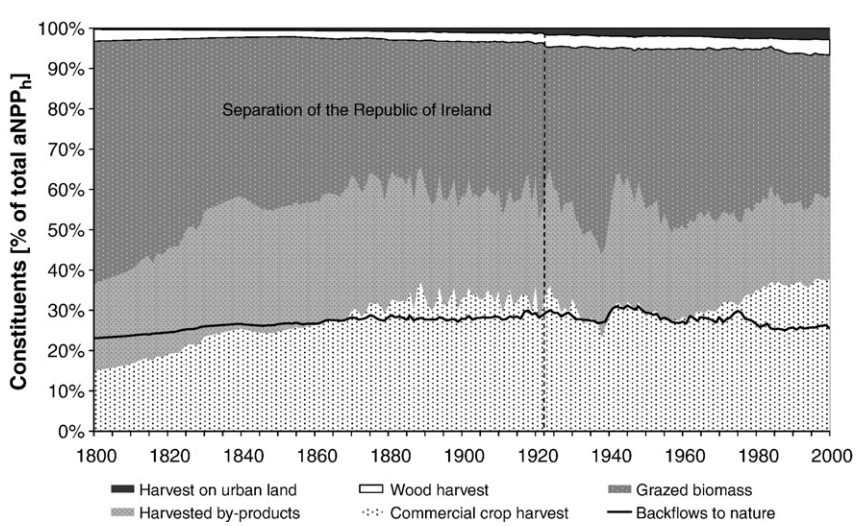

Fig. 3. Constituents of harvested biomass ($aNPP_h$), as percentage of total $aNPP_h$, in the United Kingdom, 1800–2000. Source: Own calculations. See text.

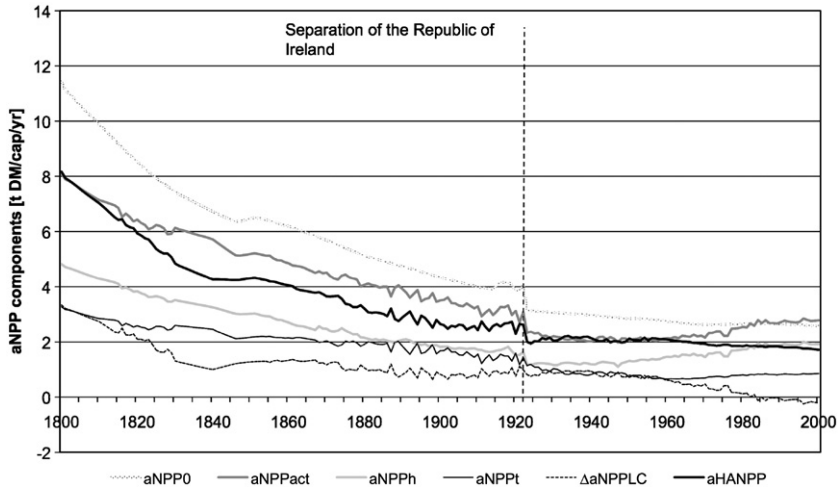

Fig. 4. Human appropriation of aboveground net primary production (aHANPP), per capita, in the United Kingdom, 1800–2000. Productivity of actually prevailing vegetation (aNPPact), biomass harvest (aNPPh), aNPP remaining in ecosystems after harvest (aNPPt), productivity of potential vegetation (aNPP0), land use induced productivity changes ($\Delta aNPP_{LC}$) and aHANPP, in tons dry matter per capita and year. Source: Own calculations. See text.

the beginning of the 19th century, had been reduced to around 11%. Permanent pastures continued to expand up until the early 20th century at which point in time they made up 37% of the total land area (Fig. 2). Even though the secession of Ireland led to a reduction of the area of permanent pastures by almost 30%, these continued to make up a comparably big portion of the new total land area and only significantly declined between 1940 and 1945.

When looking at related productivities per hectare of both cropland and cultivated grassland between the mid nineteenth and mid 20th century, these show little development up until 1905 and even decrease thereafter. This is also reflected quite visibly in the development of overall $aNPP_{act}$ and respectively $\Delta aNPP_{LC}$. At the same time, harvested biomass remained relatively stable at a high level of around 2.5 t DM/ha/yr. In 1800, crops and their residues had made up around 35% of total harvested biomass, while biomass harvest through grazing amounted to 60%. By the 1840s, this relation had been reversed and the distribution between the two remained relatively stable up to the beginning of the 20th century, after which it was subject to strong fluctuations during the war and interwar years. While in total, crop harvest remained at around 60% up to the first World War, there was a visible shift in the ratio between primary crop harvest and harvest of crop residues as from the late 19th century (Fig. 3). aHANPP per capita, on the other hand, continued to decline throughout the entire phase and lies at 2.1 t DM/cap/yr during this time (Fig. 4).

When looking at the development of HANPP and its constituents between 1950 and the year 2000, this is most striking: Overall harvest ($aNPP_h$) increased by around 70% during this time and amounts to 69% of $aNPP_{act}$ at the end of the 20th century. In spite of this, aHANPP decreased again from its peak in the late 1950s, as the strong increase in $aNPP_{act}$ also led to $\Delta aNPP_{LC}$ becoming negative (Fig. 1). The extreme rise in overall $aNPP_{act}$ by 58% during this time is primarily attributable to the huge increases in aboveground productivity on cropland and permanent pastures, by around 90% and 80% respectively. At the same time there was a decrease in area, related to both of these land use categories (Fig. 2).

While commercial crop harvest continuously increased during the last fifty years under observation, harvest of crop residues persisted to decline. After a reduction of grazed biomass during the war years, it increased again up to the late 1950s. Timber harvest and harvest in urban areas increased with the expansion of the related land use categories throughout the second half of the 20th (Fig. 3), as did their contribution to overall $aNPP_{act}$. Even though per capita harvest increased from 1.3 t DM/cap/yr to around 2.0 t DM/cap/yr between 1950 and the year 2000, aHANPP per capita continued to decline down to 1.7 t DM/cap/yr until the end of the studied period (Fig. 4).

4. Discussion

Long-term studies such as the one presented here are fraught with methodological difficulties and uncertainties. Every effort was undertaken to minimize errors and uncertainty and maximize consistency and transparency of methods and assumptions (Table A1, Appendix). Wherever statistical data were available, these were used in my assessment and modelling methods were only used where data were lacking. For example, harvest not accounted for in agricultural statistics (e.g., biomass grazed by livestock on grazing lands) had to be modelled, but the methods used is well-established in both HANPP and material flow analysis (Haberl et al., 2007; Krausmann et al., 2008). Data and methods established in previous research (e.g., Schandl and Schulz, 2002; Krausmann et al., 2003; Krausman et al., 2007) were used as far as possible, as their data and methods have been published and evaluated several times. Moreover, this approach makes my results comparable with theirs and allow for analyses of the interrelations between the different biophysical indicators assessed in these studies. In particular, the modelling of land use prior to the second half of the 19th century (that is, prior to the time for which statistical data exist) was based on these studies. In all calculations I aimed to derive conservative estimates and perform all possible cross-checks. Of course, lack of data, the use of models and factors and inconsistencies in data sets result in some uncertainties, in particular with respect to the results prior to the second half of the 19th century. It is therefore important to avoid over-interpretation of the above-presented results and in particular of the data reported in Table S1 in the supplementary online material. But the order of magnitude of the flows reported here, and in particular the trajectories depicted by my time series, are plausible and can be considered to be robust. They are well in line — and have been extensively cross-checked — with other aHANPP time series presented in this special issue (Kastner, 2009-this issue; Kohlheb and Krausmann, 2009-this issue; Schwarzlmüller, 2009-this issue).

My results show that the changes in the socioeconomic metabolism of the United Kingdom during the process of industrialisation discussed, for example, by Schandl and Schulz (2002) and Krausmann et al. (2003), Krausman et al. (2007) had repercussions on land use. This is reflected in the development of domestic human appropriation of net primary production (HANPP), which measures the combined effect of harvest and land use on the availability of primary energy, in

the form of net primary production (NPP), for ecosystem processes (Haberl, 1997). At the beginning of the examined timeframe, aHANPP in the United Kingdom lies at just over 70%. While there was a gradual decrease of around 10% in appropriated aNPP between 1800 and the beginning of the 20th century, aHANPP again increased to an even higher level up to the mid 20th century, after which it shows a rapid decline and finally lies at a level of 67% in the year 2000. Looking at the last four decades under investigation, similar developments have been shown by historical HANPP studies on other European countries such as Austria (Krausmann, 2001) and Spain (Schwarzlmüller, 2009-this issue) related to the parallel industrialisation of agriculture during this period. Compared to these studies, the aHANPP value of 67% in the year 2000 is relatively high. This can be explained by the fact that the area of forest in the United Kingdom, while showing the same expanding trend, remains comparatively small.

Using country level statistical input data on harvest, livestock numbers etc. in combination with a grid-based GIS land use data set and higher productivity values relating to grassland areas, Haberl et al. (2007) calculated human appropriation of aboveground NPP, in the year 2000, to be 46,5% for Western Europe and 56% for the United Kingdom (Erb, personal communication 2007; Haberl et al., 2007), suggesting that global studies based on international databases might tend to result in more conservative (i.e. lower) aHANPP estimates than in-depth country analyses based on national statistics.

In essence, the extent of aHANPP in the United Kingdom is determined by the limited availability of forest and woodland in comparison to large agricultural areas, as well as the development of biomass harvest and productivities on intensively cultivated areas, i.e. cropland and permanent pastures. Fig. 5 shows the development of yields in the United Kingdom, between 1800 and 2000. It demonstrates the paramount importance of yield increases in "decoupling" biomass harvest from aHANPP found also in other studies (Krausmann, 2001; Kastner, 2009-this issue; Kohlheb and Krausmann, 2009-this issue; Schwarzlmüller, 2009-this issue).

Agricultural areas including cropland, permanent pastures and rough grazing land, make up 86% of the total land area at their peak expansion in the late 19th century and about three quarters of the land area in the year 2000 and are responsible for between 75 to 90% of aHANPP during the investigated period. While the aboveground productivity of rough grazing lands is relatively low and these contribute to aHANPP through land use induced productivity changes ($\Delta aNPP_{LC}$), high levels of aboveground productivity on both cropland and permanent pastures lead to a decrease in overall $\Delta aNPP_{LC}$, especially in the second half of the 20th century. The big increase in $aNPP_{act}$ and the subsequent low and negative values for $\Delta aNPP_{LC}$ at the end of the studied period are well in line with findings in other studies (e.g. DeFries, 2002; Haberl et al., 2007). In relation to aNPP appropriation through biomass harvest ($aNPP_h$), results have shown harvest from cropland and grazed biomass to be by far the biggest contributors. While variations in crop harvest follow variations of $aNPP_{act}$ on related crop areas, and are therefore not discernable in overall aHANPP, changes in the amount of grazed biomass are indeed reflected in the development of overall aHANPP.

How then can the described trajectory of aHANPP and its constituents be related to socioeconomic developments during the investigated timeframe? Hence, how does it relate to different stages identified within the United Kingdom's socio-metabolic transition?

Results show that the decline in aHANPP up to the beginning of the 20th century can be primarily attributed to a decrease in $\Delta aNPP_{LC}$ as well as a reduction in the amount of grazed biomass. $\Delta aNPP_{LC}$ declines in connection with a strong reduction of areas of low productivity, namely rough grazing and other land and a related expansion of areas of cropland and permanent pasture together with an increase in $aNPP_{act}$ per area of the same.

The first growth phase within the United Kingdom's industrial transition localised by Schandl and Krausmann (2007) between 1700 and 1830 had been characterized by rapid population growth accompanied by incisive structural and technical changes within the agricultural sector. These allowed for increases in agricultural yields, to meet growing nutritional demands, within the bounds of the solar-based energy system and an increase in non-agricultural labourers, which drove on urbanisation (Sieferle et al., 2006). The progression of urbanisation during the 19th and 20th century is clearly reflected in the continuous increase in urban land throughout the entire studied period. Amongst the changes that allowed for increases in agricultural production were the enclosure of open fields and the introduction of new crop rotations, with a related reduction of the area fallow. In 1800, only 40% of the cropland area was still managed according to the old common field system and 60% according to new crop rotation of wheat, roots for food and fodder, barley/oats and grass/clover (Sieferle et al., 2006).

The described developments within the agricultural sector were accompanied by the progressing utilization of coal for domestic heating and cooking as well as for process heat and power in industry. In turn, the replacement of wood as a source of primary energy and the related substitution of timber as a building material by bricks reduced the demand for woodland areas and made land available for agricultural production (Schandl and Krausmann, 2007). At the beginning

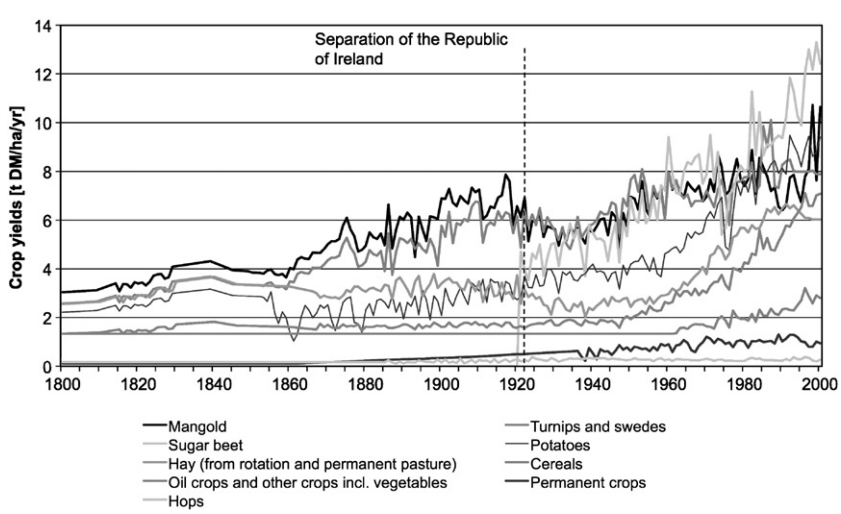

Fig. 5. Crop yields in the United Kingdom, 1800–2000 in tons dry matter per hectare and year. Sources: Calculated from figures on production and land uses. See text.

of the 19th century, the area of forest and woodland had therefore been reduced to 5% of the total land area and continued to decline (down to 3%) until the mid 19th century. The use of coal for process heat in the iron industry also played a key role in the development of new agricultural tools which allowed for increases in crop production (e.g. the use of iron ploughs or the use of steam engines for threshing; Sieferle, 1982; 2001) but also brought with it technical innovations for the improvement of wasteland (through drainage of moor areas etc.) to pasture and cropland (Allen, 1994; Sieferle et al., 2006).

The increase in the area of cropland up to the mid 19th century primarily entailed the expansion of areas of high quality cereals and fodder crops (Sieferle et al., 2006). Moreover, the increase in yields of these crops most strongly contributes to the rise of $aNPP_{act}$ on cropland during this time and the increase in the amount of available fodder crops between 1800 and 1840 correlates with the described decrease in biomass harvest through grazing.

Between 1830 and the mid 19th century, coal became the leading constituent of the United Kingdom's energy system. At the beginning of the 20th century it amounted to 80% of primary energy use and per capita energy consumption had risen, to 150 GJ/cap (Schandl and Krausmann, 2007). This increase in energy use was primarily driven by the increase in energy intensive industries and the development of the transport system and was coupled with a growing requirement of human and animal labour and population growth (Krausman et al., 2007). At the same time, agricultural production within the bounds of the solar-based energy system was reaching its limits and growing demands for food and animal feed were increasingly met by oversees imports (Krausmann et al., 2003; Sieferle et al., 2006; Schandl and Krausmann, 2007). In turn, cheap oversees imports lead above all, to a reduction in local cereal areas as well as stagnation in yields (Martin, 2000; Sieferle et al., 2006) and therefore a decline in harvest on cropland. This agricultural depression from around 1870 up to the first World War (Martin, 2000; Simmons, 2001) is quite visibly reflected in the development of $aNPP_{act}$ and $aNPP_h$ The area of cropland only grew again due to the food production campaigns of the First, but most noticeably, the Second World War, when areas of cropland that had reverted to grassland were again ploughed up for arable cultivation (Martin, 2000; Sieferle et al., 2006). While productivities and harvest on cropland only increased again markedly during the second half of the 20th century the amount of grazed biomass already increased as from around 1920 associated with an increase in feed demand of cattle. As productivities of permanent pastures remained relatively unchanged up to the mid 20th century, this increase in grazed biomass contributed substantially to the increase in aHANPP between 1900 and 1960.

The industrialisation of agriculture during the second half of the 20th century, associated with the substitution of coal by oil and later natural gas and the emergence and spread of technologies such as the internal combustion engine, electricity networks and the Haber–Bosch process (Schandl and Krausmann, 2007), and the complete substitution of traction based on animal labour (draught animals) by mechanical traction, in the course of this period, finally lead to energy provision in the United Kingdom becoming largely decoupled from land use, as discussed by Krausman et al. (2007) as well as Schandl and Krausmann (2007). Direct and indirect fossil fuel inputs into agriculture, including vast amounts of fertilizer, allowed for huge increases in agricultural production, de-linked from area expansion and the decoupling of increases in biomass harvest from aHANPP. Despite the surge in harvested biomass ($aNPP_h$) during this time, the high increases in aboveground productivity on cropland and permanent pastures together with an expansion of forest and woodland land led to a sharp decrease in overall $\Delta aNPP_{LC}$ and a reduction of aHANPP down to 67% in the year 2000. Table 2 shows the development of the combined area of cropland and permanent pastures and the development of aHANPP, $aNPP_{act}$ and $aNPP_h$ related to this area, for selected years between 1961 and 1999, in comparison to the total consumption of fertilizer (incl. nitrogenous, phosphate and potash) in the United Kingdom for these years, according to FAO (2004). Earlier increases in $aNPP_{act}$ of cropland had not led to a noteworthy decrease in aHANPP of the same, due to accompanying increases in biomass harvest. During the second half of the 20th century, aHANPP on cropland declines from still around 80% of $aNPP_0$ after the Second World down to 66% of $aNPP_0$ in the year 2000.

Table 2
Development of the combined area of cropland and permanent pasture in million hectares, and appropriated aNPP (aHANPP), productivity of actually prevailing vegetation ($aNPP_{act}$) and biomass harvest ($aNPP_h$), in tons dry matter per year, related to this area, in comparison to fertilizer consumption in kg per hectare cropland and permanent pasture, in the United Kingdom, for selected years between 1961 an 1999.

Year	Area [Mha]	aHANPP [t DM/ha/yr]	$aNPP_{act}$ [t DM/ha/yr]	$aNPP_h$ [t DM/ha/yr]	Fertilizer consumption [kg/ha/yr]
1961	12.5	4.8	5.7	4.5	112
1965	12.5	4.8	6.2	5.0	128
1969	12.3	4.8	6.5	5.2	130
1973	12.2	4.6	7.4	5.9	156
1977	12.2	4.6	7.8	6.2	164
1981	12.4	4.6	8.0	6.3	185
1985	12.3	4.6	8.7	6.9	203
1989	12.1	4.6	8.8	7.0	207
1993	12.2	4.5	9.1	7.2	172
1997	12.1	4.4	9.6	7.7	190
1999	12.1	4.4	9.5	7.6	165

Sources: FAO (2004) and own calculations.

5. Conclusion

This study shows that the trajectory of aHANPP and its constituents can be related to specific developments identified during the United Kingdom's socio-metabolic transition to a fully industrialised country. Traditional agricultural modernisation reached its limits in the first half of the 19th century, leading to a phase of stagnation of agricultural growth that lasted until after World War II. Finally, the industrialisation of agriculture after 1950 is reflected in the development of HANPP and its constituents. In contrast to studies of historical socioeconomic metabolism that have shown drastic increases in material and energy throughputs during industrial transformation (Schandl and Schulz, 2002; Krausmann et al., 2003; Schandl and Krausmann, 2007), this study shows that there is no equally strong impact of industrialisation on ecosystem energy flows. aHANPP remains comparatively stable over the examined timeframe and even decreases towards the end of the studied period. Nevertheless, the fact remains, that as early as in the 19th century, the amount of energy left for ecosystem processes ($aNPP_t$) has remained at a low level of around 30%. This however only represents an average value for the whole of the United Kingdom and aHANPP in regions, associated with, for example predominately urban land might lie above 80%. Further, the relative stabilisation of aHANPP was only made possible through the widespread availability and early use of coal in substitution for wood as a source of fuel, which in itself had devastating environmental consequences (e.g., Simmons, 2001), the outsourcing of biomass extraction through imports of required food and feed, on a grand scale since the mid 19th century, and the application of huge amounts of oil and gas based inputs into agriculture, which led to agriculture becoming an energy sink (Schandl and Krausmann, 2007).

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Appendix A

Table A1
Sources of land use, harvested biomass (aNPPh) and productivity of actually prevailing vegetation (aNPPact) for the United Kingdom (1800–2000).

Land use classes		Sources		
		Land use	$aNPP_h$	$aNPP_{act}$
Cropland				
Permanent crops	Orchards and small fruit	Before 1866: Sieferle et al. (2006) 1867–2000: Mitchell (1994) and UK Agricultural Statistics (followed by Digest of Agricultural Census statistics)	Commercial crop harvest (Mitchell, 1994) + harvested by-products. Assumed total by-product to be 2.5 times commercial harvest and that 1/3 of this (e.g. branches and leaves) is removed during harvest, following Haberl et al. (2007)	Commercial crop harvest + harvested by-products + pre-harvest losses. Calculation via harvest factors (Haberl et al., 2007) and pre-harvest loss factors (Oerke et al., 1994)
Arable crops	Cereals, fodder crops, oil crops, vegetable crops, and other crops	Before 1866: Sieferle et al. (2006) 1867 GB, 1847 IRL–1936: Mitchell (1994) and Collins (2000) 1937–2000: Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics), 1854ff and UK Agricultural statistics (followed by Digest of Agricultural Census statistics)	Commercial crop harvest (Thirsk, 1985; Mingay, 1989; Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics), 1854ff; UK Agricultural statistics (followed by Digest of Agricultural Census statistics); Mitchell, 1994 and FAO, 2004) + Harvested by-products calculated via harvest indexes for individual crops (for sources see aNPPact)	Commercial crop harvest + harvested by-products + pre-harvest losses. Calculation via harvest indexes (Krausmann, 2001; own estimates based on Krausmann, 2001; Adger and Subak, 1996; Jölli and Giljum, 2005) for individual crops and pre-harvest loss factors (Oerke et al., 1994)
Bare fallow and set-aside		Before 1866: Sieferle et al. (2006) Thereafter: Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)	Grazing, calculated via feed demand of grazers (refer to text)	Own estimate: value of permanent pastures for grazing at the beginning of the 19th century, kept constant over entire period
Rotation pasture	Rotation pasture for hay	Sieferle et al. (2006) and Schandl and Schulz (2001), Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)	Commercial crop harvest (Mitchell, 1994)	Calculation via harvest data. Assumption, that 75% of grass is removed during harvest (Krausmann, personal communication 2006; Suttie, 2000)
	Rotation pasture for grazing	Sieferle et al. (2006) and Schandl and Schulz (2001), Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)	Grazing, calculated via feed demand of grazers (refer to text).	Own estimate: same value as rotation pasture for hay, cross-checked with Hopkins (2000a,b) and Radcliffe and Baars (1987)
Permanent pasture	Permanent pasture for hay	Sieferle et al. (2006) and Schandl and Schulz (2001), Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)	Commercial crop harvest (Mitchell, 1994)	Calculation via harvest data and assumption, that 75% of grass is removed during harvest (Krausmann and Erb, personal communication 2006 and Suttie 2000)
	Permanent pasture for grazing	Sieferle et al. (2006) and Schandl and Schulz (2001), Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)	Grazing, calculated via feed demand of grazers (refer to text)	Average productivity of permanent pasture for hay and rough grazing land, cross-checked with Hopkins (2000a,b) and Radcliffe and Baars (1987)
Rough grazings		Before 1837: Sieferle et al. (2006) and Schandl and Schulz (2001), Annual Abstract of Statistics (1837ff)	Grazing, calculated via feed demand of grazers (refer to text)	Own estimate based on Milne et al. (2002), Hopkins (2000a,b), Williamson and Pitman (1998), Palmer (1997) and Stapledon and Davies (1948) — kept constant over entire period
Forest and woodland		Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff), for Ireland from 1867–1918, for Great Britain from 1871–1912 and for the United Kingdom as from 1937 Model assumptions for preceding and intermediate years, complying with Schandl and Schulz (2001) and Sieferle et al. (2006).	Commercial wood harvest 1964–2000: from UNECE TIMBER database (2004) Preceding years: Model assumption based on Sieferle (1982; 2001) + bark: bark percentage of 11% on removals for both coniferous and non-coniferous wood (UN, 2000) + wood not recovered: recovery rate of 88% and 74% for coniferous and non-coniferous wood respectively (UN, 2000)	Assigned NPP of potential vegetation (NPP0) following Haberl et al. (2007)
Urban land		Calculated via historical values on urban land provision adapted from Best (1981) and population figures from Mitchell (1988) and Annual Abstract of Statistics (2004)	Assumed 50% of yearly actually prevailing vegetation (aNPPact) to be harvested (trough mowing etc.) following Haberl et al. (2007)	Own estimate: Assumed 1/3 of area to be covered with vegetation following Haberl et al. (2007) and assigned average productivity value of forest and woodland and permanent pastures for grazing
Other land		Obtained by subtracting the area sum of all other land use classes from the total land area	Grazing, calculated via feed demand of grazers (refer to text)	Own estimate: productivity assumed to be similar to that of rough grazing land and to decline slightly over the studied period.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2009.08.012.

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