Human Appropriation of Net Primary Production (HANPP) in the United Kingdom, 1800-2000: A socio-ecological analysis
Annabella Musel, 2008:
Human Appropriation of Net Primary Production (HANPP)
in the United Kingdom, 1800-2000: 
A socio-ecological analysis
Social Ecology Working Paper 101, Vienna

Social Ecology Working Paper 101
Vienna, March 2008

ISSN 1726-3816

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Foreword

The current study was carried out with the support of Helmut Haberl, Karlheinz Erb and Fridolin Krausmann.

It presents a time series analysis of human appropriation of net primary production (HANPP) in the United Kingdom over a period of 200 years. The concept of “Human Appropriation of Net Primary Production” (HANPP), as developed by Vitousek et al. (1986) and Haberl (1997), serves as an indicator to quantify the pressure humans exert on ecosystems by altering ecosystem energy flows, through the appropriation of net primary production (NPP). Covering the period from 1800 to 2000, it extends on previous socio-ecological research on changing society-nature relations during the United Kingdoms industrial transformation. I was therefore able to benefit from the work of Heinz Schandl who gave me access to his data sets, published in Sieferle et al. (2006). The current study also works with assumptions and methods developed within the course of research of the Global HANPP-project, of which results have recently been published in Haberl et al. (2007).

A time series analysis of HANPP over a period of 200 years poses a special methodological challenge in terms of obtaining the historical input data needed for the HANPP calculation and where these are not available at least an understanding of how certain factors might have developed. Work on the present study therefore included extensive literature review, including time spent at the University Library at London School of Economics, the British Library and the National Archives during a one months research stay in London, for which I got financial support through the KWA-studentship granted by the University of Vienna.

Next to the paper, the manuscript at hand contains a German executive summary, as well as three appendixes: A supplementary, detailed report on used data and the applied methodology (Appendix A), figures of additional results and input data (Appendix B) and a Downloads¹ (Appendix C), which include two Microsoft Excel workbooks – one containing tables of additional results and input data, and the other factors used in my calculations.

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Deutsche Kurzfassung


Im Vergleich zu vorhergegangenen sozialökologischen Studien, welche sich mit dem im Vereinigten Königreich während der Industriellen Transformation verändernden gesellschaftlichen Stoffwechsel auseinandersetzen (z. B. Schandl und Schulz, 2002; Sieferle et al., 2006; Schandl und Krausmann, 2007), erlaubt eine HANPP-Studie darüber hinaus die Auswirkung dieser Veränderung auf ökosystemare Prozesse sichtbar zu machen.

Die Berechnung der HANPP bedarf neben eines über die Zeitreihe konsistenten Landnutzungsdatensatzes der Erhebung folgender Größen: NPP der ohne menschlichen Einfluss vorherrschenden, hypothetischen natürlichen Vegetation (NPP₀), NPP der aktuellen Vegetation (NPPₐₐₜ), geerntete NPP (NPPₙ), tatsächlich im
Ökosystem verbleibende NPP (NPPₜ) und den Produktivitätsverlust durch Landnutzung (ΔNPPₜₗₗ). Dabei kann HANPP als die Differenz aus NPP₀ und NPPₜ berechnet werden, wobei NPPₜ = NPPₚₑ₋ₙ, NPPₚₑ minus NPPₙ ist:

\[
HANPP = NPP₀ - NPPₜ
\]

wobei

\[
NPPₜ = NPPₚₑ - NPPₙ, \quad \text{(Haberl et al., 1997)}
\]

Gemäß der in dieser Studie angewandten HANPP Definition als die Summe von geernteter Biomasse (NPPₙ) und Produktivitätsverlust durch Landnutzung bzw. Landnutzungsveränderungen (s. o.) gilt außerdem:

\[
HANPP = ΔNPPₗₗ + NPPₙ
\]

wobei

\[
ΔNPPₗₗ = NPP₀ - NPPₚₑ \quad \text{(Haberl et al., 2004)}
\]

Aufgrund der Tatsache, dass die Datenlage zur unterirdischen Komponente der NPP verschiedener Pflanzengesellschaften im Vergleich zur oberirdischen Komponente noch recht begrenzt ist (Haberl et al., 2002), wurde in dieser Studie nur die oberirdische NPP (ANPP, aboveground NPP) berücksichtigt. Diese wurde in Tonnen Trockenmasse pro Jahr (t TM/a) dokumentiert.

Da HANPP ein flächenbasierter Indikator ist, das Vereinigte Königreich als ökonomische und politische Einheit während des untersuchten Zeitraums jedoch einer flächenmäßigen Veränderung unterlag (als sich die Republik Irland 1923 abspaltete), werden bei Vergleichen über diesen Bruch hinweg Werte pro Fläche (t dm/ha/a) und pro Kopf (t dm/cap/a) verwendet.

Der durch die Abspaltung der Irischen Republik verursachte Territoriumsverlust lag bei rund 22 % (FAO, 2004) und betraf hauptsächlich Wiesen und Weideflächen. Andere Landnutzungskategorien waren hingegen weniger betroffen. Die Bevölkerung wurde durch die Abspaltung der Irischen Republik lediglich um 6 % reduziert und auch bezüglich der landwirtschaftlichen Produktion des Vereinigten Königreichs änderte sich, bis auf einen Rückgang der Heuernte und eine Abnahme der Rinderzahlen um 35 %, nur wenig.


Die im Vereinigten Königreich durch anthropogen verursachte Feuer zerstörte Biomasse, ist laut unterschiedlichen Quellen (u. a. Annual Abstract of Statistics, 1956ff and Global Burned Area 2000 Project) so gering, dass sie für die Gesamtrechnung keine Rolle spielt und deshalb auch nicht in die Berechnung mit einbezogen wurde. Wie in anderen aktuellen HANPP-Studien (z. B. Haberl et al., 2007), wurde auch in dieser Studie jene Menge an angeeigneter Biomasse, die für den Menschen keinen weiteren Nutzen hat und in Ökosysteme zurückfließt (in der Fachterminologie 'backflows to nature' genannt), gesondert ausgewiesen.

Die ANPP der einzelnen Ackerflächen sowie der Wiesen wurde über die Erntemengen dieser Flächen als Summe der kommerziellen Ernte und Erntenebenprodukte berechnet. Außerdem wurde anhand so genannter „pre-harvest-loss factors“ auch jene Menge an ANPP dazu geschätzt, welche vor der Ernte verloren geht (z. B. durch Fraßverlust) und die am Ackerland vorhandenen Unkräuter berücksichtigt. Den anderen Landnutzungsklassen wurden auf Basis der vorherrschenden Vegetation und der Literatur gefundener Produktivitätswerte durchschnittliche ANPP Pro-Fläche-Werte zugeordnet.

Die Ergebnisse der vorliegenden Studie im untersuchten Zeitraum - zwischen 1800 und 2000 – zeigen die HANPP trotz Schwankungen insgesamt auf einem hohen Niveau: Während sie zu Beginn des untersuchten Zeitraums bei 74 % liegt, nimmt sie während


\( \text{ANPP}_{\text{act}} \) und \( \text{ANPP}_{\text{h}} \) pro Fläche entwickeln sich über die gesamte Zeitspanne nahezu parallel, wodurch sich \( \text{ANPP}_{\text{h}} \) nur wenig verändert. Sowohl \( \text{ANPP}_{\text{act}} \) als auch \( \text{ANPP}_{\text{h}} \) steigen bis zur Mitte des 19. Jahrhunderts und bleiben über die folgenden 100 Jahre auf einem relativ hohem Niveau. Zwischen 1950 und 2000 zeigt sich ein starker Anstieg beider Größen. Gleichzeitig kommt es in der zweiten Hälfte des 20. Jahrhunderts zu einer starken Verminderung von \( \Delta \text{ANPP}_{\text{LC}} \) pro Fläche. Während \( \Delta \text{ANPP}_{\text{LC}} \) bis 1950 noch maßgeblich zur HANPP beiträgt, wird diese ab Mitte der achtziger Jahre alleine von Biomasseernte bestimmt. Für \( \Delta \text{ANPP}_{\text{LC}} \) ergibt sich während dieser Zeit sogar ein negativer Wert. Die landwirtschaftliche Ernte, d. h. die Ernte von Feldfrüchten und ihren Nebenprodukten sowie abgeweidete Biomasse, beträgt während des gesamten Zeitraums mehr als 90 %, während die Holzernte nie mehr als 5 % ausmacht. Interessant ist weiters, dass sich die Menge an "backflows to nature" über die Zeitreihe insgesamt nur wenig verändert, obwohl \( \text{ANPP}_{\text{h}} \) in der zweiten Hälfte des 20. Jahrhunderts so stark ansteigt.

Diese Abnahme bzw. relative Stabilisierung der HANPP trotz ständig wachsender Bevölkerung wurde zu Beginn des untersuchten Zeitraums primär durch die Ausdehnung intensiv bewirtschafteter Flächen und einer Produktivitätssteigerung bzw. Intensivierung dieser Flächen ermöglicht. Der zunehmende Einsatz von Kohle als primärer Energieträger führte zur Reduktion forstwirtschaftlicher Flächen zugunsten landwirtschaftlicher (Sieferle et al., 2006). Außerdem ermöglichten neue technische Entwicklungen Effizienzsteigerungen und die Urbarmachung vorher nicht bewirtschaftbarer Flächen mit geringer ANPP (Sieferle, 1981; 2001; Sieferle et al., 2006; Allen, 1994). Eine Produktivitätssteigerung am Ackerland wurde unter anderem durch die Einführung neuer Fruchtfolgen und einem damit verbundenen Rückgang der Brachen erreicht (Sieferle et al., 2006). Ab 1870 wurde der zunehmende Futter- und Lebensmittelbedarf verstärkt durch Importe abgedeckt, was sich rückwirkend negativ auf die lokale Produktion auswirkte (Martin, 2000). Die bis zu Beginn des Ersten Weltkrieges vorherrschende landwirtschaftliche Depression spiegelt sich auch in der Entwicklung der ANPP$_{act}$ und ANPP$_{h}$ wider.

Human Appropriation of Net Primary Production in the United Kingdom, 1800 - 2000

Changes in society’s impact on ecosystem energy flows during the agrarian-industrial transition

Abstract

This paper presents an empirical analysis of the United Kingdom’s society’s long-term intervention into the energy flows of terrestrial ecosystems through the appropriation of aboveground net primary production (ANPP) covering the period 1800 - 2000. The depicted HANPP 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 socio-ecological regime.

During the 19th century, HANPP shows a steady decline from its level of 74 % in 1800. While similar levels were reached again during the mid 20th century, the trend during the last forty years of the period under investigation again shows a reduction of HANPP, which lies at 67 % in the year 2000. The high values of HANPP 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 HANPP 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 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.

Key words: HANPP, NPP, Socio-economic metabolism, Transition, Land use
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 (Hobsbawm, 1969). Next to a multitude of studies dealing with industrial transformation from a social and classical economic-historical point of view, 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 societies natural relations, based on the concept of social metabolism (see for example Fischer-Kowalski et al., 1997; Schandl and Schulz, 2002) and the methods of material and energy flow analysis (see for example Schandl et al., 2002). Within this context, the core aspect of industrialisation lies within the transformation of the socio-economic energy system from a solar-energy, i.e. biomass based, area dependent energy system, characteristic of agricultural societies, to one relying predominantly on area independent energy sources, above all fossil fuel 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). While coal had, by the beginning of the 19th century, on a large scale replaced wood as a fuel for both industrial and domestic proposes, as well as gaining increasing importance as a source for power in connection with the development of the steam engine (Sieferle 1982, 2001 and Schandl and Krausmann, 2007), agricultural production still remained within the limits of the solar-based energy system up until the 1950s. In a recent publication, Schandl and Krausmann (2007), identify three distinct stages during the course of the United Kingdoms 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 1945 up to around 1980 (Schandl and Krausmann, 2007).

Extending on the research on society’s changing natural relations during industrial transformation, the paper at hand explores the related impact of changes in the United Kingdom’s socio-economic metabolism on ecosystem processes. More specifically, it empirically analyses the effect of changes in land use and biomass-metabolism,
associated with the United Kingdoms socio-metabolic transition, on ecosystem energy flows using as a 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. Keeping with the spatial reference system chosen within previous socio-ecological studies, HANPP was accessed for the United Kingdom (of Great Britain and Ireland and respectively Great Britain and N-Ireland) as a political and economic unit, on a national level covering the period 1800 - 2000, based on historical statistics and extensive literature review.

2. Methodology and materials

2.1. Framework for the accession of appropriated NPP

HANPP was calculated for the United Kingdom adhering to its definition as the combined effect of harvest and changes in productivity due to land use (Haberl et al., 2004; 2007). Related formulas and detailed definitions as well as further information on the HANPP concept and its development can be referred to in Haberl et al. (2007). Variables ascertained within the HANPP calculation include NPP of the potential vegetation ($NPP_0$), i.e. vegetation that would prevail without human influence (Tüxen, 1956) and NPP of the actually prevailing vegetation ($NPP_{act}$), harvested NPP ($NPP_h$) and NPP remaining in ecosystems after harvest ($NPP_i$), as well as land-use induced productivity changes ($\Delta NPP_{LC}$). One therefore requires information on the development of land use and land cover, the productivity of vegetation units as well as data on biomass harvest (Krausmann, 2001). These factors were assessed historically, on a yearly basis, relying on official statistical sources and if these were not available, model assumptions based on extensive literature review (refer to table 1 of online supporting material). For a detailed description of the applied methodology and data sources also refer to Musel (2008).
During the period (1800 - 2000) covered within 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 Kingdoms territory (and hence the investigated spatial reference system) was reduced by 22 % (FAO, 2004). While this led primarily to a reduction of grass and grazing land, other land use classes show little variation (refer to 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 %.

**Table 1.** Land use in million hectares and population in millions in the United Kingdom, 1800 - 2000, for selected years. Sources: Population: Mitchell (1994) and Annual Abstract of Statistics (2004). Land use: Own calculations. See text and Table S1 of supporting material.

<table>
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<tbody>
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<td>6.75</td>
<td>4.64</td>
<td>9.40</td>
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The study confined itself to the accession of terrestrial aboveground net primary production (ANPP). The unit of measure used to record ANPP flows, was tons dry matter per year (t DM/yr). However, due the change in territory in 1923, when discussing the development of HANPP and related parameters between 1800 and 2000, I use relative values, i.e. per hectare (t DM/ha/yr) and per capita (t DM/cap/yr).
2.2. Data sets

2.2.1. 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. To establish a consistent time series of land use on which to base my HANPP calculations, I therefore relied above all on statistics deriving from agricultural census returns, which give continuous historical information on the greater part of the land area in the United Kingdom. The established data set consists of 24 consistent land use classes, which can be aggregated into the 6 main classes featured 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, permanent pastures were also distinguished according to their predominant use for haymaking or 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, 2000). Forest and woodland includes areas of high forest, coppices and scrublands while 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, commonly described as wasteland (Simmons, 2001). It further contains agricultural and woodland land not returned, mining areas and military land, as well as montane, subliteral and littoral areas and inland rock (Best, 1981; CS2000; 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.
Sources of area statistics for each of the individual land use categories and their constituents have been summarized in detail in Table S1 of the supporting material. This also includes sources of associated harvest and productivity values, which will be referred to in the following sections. 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). Next to complying with model assumptions made by the authors for years before official statistical documentation, I also comply with aggregates used by them when categories were reported inconsistently (refer to Table S1 of the supporting material and Schandl and Schulz, 2001 and 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.

2.2.2. Aboveground productivity of potential vegetation (ANPP₀)
NPP₀ denotes the productivity of vegetation that would prevail without human influence (Tüxen, 1956). Due to the lack of better information, a constant ANPP₀ value of 6.3 t DM/ha was used for this paper. This value derives 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 represents the average of values calculated for the years 1998-2000 (Haberl et al., 2007) relating to the total land area of the United Kingdom.
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, 2000; Green, 1990; Sala, 2001) and only form the natural climax vegetation were environmental conditions prevent tree growth (Price, 2003 citing Bell and Walker, 1992 and Archibold, 1995).

2.2.3. Biomass harvest (ANPP\textsubscript{h})

ANPP\textsubscript{h} relates to all aboveground biomass harvested in the course of human activities. Next to commercial crop harvest (according to common procedure roots and tubers are included in the aboveground compartment) and wood harvest, this also includes crop residues such as straw (whether used or remaining on the field) and the non-m 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 was not included in the calculation, since it makes up a negligibly small fraction of appropriated biomass in the United Kingdom (Annual Abstract of Statistics, 1956ff; Global Burned Area 2000 Project).

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, harvest indices (HIs), which relate the commercial harvest of a crop to its total aboveground biomass (Evans, 1993) were used. Sources of statistics for different crops and applied HIs can again be referred to in Table S1 of supporting material. Production figures used for individual crops again comply, to a large extent, with those applied by Schandl and Schulz (2000ff).

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, 1990; Watt and Merill, 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 Campbell (1999) and Brassely (2000). 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 (ANPP_{act}) respectively, could be grazed from these areas (Krausmann and Erb, personal communication 2006).

Harvest of wood is poorly documented within UK national statistics. Data used was therefore taken from the UNECE timber database (compiled by TBFRA), which provides figures on removals (1000m³ 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 removal per hectare values 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/m³, for coniferous wood and non-coniferous wood respectively. To determine the total amount of biomass harvested from commercial wood harvest, I used bark percentages on removals to account for bark 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 percentages 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 ANPP_{act} attributed to this land use class, following Haberl et al (2007).
Recent HANPP studies (e.g. Haberl at 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 (UN, 2000; Stott, 2003; Foot, 1977; Di Blasi et al., 1996; FAO, 2007). 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.

2.2.4. Aboveground productivity of actually prevailing vegetation (ANPP_{act})

Two approaches were chosen to establish ANPP_{act} relating to individual land uses. ANPP_{act} on tilled cropland and cultivated grassland was calculated from crop harvest by means of harvest indices (as previously described for ANPP_{h}), additionally considering unaccounted-for ANPP_{act} due to losses during the growth period, losses due to herbivory and the ANPP of weeds (Haberl et al., 2007). To establish ANPP_{act} on all other land use areas I used ANPP_{act} estimates, given as t DM/ha/yr values, and modelled these historically, backed by information and values found in the literature. 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 S1 of the supporting material. Further a detailed description of the applied methodology can be referred to in Musel (2008).

ANPP_{act} of individual crop areas was calculated as the sum of commercial crop harvest, crop residues and biomass lost prior to harvest (unaccounted-for ANPP_{act}). Unaccounted-for ANPP_{act} was extrapolated from ANPP_{h} using factors from Oerke et al. (1994). This makes up 23 % of ANPP_{act} in 1800, 20 % in 1850, 17 % in 1900 and 14 % as from 1950.
Fallow land was assumed to be invaded by herbaceous vegetation and ANPP\textsubscript{act} t DM/ha/yr to be similar to that of less productive permanent pastures. ANPP\textsubscript{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\textsubscript{act} (Fridolin Krausmann, personal communication 2006 and Suttie, 2000). I did not distinguish between ANPP\textsubscript{act} t DM/ha/yr of rotation pasture for hay/silage and rotation pasture for grazing. I did however do this 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 \textit{Agrostis} spp., \textit{Festuca} spp. and other plants of low productivity (Stapeldon and Davies, 1948 and Lazenby, 1981) also characteristic of rough grazing land (Stapeldon and Davies, 1948; Tansely, 1965 and Hopkins, 2000). 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 average ANPP\textsubscript{act} of cropland including rotation pasture and fallow land lies at 5.4 t DM/ha/yr at the beginning and 12.6 tons DM/ha/yr at the end of the studied period.

Rough grazing land was allocated a constant ANPP\textsubscript{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 (Stapeldon and Davies, 1948; Milne et al., 2002; Hopkins, 2000; Palmer, 1997) of these communities, as well as values found on aboveground NPP of chalk grasslands in the southern English uplands (Williamson and Pitman, 1998). It is difficult to access how the average ANPP\textsubscript{act} of these areas might have varied over the studied period. While up to today in some parts of the United Kingdom there remain rough grazing areas, which are sparsely grazed, and are at the risk of being scrubbed over, the more productive ones can be highly stocked (Lazenby, 1981) and are in some areas exposed to degradation caused by overstocking (Holden et al., 2007).
ANPP\textsubscript{act} of forest and woodland was held to be equal to ANPP\textsubscript{0}. Next to high forest areas, this category also includes 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 ANPP\textsubscript{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, road verges) and trees (e.g. parks), this was attributed the yearly averages of ANPP\textsubscript{act} per unit area of woodland an intensified grassland and lies at 1.7 t DM/ha/yr in 1800 and 2.7 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 aboveground 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 (HANPP) in the United Kingdom, remains at levels in the region of 70 %, but shows clear decreasing and increasing trends in distinct periods. While HANPP steadily declines from 74 % at the beginning of the studied period, down to a level of around 65 % in the late 19\textsuperscript{th} and early 20\textsuperscript{th} century, this is followed by a visible increase in HANPP up to the late 1950s, after which it declines once again to a value of 67 % in the year 2000. This decline at the end of the studied period coincides with a strong decrease in HANPP due to land-use induced productivity changes (\(\Delta\text{ANPP}_{\text{LC}}\)), while harvest (ANPP\textsubscript{h}) and ANPP of actually prevailing vegetation (ANPP\textsubscript{act}) show the reverse trend (Figure 1).
Figure 1. Human appropriation of aboveground net primary production (HANPP), in the United Kingdom, 1800 - 2000. Primary axis: Aboveground productivity of actually prevailing vegetation (ANPP_{act}), Biomass harvest (ANPP_h), aboveground NPP remaining in ecosystems after harvest (ANPP_t) and land-use induced productivity changes (ANPP_{LC}), in tons dry matter per hectare and year. Secondary axis: Appropriated ANPP (HANPP) as percentage of aboveground productivity of potential vegetation (ANPP_0). HANPP was calculated assuming a constant value of 6.3 tons dry matter per hectare and year for ANPP_0. Source: Own calculations. See text.

Related developments in land use (Figure 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 Kingdoms 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.
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 aboveground productivity and harvest of biomass up to the mid 19$^{th}$ 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$_{LC}$ (Figure 1). While this had still contributed considerably to total HANPP up to the mid 20$^{th}$ century, as from the mid 1980s HANPP is in sum attributable solely to harvested ANPP and $\Delta$ANPP$_{LC}$ even becomes negative. When looking at the contribution of individual harvest types to total ANPP$_{h}$, agricultural harvest, i.e. harvest of crops and their residues along with grazing, are responsible for over 90 % of total biomass harvest, over the entire period under investigation, while wood harvest never makes up more than 5 % (Figure 3).
Backflows of harvested biomass, remain relatively stable up to the end of the observed period (Figure 3), even with the dramatic increase in ANPP$_h$ during the second half of the 20$^{th}$ century.

**Figure 3.** Constituents of harvested biomass (ANPP$_h$), as percentage of total ANPP$_h$, in the United Kingdom, 1800 - 2000. Source: Own calculations. See text.

While population shows a steep, almost linear overall increase over the examined period, as Figure 1 illustrates, HANPP and its related parameters did not follow this growth pattern. When looking at per capita developments, values are therefore considerably lower in 2000 than in 1800. Per capita HANPP 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 1950s, in spite of an increase in per capita biomass harvest during this time (Figure 4).
Figure 4. Human appropriation of aboveground net primary production (HANPP), per capita, in the United Kingdom, 1800 - 2000. Aboveground productivity of actually prevailing vegetation (ANPP$_{act}$), biomass harvest (ANPP$_{h}$), aboveground NPP remaining in ecosystems after harvest (ANPP$_i$), aboveground productivity of potential vegetation (ANPP$_0$), land-use induced productivity changes (ΔANPP$_{LC}$) and HANPP, in tons dry matter per capita and year. Source: Own calculations. See text.

Taking a closer look at individual developments of investigated units, during the first half of the 19th century, one can observe that between 1800 and the 1830s cropland expanded by around 7 % and permanent pastures by almost 10 % (Figure 2) and that this expansion was accompanied by a simultaneous increase in the aboveground productivity of these areas. While ANPP$_{act}$ on cropland increased by about one quarter, ANPP$_{act}$ 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. According to these developments, overall ΔANPP$_{LC}$ declined from around 68 Mt DM/yr (2.2 t DM/ha/yr) in 1800 to 44 Mt DM/yr (1.4 t DM/ha/yr) in the late 1830s. At the same time biomass harvest increased from around 76 to 86 Mt DM/yr (2.4 to 2.8 t DM/ha/yr) but remained at a level of nearly 60 % of ANPP$_{act}$, which increased from 127 to 151 Mt DM/yr (4.1 to 4.9 t DM/ha/yr) (Figure 1 and Table 2).
HANPP consequently shows a decline of almost 10% during this period: from slightly over 144 Mt DM/yr (74 %) in the early 19th century to around 131 Mt DM/yr in the 1830s (68 %). As the average population growth during this time was around 1.33 %, HANPP per capita declined even more drastically, from 9.3 t DM/cap/yr down to 5 t DM/cap/yr (Figure 4), in other words by more than 50 %.

Table 2. Five-year averages of aboveground productivity of actually prevailing vegetation (ANPP\textsubscript{act}), biomass harvest (ANPP\textsubscript{h}), aboveground NPP remaining in ecosystems after harvest (ANPP\textsubscript{t}), appropriated aboveground NPP (HANPP) and land-use induced productivity changes (∆ANPP\textsubscript{LC}) in million tons dry matter, for the United Kingdom, 1800 - 2000. Source: Own calculations.

<table>
<thead>
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<th>Years</th>
<th>ANPP\textsubscript{0} [Mt DM]</th>
<th>ANPP\textsubscript{act} [Mt DM]</th>
<th>ANPP\textsubscript{h} [Mt DM]</th>
<th>ANPP\textsubscript{t} [Mt DM]</th>
<th>HANPP [Mt DM]</th>
<th>∆ANPP\textsubscript{LC} [Mt DM]</th>
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A different rate of development becomes visible between 1840 and 1945 (Figure 1). Up to the beginning of the 20th century, HANPP shows a further decline down two around 65 %. Subsequent decreases in HANPP and related parameters in terms of absolute values (Table 2) occur due to the reduction in total land area in connection with the separation of the Republic of Ireland. HANPP as percentage of ANPP\textsubscript{0} however, increases after 1905 and amounts to 70 % in 1945 (Figure 1). HANPP per capita on the other hand continued to decline throughout the entire phase and lies at around 2.2 t DM/cap/yr in 1945 (Figure 4).
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 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 (Figure 2). Even though the secession of Ireland led to a reduction of the area of permanent pastures by almost 30 % (Table 1), 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 area productivities on 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 \( \Delta ANPP_{LC} \) shown in Figure 1.

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 almost 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 (Figure 3).

The most striking development in the trajectory of HANPP and its constituents takes place during the second half of the 20th century. Even though per capita harvest increased from 1.3 t DM/cap/yr to around 2.0 t DM/cap/yr between 1945 and the year 2000, HANPP per capita continued to decline down to 1.7 t DM/cap/yr until the end of the studied period. Figure 1 shows that overall harvest increased by 70 % during this time and amounts to 69 % of \( ANPP_{act} \) at the end of the studied period. HANPP at the same time however, shows a decline of around 10 % as the strong increase in \( ANPP_{act} \) also led to \( \Delta ANPP_{LC} \) becoming negative. 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 this
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 (Figure 3), as did their contribution to overall ANPP_{act}.

The extreme rise in overall ANPP_{act} by 57 % during this time is however primarily attributable to the huge increases in aboveground productivity on cropland and permanent pastures, by around 90 % and 60 % respectively. At the same time there was a decrease in area, related to both of these land use categories (Figure 2).

4. Discussion

Changes in the socio-economic metabolism of the United Kingdom, during the process of industrialisation, included changes in the UK’s society’s bio-metabolism and also had repercussions on land use. This is reflected in the development of 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 (Schandl et al., 2002).

At the beginning of the examined timeframe, human appropriation of aboveground net primary production in the United Kingdom lies at over 70 %. While there was a gradual decrease of around 10 % in appropriated ANPP between 1800 and the beginning of the 20th century HANPP again increased to its’ 1800 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, 2008) related to the parallel industrialisation of agriculture during this period. Compared to these studies, the HANPP value of 67 % in the year 2000 is relatively high but 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 dataset 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) HANPP estimates than in-depth country analyses based on national statistics.

In essence, the extent of HANPP 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. 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 three quarters of the land area in the year 2000 and are responsible for between 74 to 90 % of HANPP during the investigated period. While the aboveground productivity of rough grazing lands is relatively low and these contribute to HANPP 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 extreme 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. De Fries 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. In allocating the amount of grazed biomass I chose to use a conservative approach assuming the amount of biomass that can be removed from determined grazing areas to be limited. Using the established methodology (refer for example to Haberl et al., 2007) of determining the amount of grazed biomass via feed demand of grazing livestock, in the case of this study, for some years, yielded very high amounts of calculated grazing demand, exceeding the grazing potential of these areas, especially between 1961 and 2000. While variations in crop harvest, follow variations of ANPP act on related crop areas and therefore are not discernable in overall HANPP, changes in the amount of grazed biomass, are indeed reflected in the development of overall HANPP.
Giving a more detailed interpretation of the different stages in the development of HANPP in the United Kingdom, the decline in HANPP at the beginning of the studied period 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, 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. As results have shown, the progression of urbanisation during the 19$^{th}$ and 20$^{th}$ 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 of the 19$^{th}$ 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 19$^{th}$ 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 (Sieferle et al., 2006; Allen, 1994). 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). Further, the increase in area productivity of these crops most strongly contributes to the rise of ANPP 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.

During the following period, the development of overall $\text{ANPP}_{\text{act}}$ and $\text{ANPP}_{\text{h}}$ reflects quite visibly the agricultural depression prevailing in the United Kingdom from around 1870 up to the First World War (Martin, 2000; Simmons, 2001). During this time, coal became the leading constituent of the United Kingdoms energy system. At the beginning of the 20th century it amounted to 80 percent 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 ‘linked to a growing demand for human and animal labour and population growth’ (Krausmann, Schandl and Sieferle, 2007, in print, pg.7). 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 (Schandl and Krausmann, 2007; Sieferle et al., 2006; Krausmann et al., 2003). 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. 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 aboveground productivities and harvest on cropland only increase again markedly during the second half of the 20th century the amount of grazed biomass again 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 HANPP 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-Bosh process (Schandl and Krausmann, 2007), and the complete substitution of animate by mechanical traction, in the course of this period, finally lead to energy provision in the United Kingdom, becoming entirely decoupled from land use (Schandl and Krausmann, 2007; Krausmann, Schandl and Sieferle, 2007, in print). 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 HANPP. Despite the surge in harvested biomass 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 HANPP down to 67% in the year 2000.

Table 3 shows the development of the combined area of cropland and permanent pastures and the development of HANPP, $ANPP_{act}$ 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 HANPP of the same, due to accompanying increases in biomass harvest. During the second half of the 20th century HANPP on cropland declines from still around 80% after the Second World down to 66% in the year 2000.

Table 3. Development of the combined area of cropland and permanent pasture in million hectares, and appropriated ANPP (HANPP), aboveground 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 million tons, in the United Kingdom, for selected years between 1961 an 1999. Sources: FAO (2004) and own calculations.

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<tbody>
<tr>
<td>1961</td>
<td>12.5</td>
<td>5.1</td>
<td>5.7</td>
<td>4.5</td>
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<tr>
<td>1965</td>
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<td>5.1</td>
<td>6.2</td>
<td>5.0</td>
<td>1.6</td>
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<tr>
<td>1969</td>
<td>12.3</td>
<td>5.0</td>
<td>6.5</td>
<td>5.2</td>
<td>1.6</td>
</tr>
<tr>
<td>1973</td>
<td>12.2</td>
<td>4.8</td>
<td>7.4</td>
<td>5.9</td>
<td>1.9</td>
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<tr>
<td>1977</td>
<td>12.2</td>
<td>4.7</td>
<td>7.8</td>
<td>6.2</td>
<td>2.0</td>
</tr>
<tr>
<td>1981</td>
<td>12.4</td>
<td>4.7</td>
<td>8.0</td>
<td>6.3</td>
<td>2.3</td>
</tr>
<tr>
<td>1985</td>
<td>12.3</td>
<td>4.6</td>
<td>8.7</td>
<td>6.9</td>
<td>2.5</td>
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<tr>
<td>1989</td>
<td>12.1</td>
<td>4.5</td>
<td>8.8</td>
<td>7.0</td>
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<tr>
<td>1993</td>
<td>12.2</td>
<td>4.4</td>
<td>9.1</td>
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<tr>
<td>1997</td>
<td>12.1</td>
<td>4.4</td>
<td>9.6</td>
<td>7.7</td>
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<tr>
<td>1999</td>
<td>12.1</td>
<td>4.4</td>
<td>9.5</td>
<td>7.6</td>
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</table>
While increasing levels of material and energy throughputs linked to industrial transformation (see for example Schandl and Schulz, 2002; Krausmann et al., 2003 and Schandl and Krausmann, 2007) might suggest an equally strong impact on ecosystem energy flows, it has been shown that HANPP remains relatively stable over the examined timeframe and even decreases towards the end of the studied period. The same applies to the development of HANPP in relation to economic growth. Based on data from GGDC (2007), GDP increased more than thirty fold between 1820 and the year 2000, while HANPP per unit of GDP decreased by 98 \%. Nevertheless, the fact remains, that as early as in the 19\textsuperscript{th} century, the amount of energy left for ecosystem processes has remained at a low level of around 30 \%. This however only represents an average value for the whole of the United Kingdom and HANPP in regions, associated with, for example predominately urban land might lie above 80 \%. Further, the relative stabilisation of HANPP 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 (refer for example to Simmons, 2001), the outsourcing of biomass extraction through imports of required food and feed, on a grand scale since the mid 19\textsuperscript{th} century and the application of huge amounts of oil and gas based inputs into agriculture, which led to agriculture becoming an energy sink (Krausmann and Schandl, 2007).
Acknowledgments

I would like to thank Helmut Haberl, Karlheinz Erb and Fridolin Krausmann, for their important inputs and their assistance concerning the empirical work of my study, Heinz Schandl for letting me use his material and sharing his expertise on the investigated reference system, Elmar Schwarzmüller and Thomas Kastner for their support and fruitful discussions and Simone Gingrich and Veronika Gaube for supporting me in writing this paper. This research benefits from the Austrian Science Fund (FWF), project P-16692, and contributes to the Global Land Project and to ALTER-Net.

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**Supporting material**

**Table S1.** Sources of land use, harvested biomass (ANPP\(_h\)) and productivity of actually prevailing vegetation (ANPP\(_{act}\)) for the United Kingdom (1800 - 2000)

<table>
<thead>
<tr>
<th>Land use classes</th>
<th>Sources</th>
<th>ANPP(_h)</th>
<th>ANPP(_{act})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cropland</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permanent crops</td>
<td>Orchards and small fruit</td>
<td>Before 1866: Sieferle et al. (2006) 1867-2000: Mitchell (1994) and UK Agricultural Statistics (followed by Digest of Agricultural Census statistics)</td>
<td>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)</td>
</tr>
<tr>
<td>Bare fallow and set-aside</td>
<td></td>
<td>Before 1866: Sieferle et al. (2006) Thereafter: Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)</td>
<td>Grazing, calculated via feed demand of grazers (refer to text)</td>
</tr>
<tr>
<td></td>
<td>Rotation pasture for grazing</td>
<td>Sieferle et al. (2006) and Schandl and Schulz (2001), Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff)</td>
<td>Grazing, calculated via feed demand of grazers (refer to text)</td>
</tr>
<tr>
<td>Land Use</td>
<td>Permanent pasture for hay</td>
<td>Permanent pasture for grazing</td>
<td>Rough grazings</td>
</tr>
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<tr>
<td>Calculation via harvest data and assumption, that 75% of grass is removed during harvest (Fridolin Krausmann 2006, personal communication and Suttie 2000)</td>
<td>Average productivity of permanent pasture for hay and rough grazing land, crosschecked with Hopkins (2000) and Radcliffe and Baars (1987)</td>
<td>Own estimate based on Mline et al. (2002), Hopkins (2000), Williamson and Pitman (1998), Palmer (1997) and Stapeldon and Davies (1948) - kept constant over entire period</td>
<td>Assigned ANPP of potential vegetation (ANPP\textsubscript{0}) following Haberl et al. (2007)</td>
</tr>
</tbody>
</table>

Own estimate: Assumed 1/3 of area to be covered with vegetation following Haberl et al. (2007) and assigned average productivity value of forest/woodland and permanent pastures for grazing | Own estimate: productivity assumed to be similar to that of rough grazing land and to decline slightly over the studied period. |
Appendix A: Report on methodology and materials

The report at hand documents the empirical work done within my study on human appropriation of terrestrial aboveground NPP (ANPP) in the United Kingdom for the period 1800 - 2000, recording the materials used and methods applied to arrive at the data sets needed to calculate HANPP for the chosen spatial reference system and time series.
1. HANPP Calculation

Adhering to the definition of HANPP, as the combined effect of harvest and changes in productivity due to land use (Haberl et al., 2007), HANPP was calculated as the difference between the NPP of the potential vegetation ($NPP_0$), i.e. vegetation which would prevail without human influence, and NPP remaining in ecosystems after harvest ($NPP_t$) according to the formula:

$$HANPP = NPP_0 - NPP_t$$

With,

$$NPP_t = NPP_{act} - NPP_h,$$  \hspace{1cm} \text{(Haberl et al., 1997)}

where $NPP_{act}$ is the NPP of the actually prevailing vegetation and $NPP_h$ the NPP harvested by human activities. If the amount of NPP appropriated through land cover and land use change is termed $\Delta NPP_{LC}$ then:

$$HANPP = \Delta NPP_{LC} + NPP_h$$

With,

$$\Delta NPP_{LC} = NPP_0 - NPP_{act}$$  \hspace{1cm} \text{(Haberl et al., 2004)}

Within my study of HANPP in the United Kingdom, I considered terrestrial aboveground NPP flows (ANPP) only, since existing information on belowground NPP for different vegetation units is still limited (Haberl et al., 2002). The unit of measure used to record ANPP flows, is tons dry matter per year (t DM/yr) and tons dry matter per hectare and year (t DM/ha/yr).
2. Land cover and land use dataset

In order to assess HANPP, next to essential information on biomass harvest, it is vital to construct a solid land use data set on which calculations can be based.

2.1. Reference system

During the period under investigation (1800 - 2000), there was a change in the United Kingdom’s constituent countries. Up to 1922 its territory consisted of England, Wales, Scotland (Great Britain) and the whole of Ireland. After Ireland’s separation, only Northern Ireland remained part of the union. Hence, in 1923, the United Kingdom’s total area was reduced from 31 318 to 24 291 thousand hectares, including 1.1 % and 0.8 % of inland water respectively. When comparing results between points in time before and after 1923, it is therefore necessary to use per capita or per hectare values.

While the secession of the Republic of Ireland, led primarily to a reduction of grass and grazing land, essentially permanent pasture (29 %), areas of annual and permanent crops, urban land and forest and woodland were only marginally affected. This is similarly true for other indicators such as total population, crop production and livestock numbers. Population was reduced by merely 6 % and production from cropland (incl. straw) by about 17 %, (mainly due to the loss in the production of hay). With a decrease in the area of permanent pasture, there was also a decrease in the number of cattle by about 35 %. While sheep numbers were little affected, poultry numbers were reduced by 25 %.

I chose to base my calculations on this varying reference system due to the availability of input data needed for my calculation, from previous case studies on the United Kingdom as well as for the sake of comparability with these studies.²

2.2. Data availability

There is no official land use inventory compiled for the United Kingdom at regular intervals of time, especially ranging back as far as 1800. Official statistical sources predominantly provide historical information on agricultural land uses and the extent of woodland. These are: ‘UK Agricultural Statistics followed’ by ‘Digest of Agricultural Census Statistics’ by the Ministry of Agriculture Fisheries and Food (MAFF), now part of the Department for Environment Food and Rural Affairs (DEFRA) and the ‘Statistical Abstract for the United Kingdom’ followed by ‘Annual Abstracts of Statistics’ formerly by the Board of Trade currently by the Department of National Statistics, printed by ‘Her Majesties Stationary Office’. The primary sources of these Statistics are: the ‘Censuses of Woodland and Trees’ (1924 first published 1928, 1947 - 1949 first published 1952, 1979 - 82 first published 1987) and the agricultural returns of Great Britain, Ireland and N-Ireland. Next to official statistics, which are published on a yearly basis, there are also a number useful statistical compilations available, such as those by B. R. Mitchell (especially, ‘British Historical Statistics’, first printed 1988), ‘A Century of Agricultural Statistics 1866 - 1966’ by MAFF together with the Department of Agriculture an Fisheries for Scotland and ‘A Hundred Years of British food and farming, A Statistical Survey’ by H. F. Marks edited by D.K. Britton (1989).

There have been some national land use surveys undertaken, varying in both approach and area scale. Examples are: ‘The Ordnance Survey’, for different parishes, in the last half of the nineteenth century, ‘The First Land Utilisation Survey of Great Britain’, in the 1930s by Dudely Stamp\(^3\) and the ‘Second Land Utilisation Survey’ in the 1960’s for England and Wales by Alice Coleman, the ‘Country Side Surveys’ for the years 1978, 1984, 1990, and 1998 (reported in 2000)\(^4\), for all UK constituent countries, as well as other more recent and local studies. These are partly merely cartographical and to a lesser extent also contain statistical information. Amongst the authors that have evaluated different sources concerning land use and have attempted to bring together


different records R. H. Best\(^5\) proved most valuable. He gives a good insight into the reliability and availability of data and has dealt extensively with the development of urban land. Together the sources mentioned above, allow a good approximation of the historical composition of land use in the United Kingdom.

### 2.3. General overview

The United Kingdom can be divided into the lowland zone of the southeast, which lies within England, and the highland zone of northwest characterizing Scotland and parts of Wales. The lowland zone with its mostly fertile soils and drier summers is suited for large-scale cultivation of crops and intensified grassland. The highlands are characterised by higher rainfall, steep slopes and nutrient-poor stony soils and moor areas, limiting cultivation. These are predominantly used as rough grazing and pasture land (Best, 1981; Krausmann et al., 2003; Hopkins, 2000) but also support a great part of Britain’s woodlands (Woodcock, 1994). Large areas of grass and extensive grazing land are also characteristic of Ireland. It's terrain consists of a mostly level interior plain, with a calcium-rich base layer surrounded by higher lying coastal stretches of various geological origins (Krausmann et al., 2003; Woodcock, 1994).

### 2.4. Categories of land use and land cover

The present land use data set is made up of the following categories, which have been summarized in Table A1: Cropland land, including different categories of annual and permanent crops, bare fallow and set-aside land and rotation pasture for hay/silage as well as rotation pasture for grazing; permanent pastures also distinguished further into permanent pastures for hay hay/silage and grazing; rough grazing land; forest and woodland; urban land; other land and inland water. Areas are given in ha. Where necessary, these were converted from $\text{km}^2$ to ha by a factor 0.01 and from acres to ha by a factor 0.405. Figures for agricultural areas and woodland (i.e. all but the last three categories) derive largely from the data sets compiled by Schandl and Schultz in their studies on the social metabolism of the United Kingdom, different parts of which have been published in Schandl and Schulz (2000) Schandl and Schulz (2001) and Schandl

\(^5\) Best (1964) and Best (1981)
and Schulz (2002), Krausmann, et al. (2003) and most recently in Sieferle et al. (2006). These 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). For years were data is not, or only partly available I predominantly comply with estimates made by Schandl and Schulz based on model assumptions, described in detail in Schandl and Schulz (2001).

**Table A1.** Land use categories and their aggregates

<table>
<thead>
<tr>
<th>Cropland</th>
<th>Small fruit</th>
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<tr>
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<td>Orchards</td>
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<tr>
<td><strong>Permanent crops</strong></td>
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<td><strong>Annual crops</strong></td>
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<tr>
<td>Wheat</td>
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<tr>
<td>Barley</td>
<td></td>
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<tr>
<td>Oats</td>
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<tr>
<td>Other com</td>
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<tr>
<td>Potatoes</td>
<td></td>
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<td>Sugar beet</td>
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<td>Turnips and swedes</td>
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<tr>
<td>Mangold</td>
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<tr>
<td>Cabbage, kohlrabi and rape</td>
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<tr>
<td>Other green crops</td>
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<tr>
<td>Flax</td>
<td></td>
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<tr>
<td>Hops</td>
<td></td>
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<tr>
<td><strong>Fallow land</strong></td>
<td>Bare fallow and set aside land</td>
</tr>
<tr>
<td><strong>Rotation pasture</strong></td>
<td>Rotation pasture for hay and silage</td>
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<tr>
<td></td>
<td>Rotation pasture for grazing</td>
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<tr>
<td><strong>Permanent pasture</strong></td>
<td>Permanent pasture for hay and silage</td>
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<tr>
<td></td>
<td>Permanent pasture for grazing</td>
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<tr>
<td><strong>Rough grazing land</strong></td>
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<tr>
<td><strong>Forest and woodland</strong></td>
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<tr>
<td><strong>Urban land</strong></td>
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<tr>
<td><strong>Other land</strong></td>
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<tr>
<td><strong>Inland water</strong></td>
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</table>
2.4.1. Total land area and inland water

Except for the change in territory in 1923, constant values were used concerning these areas. Changes that might have occurred along the coastlines or because of inland flooding are negligible and were not considered within the scope of this study. Figures were taken from the Food and Agricultural Organisation’s (FAO) statistical database⁶, which provides data as from 1961. To arrive at values before 1923, current area figures for the United Kingdom and the Republic of Ireland were simply added up. I included inland water in my land use data set, for the sake of completeness, whilst my calculations of HANPP, only take into account to the appropriation of terrestrial NPP.

2.4.2. Annual and permanent crops

These include areas of the following crops and aggregate crop categories: wheat, barley, oats, other corn, potatoes, sugar beet, turnips and swedes, ‘mangold and fodder beet’, ‘cabbage, kohlrabi and oilseed rape’, ‘other green crops’, flax, hops, small fruits and orchards. For the most part figures were taken from Mitchell (1994) and Collins (2000) before 1937 and from Annual Abstracts of Statistics (which from 1937 onwards, gives information on individual crops in a more detailed and consistent manner for the whole of the United Kingdom (Schandl and Schulz, 2001), thereafter. As from 1937 the category ‘other corn’ next to areas for mixed corn, rye, and beans and peas, also includes areas of maize (incl. maize for silage) and triticale. The area of other green crops includes areas for vetches, lucerne, vegetables and other minor categories. Areas for small fruits and orchards were taken wholly from Mitchell (1994) and relate to Great Britain.⁷ The areas for mangold and turnips and swedes were altered slightly from those used by Schandl and Schulz, using figures from UK Agricultural Statistics (followed by Digest of Agricultural Census Statistics) and FAO (2004).

Reliable figures for most of the areas of individual crops were first made available by agricultural returns in Great Britain as from 1867 and in Ireland as from 1847. Figures for preceding years are estimates based on the methods of Schandl and Schulz (2001).

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⁷ These make up but a minor percentage both in terms of cropland area and production in Britain and are not even included in returns for Ireland or Northern Ireland.
2.4.3. Fallow land

This includes ‘bare fallow’ and ‘set aside’ land. The area of bare fallow was taken from Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff). Area figures used for preceding years comply with those given in Sieferle et al. (2006). Set-aside land is ‘land, which is taken out of production to reduce the risk of food surpluses, while increasing the opportunity for environmental benefits’ (DEFRA)\(^8\). Set-aside was introduced by the European Union in 1992. Area figures for set aside lands in the United Kingdom are given in Annual Abstract of Statistics 2005ff. According to Ansell and Tranter (1992) most of the land set aside, was set aside to fallow\(^9\), which is why I included them under the same category.

2.4.4. Rotation pastures, permanent pastures and rough grazings

Grasslands and grazing lands cover large areas, in the northern and western regions of the United Kingdom (Lazenby, 1981). In my land use data set I follow the agricultural census categories differentiating between permanent and rotation pastures, distinguished further according to their use for hay and silage making or grazing, and rough grazings.

According to the Ministry of Agriculture Food and Forestry, rotation pasture is defined as temporary grassland, which has been sown within the previous five years. This is made up predominantly of ryegrasses (\textit{Lolium perenne} or \textit{L. multiflorum}) sometimes sown together with a legume. Permanent pasture consists of a mix of older sown species and invading volunteer grasses, as well as semi-natural swards (Hopkins, 2000).

Agricultural returns for Great Britain in some years did not distinguish different uses of rotation and permanent pastures. For such years I follow the method of Schandl and Schulz (2001), assuming that 50% of the area of rotation pastures is used for haymaking and 50% is used for grazing, while for permanent pastures I assign 20% and 80% respectively to haymaking and grazing. The same model was applied for N-Ireland, for which data on permanent and rotation pasture exists as from 1923. Irish returns only distinguish between pasture for haymaking and pasture for grazing irrespective of

\(^8\) http://www.defra.gov.uk/farm/environment/land-manage/setaside.htm (Last accessed 10.03.2007)
\(^9\) 95% of the set-aside area of 259 survey farms in England and Wales
permanent or rotation grass. Here Schandl and Schulz assumed both pasture for haymaking and pasture for grazing to be permanent pasture (Schandl and Schulz, 2001). Within agricultural literature rotation pastures are also referred to as leys, while permanent pastures for hay and silage production are commonly called meadows and those used for grazing purposes are termed pastures.

‘Rough and hill grazings occupy land above the limits of cultivation, and infertile heath soils at lower elevations’ (Hopkins, 2000, pg. 105), giving rise to vegetation of low productivity. According to their management, agricultural statistics distinguish common and sole right (fenced in) rough grazings and include areas of deer forest in Scotland. The area of rough grazing land is only reported as such in Annual Abstract of Statistics as from 1937. UK Agricultural Statistics included the category of ‘mountain moor and heath land used for grazing’ as from 1891 but this was not used consistently. I therefore comply with Schandl and Schulz, who used figures from Annual Abstract of Statistics and a model assumption to establish figures for earlier years. This can be referred to in detail in Schandl and Schulz (2001).

Next to the agricultural classification of UK grassland and grazing lands, these were classified botanically, with an emphasis on economically important plant species (Hopkins, 2000), within the Grassland Survey of England and Wales, undertaken by the Welsh Plant Breeding Station under the direction of Sir George Stapeldon, in the years 1938-1940. They have also been distinguished within the National Vegetation Classification (NVC) based on soil type and according to Broad Habitats within the Countryside Surveys. Table A2 gives an overview of different classifications and of how these relate to the agricultural classification.

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10 Prior to 1932, the area of rough grazings only included deer forests which was returned as being actually used as for grazing purposes: since then, the total area of deer forest has been included (Best, 1981).

<table>
<thead>
<tr>
<th>a) Agricultural</th>
<th>b) Grassland Survey</th>
<th>c) CS2000 Broad Habitats</th>
<th>d) NVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation Pasture</td>
<td>Ryegrasses, cocksfoot and timothy together with red and an white clover(^{11})</td>
<td>Improved grassland</td>
<td>Mesotrophic grassland</td>
</tr>
<tr>
<td>Permanent Pasture</td>
<td>1st grade (ryegrass) pastures</td>
<td>1.6</td>
<td>Improved grassland and neutral grassland</td>
</tr>
<tr>
<td></td>
<td>2nd grade (ryegrass) pastures</td>
<td>5.8</td>
<td>Mesotrophic grassland</td>
</tr>
<tr>
<td></td>
<td>3rd grade (Agrostis-with-ryegrass) pastures</td>
<td>27.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4th grade (Agrostis or Agrostis-with-fescue) pastures</td>
<td>60.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5th grade (Agrostis-fescue with rushes and sedges pastures)</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>Rough and Hill Grazings</td>
<td>Fescue pastures, including hill fescues and the downs</td>
<td>27.1</td>
<td>Calcareaous Grassland</td>
</tr>
<tr>
<td></td>
<td>Fescue pastures, including hill fescues and the downs</td>
<td>27.1</td>
<td>Calciculous grasslands</td>
</tr>
<tr>
<td></td>
<td>Fescue-with-Agrostis, invaded by dense bracken fern</td>
<td>7.3</td>
<td>Acid Grassland</td>
</tr>
<tr>
<td></td>
<td>Fescue-with-Agrostis, invaded by mixed fern, gorse and scrub</td>
<td>2</td>
<td>Bracken</td>
</tr>
<tr>
<td></td>
<td>Nardus moors with fescue, rushes, bilberry, heather</td>
<td>7.7</td>
<td>Dwarf Shrub Heath</td>
</tr>
<tr>
<td></td>
<td>Molinia moors, including mixed heather, fern and scrub</td>
<td>5.1</td>
<td>Bog</td>
</tr>
<tr>
<td></td>
<td>Mixed Molinia-with-Nardus moor</td>
<td>15.7</td>
<td>Mires (fen meadow)</td>
</tr>
<tr>
<td></td>
<td>Heather moor</td>
<td>14.4</td>
<td>Fen, Marsh and Swamp</td>
</tr>
<tr>
<td></td>
<td>Heather 'Fell'</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cotton grass and deer grass moor</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lowland heaths (New Forest and Breckland type)</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dense thorn and scrub-infested fields</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lowland bog, swamp and fen ‘carr’</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coastal dunes and estuarine saltings</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

\(^{11}\) These species were not ascertained as part of the grassland survey but are mentioned by Stapledon and Davies (1948) as valuable species for the production of high-class ‘leys’
2.4.5. Forest and woodland

Area figures used were again taken from the Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff), which contains areas for ‘woods, coppices and plantations’ for Ireland from 1867-1918 and for Great Britain from 1871-1912 and the area of forest and woodland\(^{12}\) for the United Kingdom as from 1937. Early figures were compiled by the Boards of Agriculture from statutory returns by woodland owners (Census of Woodlands and Trees, 1952 and Best, 1981), while later figures derive from the Forestry Commission’s censuses of woodland and trees. Up to the middle of the 20\(^{th}\) century broadleaves (oak and other mixed broadleaves) made up the greater part of forest and woodland in GB and hence the UK. Since the 1950 conifers (pine, spruce, larch and other mixed conifers) have become predominant, owing to the fact, that new plantations have been mostly coniferous (Forestry Commission, 2004 based on National inventory of woodland and trees 1995-99)\(^{12}\).

2.4.6. Urban land

The extent of urban land was determined by means of values on urban land provision given by Robin H. Best (1981), relating the number of people to the land available for their use. Best (1981) gives historical ha/1000p values for England and Wales derived from information on the total population of England and Wales and the area of urban land in England and Wales,\(^{14}\) as shown in Table A3 below. Urban land in this definition includes cities, towns and villages (i.e. residential and industrial areas and associated space) as well as farmsteads and other isolated development, roads, railways and civil airfields outside settlements (Best, 1981).

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\(^{12}\) This includes: High forest, coppice and coppice-with-strands, scrub, felled or devastated and uneconomic woodland, all of five acres and over.

\(^{13}\) Downloaded (18.06.06) from: www.forestry.gov.uk/statistics

\(^{14}\) Refer to Chapter 4 and Chapter 5 of: Best, R. H. 1981. Land Use and Living Space. METHUEN, London and New York.
Since the population of England and Wales makes up the bulk of the population of the United Kingdom I found it permissible to apply figures given by Best (1981) to the whole of the UK. For the years were data on urban land provision was not given I used linear interpolation between available data points. To arrive at values for urban land provision before 1901, I extrapolated values up to 1850 based on their development in previous years. Between 1850 and 1800 the value was kept constant, based on the assumption that, due to primitive and costly transport facilities (Best, 1981; Mitchell, 1988), the increase in population during this time had the effect of higher living densities, rather then the dispersion of settlement. Population figures for the United Kingdom derive from Annual Abstract of Statistics (2004) and Mitchell (1988). By multiplying these with the ha/1000p values I arrive at the area of urban land use as shown in Table A4 below.

Table A3. Urban Growth in England and Wales, 1901-2001 according to Robin H. Best (1981)

<table>
<thead>
<tr>
<th>Year</th>
<th>Population</th>
<th>Urban area</th>
<th>Urban land provision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions</td>
<td>000 ha</td>
<td>% a)</td>
</tr>
<tr>
<td>1901</td>
<td>32.5</td>
<td>674</td>
<td>4.5</td>
</tr>
<tr>
<td>1921</td>
<td>37.9</td>
<td>854</td>
<td>5.7</td>
</tr>
<tr>
<td>1931</td>
<td>40.0</td>
<td>1005</td>
<td>6.7</td>
</tr>
<tr>
<td>1939</td>
<td>41.5</td>
<td>1206</td>
<td>8.0</td>
</tr>
<tr>
<td>1951</td>
<td>43.8</td>
<td>1339</td>
<td>8.9</td>
</tr>
<tr>
<td>1961</td>
<td>46.1</td>
<td>1490</td>
<td>9.9</td>
</tr>
<tr>
<td>1971</td>
<td>48.8</td>
<td>1646</td>
<td>11</td>
</tr>
<tr>
<td>2001 b)</td>
<td>51.3</td>
<td>2117</td>
<td>14.1</td>
</tr>
</tbody>
</table>

a) Proportion of total land surface
b) Urban land and population estimated
Table A4. Figures of urban land provision used in own calculation to determine the area of urban land in the United Kingdom.

<table>
<thead>
<tr>
<th>Years</th>
<th>Population UK</th>
<th>Urban land provision</th>
<th>Urban area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions</td>
<td>Ha/1000p</td>
<td>'000 ha</td>
</tr>
<tr>
<td>1800</td>
<td>15.5</td>
<td>16.1</td>
<td>249</td>
</tr>
<tr>
<td>1850</td>
<td>27.5</td>
<td>16.1</td>
<td>443</td>
</tr>
<tr>
<td>1901</td>
<td>41.5</td>
<td>20.7</td>
<td>860</td>
</tr>
<tr>
<td>1921</td>
<td>47.2</td>
<td>22.5</td>
<td>1061</td>
</tr>
<tr>
<td>1931</td>
<td>46.1</td>
<td>25.1</td>
<td>1156</td>
</tr>
<tr>
<td>1939</td>
<td>47.8</td>
<td>29.1</td>
<td>1390</td>
</tr>
<tr>
<td>1951</td>
<td>50.3</td>
<td>30.6</td>
<td>1539</td>
</tr>
<tr>
<td>1961</td>
<td>52.8</td>
<td>32.3</td>
<td>1706</td>
</tr>
<tr>
<td>1971</td>
<td>55.9</td>
<td>33.7</td>
<td>1885</td>
</tr>
<tr>
<td>2000</td>
<td>58.7</td>
<td>41.0</td>
<td>2404</td>
</tr>
</tbody>
</table>

2.4.7. Other Land

Other land represents all remaining land, not accounted for in the categories mentioned above and is obtained by subtracting the area sum of these categories 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, and commonly described as wasteland. Between 1800 and 1846 large parts of this land, were converted to farmland and pastureland by methods of land improvement such as drainage and enclosure (Sieferle et al., 2006; Tansely, 1965; Simmons, 2001). Other land further contains agricultural and woodland land not returned, mining areas and military land (Best, 1981), as well as montane, subliteral and literral areas and inland rock (about 26 % of other land according to CS2000).
2.5. Data reliability

The present land use data-set evidently has an agronomical bias, however statistics based on agricultural returns are the only ones giving continuous historical information on the greater part of the land area of the UK. Inaccuracies occur due to inconsistencies in collection of data. Best (1981, pg.54) states that, ‘ten years are not normally long enough to allow shifts of any great magnitude in the land use pattern except for the war years, when cropland increased significantly, and that changes that might seem significant often arise purely from statistical machinations’. Inconsistencies in the categories reported also cause problems and aggregates had to be established. Mostly, figures for agricultural land uses are available for the UK as from the second half of the 19th century. Model assumptions made for preceding years are based on relating indicators and model assumptions. Even though this land use data set is based primarily on agricultural classifications, data do compare in an acceptable way with those ascertained by means of cartographic methods (e.g. The First Land Utilisation Survey, 1930) and could be related to data from surveys with a more ecological focus, available for individual years (e.g. the Countryside Surveys).
3. ANPP of potential vegetation (ANPP$_0$)

ANPP$_0$ relates to ‘Net Primary Production’ of vegetation that would prevail without human influence (Tüxen, 1956). In the United Kingdom this would predominantly be forest.$^{15}$ Grasslands, which are characteristic of the landscape today, are for the most part a result of extensive forest clearance and intensive agricultural management (Hopkins, 2000; Green, 1990; Sala, 2001) and only form the natural climax vegetation were environmental conditions prevent tree growth (Price, 2003 citing Bell and Walker, 1992 and Archibold, 1995).

ANPP$_0$ data used in my study derive from calculations, within the Global HANPP project, undertaken by means of the Lund-Potsdam-Jena (LPJ) Dynamic Global Vegetation Model, with an improved representation of hydrology.$^{16}$ Model inputs used are atmospheric CO$_2$ concentration, gridded data on historical monthly climate, and a soil type classification at 0.5° spatial resolution (Haberl et al., 2007). I was supplied ANPP$_0$ and area data as generated for the United Kingdom for the year 2000, by the project associate Karlheinz Erb (personal communication, 2006). These are featured in Table A5. Values are five-year averages of the years 1998 to 2002 (Haberl et al., 2007). Distinguished land uses are not directly comparable with those established by myself. I therefore used ANPP$_0$ per ha of the total land area (i.e. average ANPP$_0$) in my calculations, multiplying areas of individual land uses of my data set with 6.29 t DM/ha/yr to determine ANPP$_0$ t DM/yr for each of the categories.$^{17}$ Up to date, data on ANPP$_0$ is only available for the year 2000. For this reason I used a constant value of 6.29 t DM/ha/yr, over the entire period under investigation, well aware this might have varied considerably.

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$^{15}$ Mainly temperate deciduous forest/woodland according to Ramankutty, N., and J.A. Foley (1999)
$^{16}$ Refer to Sitch et al. (2003) and Gerten et al. (2004)
$^{17}$ This seemed permissible, since ANPP$_0$ per ha of the total land area only deviates slightly (between 2-7 %) from all other ANPP$_0$ per ha values.
Table A5. United Kingdom ‘Global HANPP’ values of ANPP\textsubscript{0} and land use area. Source: Erb (personal communication, 2006)

<table>
<thead>
<tr>
<th>Land use</th>
<th>Area (\text{Mha})</th>
<th>ANPP\textsubscript{0} (\text{Mt DM/yr})</th>
<th>ANPP\textsubscript{0} per ha (\text{t DM/ha/yr})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>5.87</td>
<td>37.71</td>
<td>6.43</td>
</tr>
<tr>
<td>Grassland</td>
<td>13.05</td>
<td>81.42</td>
<td>6.24</td>
</tr>
<tr>
<td>Built up land</td>
<td>2.94</td>
<td>19.14</td>
<td>6.51</td>
</tr>
<tr>
<td>Forest</td>
<td>2.46</td>
<td>14.80</td>
<td>6.01</td>
</tr>
<tr>
<td>Wild</td>
<td>0.34</td>
<td>2.00</td>
<td>5.82</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24.66</strong></td>
<td><strong>155.07</strong></td>
<td><strong>6.29</strong></td>
</tr>
</tbody>
</table>
4. Biomass harvest (ANPP$^h$)

ANPP$^h$ relates to all aboveground biomass harvested in the course of human activities (resulting from social metabolism). Next to commercial crop harvest this also includes harvested crop residues such as straw (whether used or remaining on the field) and the non-merchantable parts of trees cut for timber and biomass grazed by animals.

The following types of aboveground biomass harvest were considered within this study:

- Harvest of crops and their crop residues from related crop areas and harvest of grass for hay and silage from rotation and permanent pastures
- Grazing on fallow land, ‘rotation and permanent pastures’ and ‘rough grazing land’, as well as on ‘other land’ in the beginning of the 19th century
- Harvest from urban land e.g. mowing
- Wood harvest from forest and woodland

‘Harvest’ through human induced fires was not accounted for since it was considered negligible.\(^{18}\)

4.1. Harvest of crops, grass and crop residues

Commercial harvest of crops and grass are documented within agricultural statistics. To determine the amount of crop residues harvested, I used harvest indices (HIs), which relate the commercial harvest of a crop to its total aboveground biomass (Evans, 1993).

\(^{18}\) According to Gimingham (1981) burning has for a long time been an important tool for the management of upland forage plants such as Calluna vulgaris. Heath lands, being burned in rotating strips at a rate of about once every ten years. However, there is little information to be found on the extent of burning and the historical development of this practice. Relating to recent years the extent of areas burned seems to be minimal. According to the ‘Global Burned Area 2000 Project’, the total burnt area in the United Kingdom, was 0.7 k ha in the year 2000.


Annual Abstract of Statistics (1956ff) report the area of forest lost by fire as from 1938. The maximum area lost by fire in a given year being 0.8 k ha in 1938.
4.1.1. Commercial crop harvest

Production figures for cereals (wheat, barley, oats, other corn), potatoes, sugar beet and ‘turnips and swedes’, ‘hay and silage’ used by myself, comply with those used by Schandl and Schulz (2000), Schandl and Schulz (2001) and Schandl and Schulz (2002) and Krausmann et al. (2003). These were taken from Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff), Mitchell (1994) and UK Agricultural Statistics (followed by Digest of Agricultural Census Statistics).

Concerning the production of hops and mangold I used figures given by Mitchell (1988) up to 1980 and figures from FAO (2004) and Digest of Agricultural Census Statistics thereafter. Hops are given in thousand hundredweights and were converted to tons using a factor 0.045\(^{19}\). Data on the production of small fruits and orchard fruits was taken from Digest of Agricultural Census Statistics, these are available as from 1937. Production data for constituents of ‘other corn’ are again only available as from 1937, before this time the productivity of this category is the average of wheat, barley and oats (Schandl and Schulz, 2001). Harvest relating to the areas of ‘cabbage, kohlrabi and oilseed rape’, ‘other green crops’ and flax was determined by attributing to the sum of these areas the production of remaining fodder crops, oil crops, vegetables and fibre crops, given by FAO for the years 1961 - 2000.

Except if stated otherwise, agricultural statistics on the production of crops are available for Great Britain as from 1884 and for Ireland as from 1847. Figures for years were data was not available were derived based on extrapolation of yields based on their development in previous years and available crop areas.

Agricultural Statistics report fresh weight or standardized water content (e.g. 14 % for hay) of biomass harvested. Since for HANPP calculations biomass flows have to be expressed either as dry matter or as carbon flow (Schandl et al., 2002) figures were converted to t DM/yr by using information on the water content of the crops under consideration. Specified water contents are given in Table 6.

\(^{19}\) http://www.simetric.co.uk (Last accessed 1.02.2007)

<table>
<thead>
<tr>
<th>Crops</th>
<th>Water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>14%</td>
</tr>
<tr>
<td>Barley</td>
<td>14%</td>
</tr>
<tr>
<td>Oats</td>
<td>14%</td>
</tr>
<tr>
<td>Other corn</td>
<td>14%</td>
</tr>
<tr>
<td>Potatoes</td>
<td>78%</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>77%</td>
</tr>
<tr>
<td>Turnips and swedes</td>
<td>88%</td>
</tr>
<tr>
<td>Mangold and fodder beet</td>
<td>88% a)</td>
</tr>
<tr>
<td>Hops</td>
<td>80%</td>
</tr>
<tr>
<td>Small fruit</td>
<td>85%</td>
</tr>
<tr>
<td>Orchard fruit</td>
<td>89%</td>
</tr>
<tr>
<td>Hay</td>
<td>14%</td>
</tr>
<tr>
<td>Grass for silage</td>
<td>80%</td>
</tr>
<tr>
<td>Maize for forage and silage</td>
<td>80%</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>12%</td>
</tr>
<tr>
<td>Mustard seed</td>
<td>10%</td>
</tr>
<tr>
<td>Linseed</td>
<td>10%</td>
</tr>
<tr>
<td>Cabbages</td>
<td>92%</td>
</tr>
<tr>
<td>Asparagus</td>
<td>92%</td>
</tr>
<tr>
<td>Lettuce</td>
<td>95%</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>94%</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>91%</td>
</tr>
<tr>
<td>Cucumbers and gherkins</td>
<td>95%</td>
</tr>
<tr>
<td>Chillies &amp; peppers, green</td>
<td>80%</td>
</tr>
<tr>
<td>Onions &amp; shallots, green</td>
<td>89%</td>
</tr>
<tr>
<td>Onions, dry</td>
<td>89%</td>
</tr>
<tr>
<td>Leeks and other alliac. vegetables</td>
<td>85%</td>
</tr>
<tr>
<td>Beans, green</td>
<td>80%</td>
</tr>
<tr>
<td>Peas, green</td>
<td>78%</td>
</tr>
<tr>
<td>Broad beans, green</td>
<td>80%</td>
</tr>
<tr>
<td>Carrots</td>
<td>88%</td>
</tr>
<tr>
<td>Mushrooms</td>
<td>90%</td>
</tr>
</tbody>
</table>

a) Water content of fodder beets
4.1.2. Crop residues harvested

Based on obtainable harvest indices (HI), I extrapolated the amount of available crop residues, from primary crop harvest according to the formulas below:

\[
\text{Crop residue [t DM/yr]} = \text{primary crop harvest [t DM/yr]} \times \text{harvest factor}
\]

\[
\text{With,}
\]

\[
\text{Harvest factor} = \frac{(1-HI)}{HI}
\]

For cereals, potatoes and sugar beet I used historical harvest indices supplied by Fridolin Krausmann (personal communication, 2006). These are partly given in Weisz et al. (1999) and Krausmann (2001) and are based, amongst others, on Austin et al. (1980), Donald and Hamblin (1976) and (1984), Feil (1992), Riggs et al. (1981). HIs used for ‘other corn’ are averages of those supplied for wheat, barley, oats, rye and maize. For turnips and swedes, as well as for mangold and fodder beet, I assumed the amount of crop residue in relation to the primary crop, and the development of this ratio to be similar to that of sugar beet and applied to them same harvest factors as used for sugar beet. This assumption can be baked by factors found in literature (Adger and Subak, 1996; Jölli and Giljum, 2005). Concerning crop residues of the mixed category containing predominantly oil crops, fodder crops and vegetables, I used the average of available historical harvest indices for sugar beet and rape.\(^{20}\) According to this method, primary crop biomass constitutes 55 % of total biomass for the year 2000 and about 45 % for the year 1800. As for the other crops for which assumptions were made concerning the ratio of primary crop to total biomass and how this developed, I also cross-checked my assumptions with the development of yields of the crops concerned. For hops I assumed the ratio between primary crop and by-product to be 1:1 based on information given by the ‘National Hop Association of England and Wales’\(^{21}\) and assumed the historical development to be the same as for ‘mixed corn’. For permanent crops I followed the assumption made by Haberl et al. (2007) for the year 2000, that

\(^{20}\) With regards to recent years, harvest indices relating to different vegetable crops as well as fodder crops such as green peas and green maize compare well with the harvest index available for sugar beet, while the harvest index available for rape is representative of harvest indices of oil crops (Jölli and Giljum, 2005).

\(^{21}\) http://www.hops.co.uk (Last accessed 2.02.2007)
total by-product is 2.5 times commercial and that one third of this (e.g. branches and leaves) is harvested during crop harvest assuming this not to have varied much over the examined timeframe. Figure 1 shows the development of harvest indices as used for the various crops in my study and Table A7 contains individual harvest factors as used by myself for selected years.

Table A7. Harvest factors for selected years, used in my calculation. Sources: Weisz et al. (1999), Krausmann (2001), National Hop Association and Haberl et al. (2007).

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td></td>
<td>2.21</td>
<td>2.21</td>
<td>1.98</td>
<td>1.98</td>
<td>1.85</td>
<td>1.63</td>
<td>1.36</td>
<td>1.10</td>
<td>0.88</td>
<td>0.81</td>
<td>0.76</td>
</tr>
<tr>
<td>Barley</td>
<td></td>
<td>2.93</td>
<td>2.93</td>
<td>2.62</td>
<td>2.68</td>
<td>2.22</td>
<td>1.78</td>
<td>1.36</td>
<td>1.06</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Oats</td>
<td></td>
<td>2.53</td>
<td>2.53</td>
<td>2.51</td>
<td>2.30</td>
<td>1.94</td>
<td>1.73</td>
<td>1.51</td>
<td>1.29</td>
<td>1.06</td>
<td>0.97</td>
<td>0.89</td>
</tr>
<tr>
<td>Other corn</td>
<td></td>
<td>2.48</td>
<td>2.48</td>
<td>2.26</td>
<td>2.15</td>
<td>1.89</td>
<td>1.65</td>
<td>1.38</td>
<td>1.14</td>
<td>0.95</td>
<td>0.89</td>
<td>0.83</td>
</tr>
<tr>
<td>Potatoes</td>
<td></td>
<td>0.96</td>
<td>0.96</td>
<td>0.87</td>
<td>0.87</td>
<td>0.75</td>
<td>0.62</td>
<td>0.47</td>
<td>0.33</td>
<td>0.24</td>
<td>0.22</td>
<td>0.20</td>
</tr>
<tr>
<td>Sugar beet</td>
<td></td>
<td>0.70</td>
<td>0.70</td>
<td>0.66</td>
<td>0.65</td>
<td>0.63</td>
<td>0.59</td>
<td>0.53</td>
<td>0.46</td>
<td>0.39</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td>Turnips &amp; swedes</td>
<td></td>
<td>0.70</td>
<td>0.70</td>
<td>0.66</td>
<td>0.65</td>
<td>0.63</td>
<td>0.59</td>
<td>0.53</td>
<td>0.46</td>
<td>0.39</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td>Mangold</td>
<td></td>
<td>0.70</td>
<td>0.70</td>
<td>0.66</td>
<td>0.65</td>
<td>0.63</td>
<td>0.59</td>
<td>0.53</td>
<td>0.46</td>
<td>0.39</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td>Other crops a)</td>
<td></td>
<td>1.32</td>
<td>1.32</td>
<td>1.25</td>
<td>1.21</td>
<td>1.15</td>
<td>1.09</td>
<td>1.02</td>
<td>0.94</td>
<td>0.87</td>
<td>0.84</td>
<td>0.80</td>
</tr>
<tr>
<td>Hops</td>
<td></td>
<td>2.80</td>
<td>2.80</td>
<td>2.65</td>
<td>2.55</td>
<td>2.21</td>
<td>1.92</td>
<td>1.62</td>
<td>1.35</td>
<td>1.12</td>
<td>1.06</td>
<td>1.00</td>
</tr>
<tr>
<td>Permanent crops</td>
<td></td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
</tr>
</tbody>
</table>

a) incl. oilcrops, fodder crops, vegetables
4.2. Biomass harvest through grazing

The amount of grazed biomass constitutes the difference of feed demand of grazers and the quantity of marked feed and non-marked feed, available to them after accounting for feed demand of other livestock ("grazing gap"). In my calculations, the amount of marked feed (in kt DM) available to grazers was additionally multiplied by a factor 1.5 accounting for its higher nutritive value as opposed to grazed biomass (Krausmann 2006, personal communication).

For the years 1961 - 2000, data on available marked feed was taken from FAO commodity balances (2004). Feed commodities include primary crops used as feed, as well as processed feedstuffs (of both plant and animal origin), from local production and imports. Amounts given in tons (t) were converted to tons dry matter (t DM) according to the commodity-specific water contents, summarized in Table A8.

Figure A1. Development of harvest indices. Sources: Weisz et al. (1999), Krausmann (2001), National Hop Association, own estimates.

<table>
<thead>
<tr>
<th>Feed commodities according to FAO</th>
<th>Water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>14%</td>
</tr>
<tr>
<td>Barley</td>
<td>14%</td>
</tr>
<tr>
<td>Beans</td>
<td>80%</td>
</tr>
<tr>
<td>Brans</td>
<td>10%</td>
</tr>
<tr>
<td>Cereals, other</td>
<td>14%</td>
</tr>
<tr>
<td>Copra cake</td>
<td>10%</td>
</tr>
<tr>
<td>Cottonseed cake</td>
<td>10%</td>
</tr>
<tr>
<td>Groundnut cake</td>
<td>10%</td>
</tr>
<tr>
<td>Maize</td>
<td>14%</td>
</tr>
<tr>
<td>Millet</td>
<td>12%</td>
</tr>
<tr>
<td>Molasses</td>
<td>33%</td>
</tr>
<tr>
<td>Oats</td>
<td>14%</td>
</tr>
<tr>
<td>Oilseed cakes, other</td>
<td>10%</td>
</tr>
<tr>
<td>Palmkernel cake</td>
<td>10%</td>
</tr>
<tr>
<td>Potatoes</td>
<td>78%</td>
</tr>
<tr>
<td>Pulses</td>
<td>10%</td>
</tr>
<tr>
<td>Pulses, other</td>
<td>10%</td>
</tr>
<tr>
<td>Rape and mustard cake</td>
<td>10%</td>
</tr>
<tr>
<td>Rye</td>
<td>14%</td>
</tr>
<tr>
<td>Sesameseed cake</td>
<td>10%</td>
</tr>
<tr>
<td>Sorghum</td>
<td>11%</td>
</tr>
<tr>
<td>Soyabean cake</td>
<td>10%</td>
</tr>
<tr>
<td>Soyabeans</td>
<td>10%</td>
</tr>
<tr>
<td>Sugar &amp; sweeteners</td>
<td>1%</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>83%</td>
</tr>
<tr>
<td>Sunflowerseed</td>
<td>7%</td>
</tr>
<tr>
<td>Sunflowerseed cake</td>
<td>10%</td>
</tr>
<tr>
<td>Sweet potatoes</td>
<td>70%</td>
</tr>
</tbody>
</table>
Available amounts of commodities for years before 1961 were established in the following ways:

For wheat, barley and oats and maize, beans, pulses and rye (included under other corn) I extrapolated amounts of feed from amounts of total product available for consumption (including net imports and after the deduction of seed)\textsuperscript{22} using the factors shown in Table 9. Percentages relating to wheat, barley and oats for the years 1800, 1830 and 1871 were taken from Overton and Campbell (1999). For wheat I assumed that very little was used as feed up to the beginning of the 20\textsuperscript{th} century\textsuperscript{23}. Percentages given for 1961 and later years were established by relating feed amounts of products, stemming from FAO commodity balances (2004), to total product available for consumption. Percentages given for intermediate years are based on linear interpolation between available data points. For the ‘other corn’ category the value of 80\% established for 1961 was used over the entire period based on information given by Brassely (2000) that beans, peas and maize, were important constituents of concentrated feed, supplied to livestock in the 19\textsuperscript{th} century.

Relating to the remaining feed commodities given by FAO (2004) I assumed that in sum of the amount of feed available from these commodities, steadily increased from the beginning of the 20\textsuperscript{th} up to 1961, as is the case between 1961 and 2000. This is also the trend shown by the cereal commodities and can be related to the decline in available fodder crops. Amounts of available feed from these commodities, for earlier years, were therefore linearly extrapolated from the 1961 value according to this development. Before 1850 available feed from these categories was assumed to be minimal (Brassely, 2000).

Non-marked feed consists of fodder crops from local production, not included in marked feed, as well as crop residues from local crops as summarized in Table A9. Next to turnips and swedes, mangold, fodder beet and hay I also assumed 80\% of biomass production of the mixed category of fodder crops, oil crops and vegetables, to be used as fodder, based on its composition between 1961 and 2000 (FAO, 2004) and

\textsuperscript{22} Calculated from available figures taken from Mitchell (1994) and Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) 1854ff.

\textsuperscript{23} According to Marks (1989) the importance of wheat and barley used as feed only increased during the second half of the 20\textsuperscript{th} century and he gives a value of 20\% of wheat used as feed for 1950.
on information, on the constitution of fodder crops between 1875 and 1966 (MAFF, 1968). Concerning crop residues, I assumed between 15 - 25% of straw, 26% of leaves and tops from sugar beet turnips and swedes, mangold and fodder beet and 10% of crop residues from potatoes and the mixed category to be recovered and to be used as feed over the period under investigation.24


<table>
<thead>
<tr>
<th>Feed supply</th>
<th>% Feed</th>
<th>1800</th>
<th>1830</th>
<th>1871</th>
<th>1900</th>
<th>1940</th>
<th>1961</th>
<th>1980</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARKED FEED</td>
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<td></td>
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<tr>
<td>Local prod. and imports</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>0.24</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>Barley</td>
<td></td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
<td>0.26</td>
<td>0.54</td>
<td>0.68</td>
<td>0.71</td>
<td>0.64</td>
</tr>
<tr>
<td>Oats</td>
<td></td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>0.92</td>
<td>0.94</td>
<td>0.95</td>
<td>0.74</td>
<td>0.36</td>
</tr>
<tr>
<td>Other Corn</td>
<td></td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.35</td>
<td>0.19</td>
</tr>
<tr>
<td>Potatoes</td>
<td></td>
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<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Other</td>
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<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
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<td>FODDER CROPS</td>
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<td></td>
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</tr>
<tr>
<td>Local production</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turnips and swedes</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mangold/ fodder beet</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
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<tr>
<td>Hay</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<td></td>
</tr>
<tr>
<td>Local production</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root and beet tops</td>
<td></td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Straw</td>
<td></td>
<td>0.25</td>
<td>0.22</td>
<td>0.19</td>
<td>0.17</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Leaves and stalks</td>
<td></td>
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<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

24 Refer to 5.1 ‘Backflows of crop residues’ for details on how these values were established
4.2.1. Establishing feed demand of livestock

Feed demand for different livestock classes was calculated using models developed by Haberl et al. (2007).

For cattle, feed demand was calculated based on linear correlations between daily feed intake per head and milk yield and carcass weight according to the following formulae:\(^25\)

\[
\text{Feed intake (milk) [kgDM/head/day]} = 0.00155 \times \text{milk yield [kg/head/yr]} + 4.8375
\]

and

\[
\text{Feed intake (weight) [kgDM/head/day]} = 0.036361 \times \text{carcass weight [kg/animal]} + 1.702006
\]

The development of milk yields and feed demand of cattle as used in my calculation, are featured in Figure A2 and Table A10 below. The Ministry of Agriculture Food and Fisheries (MAFF) made figures relating to milk yields on a yearly basis available between 1938 and 1962. These were taken from Marks (1989). Between 1962 and 2000 I used figures from FAO (2004). Milk yields for earlier years were constructed based on information on their development and figures for individual years given by Turner (2000) and Tailor (1976). Figures from FAO are given in Hg/head/yr and were converted to kilogram (kg) by a factor 0.1, while figures from other sources are given in gallons/head/year and were converted by a factor 4.546. Data on carcass weights are again available from MAFF and FAO (2004) between 1938 and 2000. Figures found for individual years between 1871 and 1903 (Turner, 2000) are somewhat contradictory. For this reason I chose to use the correlation between feed demand and milk yield to establish the amount of feed needed for all cattle, instead of an average of the factors calculated by means of the two equations. Feed demand factors calculated on the basis of both equations for the years for which reliable yearly data was available for both milk yields and carcass weights, barely deviate from each other.

\(^{25}\) These were derived by Haberl et al. using data derived from ‘various national feed balances and feed demand models’ for sources, refer Haberl et al. (2007)

Table A10. Development of feed demand of cattle. Source: Own calculations based on Haberl et al. (2007).

<table>
<thead>
<tr>
<th>Year</th>
<th>1800</th>
<th>1850</th>
<th>1940</th>
<th>1960</th>
<th>1980</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed demand [kg dm/animal/day]</td>
<td>7.5</td>
<td>7.9</td>
<td>8.1</td>
<td>9.3</td>
<td>12.3</td>
<td>14.5</td>
</tr>
</tbody>
</table>
Feed demand of pigs and poultry was calculated using region-specific efficiency factors for feed intake per unit of meat and egg production (as shown in Table A11), according to the formula:

\[
\text{Feed demand [kg DM]} = \text{kg produce [kg fresh weight]} \times \text{efficiency factor}
\]

Production data was taken from Marks (1989) and FAO (2004). Figures are available as from 1921. To establish produce for earlier years, I calculated ‘production per animal’ factors, from the amount of produce and livestock numbers available for later years. These only increased markedly as from around 1950 for all three categories (pork, poultry meat and eggs) under consideration, which also fits together with the development of milk yields. For this reason I calculated production of the years without available data via the factor calculated for 1921 and the livestock numbers available for earlier years.

**Table A11.** Efficiency factors used in my calculation of feed demand of pigs and poultry. Sources: Haberl et al. (2007).

<table>
<thead>
<tr>
<th>Production</th>
<th>Efficiency factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pork</td>
<td>4.0</td>
</tr>
<tr>
<td>Poultry meat</td>
<td>3.0</td>
</tr>
<tr>
<td>Eggs</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Feed demand of sheep and horses was estimated using data on daily feed intake of these classes, as given by Haberl at al. (2007) for Western European countries, shown in Table A12. Values were kept constant over the entire period. Feed demand of horses, might have been higher in earlier years, when these were still predominantly being used as draft animals (Sieferle et al., 2006) and feed demand per sheep, slightly lower due to a slight increase in carcass weight (Marks, 1989; Turner, 2000). However due to the lack of solid data constant values were deemed adequate.
Table A12. Species-specific daily feed intake [kg DM / head / day]. Source: Haberl et al. (2007).

<table>
<thead>
<tr>
<th>Species</th>
<th>Daily feed intake [kg DM / head / day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep</td>
<td>1.5</td>
</tr>
<tr>
<td>Horses</td>
<td>10</td>
</tr>
</tbody>
</table>

Data on livestock numbers were taken from Mitchell (1988), Marks (1989)\(^{26}\) and FAO (2004). Periodical figures are predominantly available as from 1841 for Ireland and from 1867 for Great Britain. Prior figures are based on figures available for individual years (taken from Sieferle et al., 2006) and linear inter- and extrapolation.

4.2.2. Attribution of grazing

Grazing was attributed primarily to fallow land, rotation and permanent pasture for grazing and rough grazing land, with the constraint, that 75 %, 75 % and 65 % of annual biomass increment (ANPP\(_{\text{act}}\)) respectively, could be grazed from these areas. I propose, that fallow land and rotation pasture are grazed to the limit of 75 % and that 60 % of remaining grazing demand is covered by grazing on permanent pastures and 40 % by grazing on rough grazing land. This allocation was made based on the fact, that permanent pastures in average are composed of species of higher forage value (Lazenby, 1981) and relates well to the ratio of feed demand of cattle to that of sheep, which are known to largely graze on rough grazing land (Lazenby, 1981). According to this method, from 1800 to 1819 and again from 1962 to 2000, grazing demand exceeds the grazing potential of these areas. This relates closely to the development in sheep numbers and a dramatic increase in feed demand of cattle due to an intensification of meat and milk production. Up to 1850 sheep were at a peak of around 42 million, decreasing thereafter due to a declining demand for wool coupled with imports of cotton (Sieferle et al., 2006 and Marks, 1989). During the 1980ies there is again a steep increase of sheep numbers correlating with the introduction of ‘Common Agricultural Policy (CAP)’\(^{27}\). Cattle numbers do not vary so markedly slowly increasing and reaching

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\(^{26}\) Figures given by Marks derive from agricultural departments of Great Britain and Ireland (agricultural censuses)

\(^{27}\) System of European Union agricultural subsidies and programs
their peak in the mid 1970ies, but per head and year feed demand increases from 3.3 t DM/head/yr to 5.3 t DM/head/yr between 1950 and 2000. For the years 1800 and 1819 excess grazing was attributed to 'other land', which as described previously, during this time still includes large areas similar to those of rough grazing land. Relating to the years 1962 to 2000, I propose that marked feed might have been underestimated due to faulty statistical data, feed demands might be slightly overestimated, and excess grazing has been accounted for in crop harvest and harvest from urban areas (as these also include isolated dwellings in the countryside etc.). The distribution of grazing established, according to the method described above has been summarized in Table A13 below.

Table A13. Amount of biomass grazed relating to different land use categories for selected years. Source: Based on own calculations.

<table>
<thead>
<tr>
<th>Grazing on</th>
<th>1800</th>
<th>1850</th>
<th>1940</th>
<th>1960</th>
<th>1980</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fallow land a)</td>
<td>4%</td>
<td>4%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>4%</td>
</tr>
<tr>
<td>Rotation pasture for grazing</td>
<td>3%</td>
<td>9%</td>
<td>9%</td>
<td>15%</td>
<td>17%</td>
<td>11%</td>
</tr>
<tr>
<td>Permanent pasture for grazing</td>
<td>26%</td>
<td>52%</td>
<td>52%</td>
<td>38%</td>
<td>44%</td>
<td>52%</td>
</tr>
<tr>
<td>Rough grazing land</td>
<td>48%</td>
<td>35%</td>
<td>38%</td>
<td>46%</td>
<td>38%</td>
<td>33%</td>
</tr>
<tr>
<td>Other land</td>
<td>19%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

a) Including set aside land as from 1993
4.3. Harvest on urban land

Due to the lack of better information on harvest from urban areas, this was said to be 50% of ANPPact as done in calculations of Global HANPP (Haberl et al., 2007).

4.4. Wood harvest

Harvest of wood is poorly documented within official statistics for the United Kingdom. In my calculations I used data, taken from the UNECE timber database28 (compiled by TBFRA), which provides figures on removals (1000m³ under bark) of coniferous and non-coniferous round wood and fuel wood, as from 1964. To convert green volumes to tons DM I used wood densities referring to dry matter per cubic metre green volume, as used by Haberl et al. (2007) in calculations for Europe, adopted from Penman et al. (2003). These are 0.41 and 0.57 [t dm/m³], for coniferous wood and non-coniferous wood respectively. Wood harvest for earlier years was determined based on available data on forest area and removal per hectare values. To determine the total amount of biomass harvested from commercial wood harvest, I used bark percentages on removals (11% for both coniferous and non-coniferous wood) to account for bark removed, and country specific recovery rates (the ratio of removals to fellings) to establish the amount of wood left in forest and destroyed during the process of logging. These are 88% and 74% for coniferous wood and non-coniferous wood respectively, relating to both round- and fuel wood. Both bark percentages and recovery rates derive from UN (2000)29 data, and relate to recent years. However due to the lack of historical data these were applied over the entire period under investigation. Quantities of total wood harvest established in this way compare well with values on ‘fellings over bark standing’ given by UK statistics (Forestry Commission, 2004) for individual years between 1970 and 2000.

28 UNECE: United Nations Economic Commission for Europe
http://www.unece.org/trade/timber/mis/fp-stats.htm (Last accessed 15.03.2007)
5. Backflows to nature

Backflows to nature relate to harvested biomass, which has no further societal use. These include on site backflows of manure from grazing live stock, crop residues from annual crops ploughed in or burnt on the field and wood left in the forest during harvest of timber.

5.1. Backflows of harvested crop residues

Backflows of harvested crop residues from individual crops are calculated as the difference between total available crop residue and the amount of crop residue recovered (Haberl et al., 2007). Proportions of recovered and unused crop residues from different crops have been summarized in Table A14. This also includes the extent of backflow of manure to grazing land and wood to forest and woodland.

Annual Abstracts of Statistics report harvested straw, from wheat barley and oats for the whole of the UK for the years 1937 to 1968. When relating this to total amount of crop residue available, calculated by means of HI’s, established recovery rates range between around 60 % in 1937 and 40 % in 1968. The recovery rate of 40 % seems relatively low, as recovery rates found in literature relating to the years 1972 (Foot, 1977 citing survey figures from the A.D.A.S\(^{30}\) and 1993 - 1996 (Stott, 2003 citing values from the Straw Disposal Survey for England and Wales, 1995) are of a magnitude of 51 % to 96 %. I therefore decided to use a constant recovery rate of 60 % between 1937 and 2000. Due to higher amounts of straw being used as feed during the 19\(^{th}\) century (Brassely, 2000), I further assumed the recovery rate to be 70 % at the beginning of the 19\(^{th}\) century and 65 % in 1850, using linear interpolation for intermediate years. These recovery rates were also applied to crop residues of the category of other corn. Recovered straw was additionally specified according to its uses (feed and other uses e.g. bedding and crop storage) based on values given by Foot (1977 citing survey figures from the A.D.A.S) for the year 1972 relating to England and Wales. Relating to unused straw the A.D.A.S survey reports 37 % of straw being burnt and only 2 % being ploughed in (Foot, 1977). Marks (1989) states that a vast amount of unused straw was still being burned at the beginning of the nineties. However, when burning of straw was

\(^{30}\) Agricultural Development and Advisory Service (http://www.adas.co.uk)
banned by the European Union in 1993, this was abandoned and the amount of straw being ploughed in rose considerably. Scott (2003) gives an average amount of 40% for the years 1996-1996 relating to winter wheat straw.

The amount of recovered crop residue from root and beet crops, is again based on a value given by Foot (1977) on the disposal of sugar beet tops in the United Kingdom. In this study it was found that 26 % of total available sugar beet tops were used as feed (18 % in situ) and that the remaining 74% were ploughed in. According to FAO 31, up to today, tops of fodder beet and turnips and swedes are also being fed to livestock and I propose, the amount to be similar to that of sugar beet tops, especially if these crops are fed straight from the field. For crop residues from all other annual crops except for hops I suggest that 10 % of these are recovered and used as feed based on recovery rates given by Di Blasi et al. (1996). Relating to hops I considered the total amount of harvested crop residue to decay on site, while for permanent crops I considered the total amount of harvested crop residue to be recovered. 32 Due to lack of information for earlier years I kept recovery rates constant over the entire period under investigation.

### 5.3. Backflows of wood

Backflows of wood were calculated as the difference between fellings and removals (over bark), which equals 12 % of coniferous wood (round and fuel wood) and 25% of non-coniferous wood (round and fuel wood) felled in a year, over the entire period under investigation. 33

### 5.2. Backflow of manure

When accounting for backflow of manure, I used assumptions from Haberl et al. (2007) based on information given by Vetter and Steffens (1986) and BMLF 34 (1991). Haberl et al. (2007) assume, that cattle excrete 35 %, and all other grazers 25 % of dry matter feed intake and that two thirds of this is dropped on site during grazing, while one third is

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31 Information provided under: http://www.fao.org/es/faodef/fedef11e.htm (Last accessed 2.03.2007)
32 Also refer to 4.2.1. Harvest of crop residues
33 Refer to: 4.4. Wood harvest
34 Austrian Ministry of Agriculture and Forestry
collected by farmers to be used on cropland. I further allocated the total amount of
manure dropped during grazing to the areas grazed, according to the amount of
biomass grazed from these areas.

Table A14. Proportions of used and unused crop residues and backflows of wood and manure.
Sources: TBFRA (2000), BMLF (1991), Steffens (1986), and own estimates based on information

<table>
<thead>
<tr>
<th>CROP RESIDUES</th>
<th>1800</th>
<th>1850</th>
<th>1940</th>
<th>1960</th>
<th>1980</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Straw (from cereals, maize, beans and peas)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>0.70</td>
<td>0.65</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>Used as feed</td>
<td>0.25</td>
<td>0.20</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Other uses</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
<td>0.30</td>
<td>0.35</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
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<tr>
<td>Burned</td>
<td>0.28</td>
<td>0.33</td>
<td>0.38</td>
<td>0.38</td>
<td>0.26</td>
<td>0.00</td>
</tr>
<tr>
<td>Ploughed in</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.14</td>
<td>0.40</td>
</tr>
<tr>
<td><strong>Sugar beet tops</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>-</td>
<td>-</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Used as feed</td>
<td>-</td>
<td>-</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
<td>-</td>
<td>-</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>Ploughed in</td>
<td>-</td>
<td>-</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>Turnip and swede tops</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Used as feed</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>Ploughed in</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>Mangold and fodder beet tops</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Used as feed</td>
<td>0.26</td>
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<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>Ploughed in</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>Stems and leaves of potatoes and 'other crops'</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Used as feed</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Ploughed in/on site decay</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td><strong>Hop leaves and stems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>On site decay</td>
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<td>1.00</td>
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<tr>
<td><strong>Twigs and leaves from permanent crops</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Recovered</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Backflow</strong></td>
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<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table A14. Continued

<table>
<thead>
<tr>
<th>BACKFLOWS OF WOOD</th>
<th>Recovered</th>
<th>Backflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundwood coniferous</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td>Roundwood non-coniferous</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>0.75</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>0.75</td>
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<tr>
<td>Fuel wood coniferous</td>
<td>0.88</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>0.88</td>
<td>0.88</td>
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</tr>
<tr>
<td></td>
<td>0.88</td>
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</tr>
<tr>
<td>Fuel wood non-coniferous</td>
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<td>0.75</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>0.75</td>
<td>0.75</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>BACKFLOWS OF MANURE</th>
<th>Recovered</th>
<th>Backflow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
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<td>0.33</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

a) 1/3 of total ‘crop residue’ is harvested during harvest of primary crop and I assume this to be removed
together with the primary crop.
6. Aboveground productivity of prevailing vegetation (ANPP\textsubscript{act})

Two approaches were chosen to establish ANPP\textsubscript{act} relating to individual land uses. ANPP\textsubscript{act} on tilled cropland and cultivated grassland was calculated from crop harvest by means of harvest indexes (as previously described for NPP\textsubscript{h}), additionally considering unaccounted-for ANPP\textsubscript{act} due to losses during the growth period, losses due to herbivory and the NPP of weeds (Haberl et al., 2007). To establish ANPP\textsubscript{act} for all other land use areas I used ANPP\textsubscript{act} tons DM per ha and year estimates, backed by information and values found in literature.

6.1. ANPP\textsubscript{act} on tilled land

ANPP\textsubscript{act} of tilled land was calculated as the sum of commercial crop harvest, total by-product and biomass lost prior to harvest (unaccounted-for ANPP\textsubscript{act}). To account for biomass loss due to natural processes I extrapolate this from ANPP\textsubscript{h} using factors calculated from Oerke et al. (1994), relating to the level of industrialization of agriculture. I assume the level of industrialization of agriculture to be that of developing countries in the beginning of the 19\textsuperscript{th} century and that of industrialized countries as from 1950 using linear interpolation for intermediate years. Factors for selected years have been summarized in Table A15 below.

| Table A15. Factors used in estimating ANPP\textsubscript{act} on cropland from ANPP\textsubscript{h}. ANPP\textsubscript{act} = ANPP\textsubscript{h} \times \text{factor} |
|------------------|---|---|---|---|---|
|                  | 1800 | 1850 | 1900 | 1950 | 2000 |
| Unaccounted-for ANPP/ANPP\textsubscript{h} | 1.23 | 1.20 | 1.17 | 1.14 | 1.14 |
6.2. ANPP\textsubscript{act} on fallow land

I assumed fallow land to be invaded by herbaceous vegetation and ANPP\textsubscript{act} tons dry matter per hectare and year (t DM/ha/yr) to be similar to that of less productive permanent pastures. I therefore assigned to fallow land, the value of permanent pastures for grazing (refer to 6.3. below) at the beginning of the 19\textsuperscript{th} century, keeping this value constant over the entire period under investigation.

6.3. ANPP\textsubscript{act} of rotation and permanent pastures

ANPP\textsubscript{act} of rotation pastures and permanent pastures for hay/silage was determined based on available data on harvest of grass from these areas\textsuperscript{35}, assuming that the amount of grass harvested in a given year constitutes 75\% of total ANPP\textsubscript{act} (Krausmann, personal communication 2006; Suttie, 2000).

Therefore:

\[ \text{ANPP}_{\text{act}} = \text{harvest} \times 1.33 \]

Production of grass in Great Britain was reported separately for grass from rotation pastures and permanent pastures in the years 1886 to 1956. For Ireland and Northern Ireland this distinction was not made in agricultural returns (Mitchell, 1988) I therefore assigned the same ANPP\textsubscript{act} per hectare value to both rotation pastures and permanent pastures based on combined production from both of these areas. For the years that the distinction was made for Great Britain, yields from permanent and rotation pasture barley deviate from each other. For later years ANPP\textsubscript{act} on rotation pastures for hay/silage might be slightly underestimated, while productivity of permanent pastures for hay/silage might be slightly overestimated relating to the amount of fertilizer currently applied to these areas\textsuperscript{36} Further I did not distinguish between ANPP\textsubscript{act} t DM/ha/yr of

\textsuperscript{35} Also refer to 4.1.1 Commercial crop harvest

\textsuperscript{36} In his study on *Fertilizer Trends in Relation to Biological Productivity within the U.K.*, Hood (1982) cites values on N fertilizer usage in England and Wales from Cooke (1980) and Challinor (1981, personal communication) for years between 1943 and 1980, showing that as from the 1950ties onward temporary grass received about double the amount of fertilizer as compared to permanent grass. Average kg/ha values, for the two, being 16 kg/ha and 6 kg/ha respectively for 1950-52, and 167 kg/ha and 93 kg/ha respectively for 1980.
rotation pasture for hay/silage and rotation pasture for grazing. I did however do this 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 (Stapeldon and Davies, 1948 and Lazenby, 1981) also characteristic of rough grazing land (Stapeldon and Davies, 1948; Tansely, 1965 and Hopkins, 2000). I therefore allocated to permanent pastures for grazing the average ANPP\textsubscript{act} t DM/ha/yr value of permanent and rotation pasture for hay/silage and rough grazing land. 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 productivity of permanent pastures.

Literature values referring to the productivity of grasslands, often relate to annual herbage production i.e. the mass of herbage that can be removed either by animals under grazing or by mechanical harvesting (Hopkins, 2000, pg. 90 citing Hodgson, 1979) rather than ANPP. Maximum obtainable yields of pure rye grass swards in Britain as given by Hopkins (2000) and Radcliffe and Baars (1987) (citing Cooper 1970 and Voightlander and Voss 1980) based on frequent cutting regimes, favourable site conditions and extremely high fertilizer inputs are 20 to 25 t DM/ha/yr. Based on current practice of fertilizer application and cutting, yields of perennial ryegrass according to Hopkins (2000) (citing Hopkins et al., 1995) vary between 10 and 18 t DM/ha/yr depending on site conditions, while grass-white clover swards receiving no fertiliser have yields ranging between 5 - 10 t DM/ha/yr (Hopkins, 2000 citing Hopkins et al., 1995). Based on this information I believe ANPP\textsubscript{act} DM/ha/yr values calculated via hay harvest to be reasonable.

\[\text{ANPP}_{\text{act}} \text{ DM/ha/yr}\]

\[\text{ANPP}_{\text{act}} \text{ DM/ha/yr}\]

37 According to Stapeldon and Davies (1948) this is not only the case for England and Wales but also applies to Ireland and Scotland.
6.4. ANPP$_{\text{act}}$ on rough grazing land

This category is quite diverse in its composition and management. Values referring to annual yields of dominant plant communities range between around 4 and 1.5 t DM/ha/yr (Milne et al., 2002; Hopkins, 2000; Palmer, 1997). Based on their distribution in 1938 (Stapeldon and Davies, 1948) the weighted average value for annual herbage production per hectare is 2.6 t DM/ha/yr. I further found values on ANPP of chalk grasslands (composed of graminaceous species and a range of forbs), compiled from a study site in the southern English uplands (Beacon Hill) by Williamson and Pitman (1998). The authors report ANPP to range between 355 (peak live biomass) and 773 g/m$^2$/yr (max live + dead).

Based on these data I chose to allocate to rough grazing land an ANPP$_{\text{act}}$ per hectare and year value of 3.5 t DM/ha/yr. This was kept constant over the entire period under investigation. It is difficult to access how ANPP$_{\text{act}}$ on these areas could have varied over the studied period. While up to today in some parts of the United Kingdom there remain rough grazing areas, which are sparsely grazed, and are at the risk of to scrubbing over, the more productive ones can be highly stocked and are in some areas exposed to overgrazing causing degradation (Holden et al., 2007).

6.5. ANPP$_{\text{act}}$ of forest and woodland

ANPP$_{\text{act}}$ of forest and woodland was held to be equal to ANPP$_0$. Next to high forest areas this category also includes areas of coppice, scrub and felled areas. Nevertheless, due to the fact the area of high forest makes up by far the greatest part over the entire period under investigation (Forestry Commission, 1987; UN, 2000) and that in total forests and woodlands make up merely a small proportion of the area of the United Kingdom (around 3 %, at their lowest expansion in the 1870s and around 12 % at their highest expansion in the year 2000) this method seemed permissible.

By using this approach effects that forest management might have on forest productivity, are not taken into account. However, this could not be considered, since there is currently no reliable data available on this subject (Haberl et al., 2007).

38 Refer to Table A2
6.6. ANPP\textsubscript{act} on urban land

When calculating ANPP\textsubscript{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, road verges) and trees (e.g. parks), this was attributed the average ANPP\textsubscript{act} t DM/ha/yr value of woodland an intensified grassland.

6.7. ANPP\textsubscript{act} on other land

As described under 2.4.7, the majority of ‘other land’ between 1800 and 1850 resembles rough grazing land, which is why it 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.
Table A16. $\text{ANPP}_{\text{act}}$ [t DM/ha/yr] attributed to different land use areas as compared to $\text{ANPP}_0$. Sources: See text.

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<tr>
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Appendix B: Additional results and input data - figures

This section contains figures of additional results and input data for the United Kingdom 1800 - 2000, including figures on land use on a less aggregated level, development of livestock numbers and commercial crop harvest, as well as calculated feed demand, feed supply, harvest through grazing, crop residues and allocation of crop residues, wood harvest and ‘backflows to nature’. It also contains figures on HANPP and its components according to the aggregate land use classes of: cropland, permanent pasture, rough grazing land, as well as comparative figures relating to overall results.
Figure B1. Development of land use in the United Kingdom, 1800 - 2000, in million hectares per year [Mha/yr]. Sources: Own estimates based on various sources. See Appendix A.

Figure B2. Constituents of cropland in the United Kingdom 1800-2000, in million hectares per year [Mha/yr]. Sources: Sieferle et al. (2006), Mitchell (1994), UK Agricultural Statistics (followed by Digest of Agricultural Census statistics), Statistical Abstract for the United Kingdom (followed by Annual Abstract of Statistics) (1854ff) and own calculations. See Appendix A.
Figure B3. Commercial crop harvest in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: 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) and own estimates. See Appendix A

Figure B4. Crop yields in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Sources: Own calculations.
Figure B5. Amounts of crop residues from crop aggregates and individual crops in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations. See Appendix A.

Figure B6. Use of crop residues from individual crops in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: own calculations. See Appendix A.
**Figure B7.** Livestock numbers in the United Kingdom, 1800 - 2000, in millions. Sources: Mitchell (1988), FAO (2004), Sieferle et al. (2006) and own estimates. See Appendix A.

**Figure B8.** Calculated feed demand of different livestock species in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations based on Haberl et al. (2007). See Appendix A.
Figure B9. Feed supply and biomass grazed on fallow land, rotation pasture and permanent pasture for grazing, rough grazing land and other land, for the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: FAO (2004), Campbell (2000) and Brassely (2000) and own estimates. See Appendix A.

Figure B10. Difference between calculated grazing demand and allocated biomass harvest through grazing. Sources: Own calculations based on Haberl et al. (2007) and personal communication with Krausmann and Erb (2006). See Appendix A.
Figure B11. Wood harvest in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Total wood harvest includes wood removals and wood left in forest (felling losses). Sources: UNECE timber database and own calculations. See Appendix A.

Figure B12. Backflows of harvested products in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations. See Appendix A.
Figure B13. Aboveground productivity of actually prevailing vegetation (ANPP$_{\text{act}}$), for aggregated land use classes, in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations. See Appendix A.

Figure B14. Aboveground productivity of actually prevailing vegetation (ANPP$_{\text{act}}$), per area, for aggregated land use classes and total land area, in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Sources: Own calculations. See Appendix A.
Figure B15. Aboveground productivity of actually prevailing vegetation (ANPP_{act}), as fraction of aboveground productivity of potential vegetation (ANPP_{0}), in the United Kingdom, 1800 - 2000, in percent [%]. Sources: Own calculations. See Appendix A.

Figure B16. Land-use induced productivity changes (ΔANPP_{LC}), per area, for aggregated land use classes, in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Sources: Own calculations. See Appendix A.
Figure B17. Biomass harvest (ANPP_h), for aggregated land use classes, in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations. See Appendix A.

Figure B18. Biomass harvest (ANPP_h) per area, for aggregated land use classes, in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Sources: Own calculations. See Appendix A.
Figure B19. Aboveground NPP remaining in ecosystem after harvest (ANPP\textsubscript{t}), for aggregated land use classes, in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations. See Appendix A.

Figure B20. Aboveground NPP remaining in ecosystem after harvest (ANPP\textsubscript{t}), per area, for aggregated land use classes, in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Sources: Own calculations. See Appendix A.
Figure B21. Human appropriation of aboveground net primary production (HANPP), for aggregated land use classes, in the United Kingdom, 1800 - 2000, in million tons dry matter per year [Mt DM/yr]. Sources: Own calculations. See Appendix A.

Figure B22. Human appropriation of aboveground net primary production (HANPP), per area, for aggregated land use classes in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Sources: Own calculations. See Appendix A.
a) Cropland

b) Permanent pasture

c) Rough grazing land
Figure B23. Development of \( \text{ANPP}_{\text{act}} \), \( \text{ANPP}_h \), \( \text{ANPP}_t \), \( \Delta \text{ANPP}_{\text{LC}} \) and \( \text{HANPP} \), for aggregated land use classes (a-f), per area, in the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Source: Own calculations. See Appendix A.
Figure B24. Development of ANPP_{act}, ANPP_{h}, ANPP_{t}, \Delta ANPP_{LC} and HANPP per area, relating to the total land area of the United Kingdom, 1800 - 2000, in tons dry matter per hectare and year [t DM/ha/yr]. Source: Own calculations. See Appendix A.

Figure B25. Contribution of biomass harvest (ANPP_{h}) and land-use induced productivity changes (\Delta ANPP_{LC}) to human appropriation of net primary production (HANPP), in the United Kingdom, 1800 - 2000, in percent [%]. Source: Own calculations. See Appendix A.
Figure B26. *Primary axis:* Biomass harvest (ANPP_h) and aboveground NPP remaining in ecosystem after harvest (ANPP_t) as percentage [%] of aboveground productivity of actually prevailing vegetation (ANPP_act), in the United Kingdom, 1800 - 2000. *Secondary axis:* Aboveground NPP remaining in ecosystem after harvest (ANPP_t) as percentage [%] of aboveground productivity of potential vegetation (ANPP_0) in the United Kingdom 1800-2000. Sources: Own calculations. See Appendix A.
Figure B27. **Primary axis:** Biomass harvest (ANPP\textsubscript{h}) and human appropriation of aboveground net primary production (HANPP), in the United Kingdom, 1800 - 2000, in tons dry matter per capita and year [t DM/cap/yr]. **Secondary axis:** Population development, in the United Kingdom 1800-2000, in millions. Sources: Mitchell (1988) and own calculations. See Appendix A.
Appendix C: Download\textsuperscript{39}

The Downloads contain two Microsoft Excel workbooks: *AppendixC_add_results_tables.xls* and *AppendixC_factors.xls*. The first includes tables (Table C1 to C22) of additional results and input data for the United Kingdom, 1800 - 2000, including tables with area figures for different land use classes, area and production figures for different crops as well as amounts of crop residues from these crops and their allocation to different uses, livestock numbers and calculated feed supply, and harvest of coniferous and non-coniferous round wood and wood fuel, all on a yearly basis. It further contains tables with absolute and per area figures for HANPP and its constituents according to the aggregate land use classes of: cropland, permanent pasture, rough grazing land, as well as tables with overall results for ANPP\textsubscript{0}, ANPP\textsubscript{act}, ANPP\textsubscript{h}, ∆ANPP\textsubscript{LC}, HANPP and backflows given in absolute, per area and per capita values, on a yearly basis.

The second workbook contains harvest factors used in the calculation of harvested crop residues in the United Kingdom 1800 - 2000 (Table C23) and factors used for the allocation of harvested residues from individual crops to different uses (Table C24), on a yearly basis.

A detailed description of how the presented results were derived is given in Appendix A: Report on methodology and materials, which also contains further tables of factors used. For additional information and access to data files contact the author under: annabella.musel@gmail.com

\textsuperscript{39}http://www.uni-klu.ac.at/socec/inhalt/1818.htm
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Band 3

Band 4
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