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Applying the Human Appropriation of Net Primary Production framework to map provisioning ecosystem services and their relation to ecosystem functioning across the European Union

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ABSTRACT

Human intervention on land enhances the supply of provisioning ecosystem services, but also exerts pressures on ecosystem functioning. We utilize the Human Appropriation of Net Primary Production (HANPP) framework to assess these relations in European agriculture, for 220 NUTS2 regions. We put a particular focus on individual land system components, i.e. croplands, grasslands, and livestock husbandry and relate associated biomass flows to the potential net primary productivity NPP. For the reference year 2012, we find that 469 g dm/m^2/yr (38% of NPP$_{pot}$) of used biomass were harvested on total agricultural land, and that one tonne of annually harvested biomass is associated with 1.67 tonnes dry matter (dm) of HANPP, ranging from 0.8 to 8.1 tonnes dry matter (dm) across all regions. EU livestock systems are a large consumer of these provisioning ecosystem services, and invoking higher HANPP flows than current HANPP on cropland and grassland within the EU, even exceeding the potential NPP in one fifth of all NUTS2 regions. NPP remaining in ecosystems after provisioning society with biomass is essential for the functioning of ecosystems and is 563 g dm/m^2/yr or 46% of NPP$_{pot}$ on all agricultural land. We conclude from our analysis that the HANPP framework provides useful indicators that should be integrated in future ecosystem service assessments.

1. Introduction

Agricultural ecosystems deliver key provisioning services to society, i.e., food, feed, fuels and fibers. Additionally, agroecosystems contribute to non-provisioning ecosystem services such as the regulation of soil and water quality, carbon sequestration, habitat provision (i.e., regulating ecosystem services) and cultural services such as tourism and recreation (Power, 2010; IPBES, 2017; Simoncini et al., 2019). In order to sustain the provision of these ecosystem services (ESS), agroecosystems rely on natural ecosystem processes that provide inputs or regulatory factors such as primary production, pollination, maintenance of soil structure and fertility or nutrient cycling. Several conceptual frameworks have been developed to describe the positive contributions of ecosystems to human well-being (Potschin-Young et al., 2018; Haines-Young and Potschin, 2010, 2018; MEA, 2005; IPBES, 2019; SEEA, 2021).

Ecosystem services literature often uses net primary production (NPP) as a proxy for the capacity of ecosystems to deliver ESS and acknowledges its pivotal role as the starting point of all heterotrophic life on Earth (Costanza et al., 1998; Costanza et al., 2007; Vitousek et al., 1986; Potschin-Young et al., 2018; Richmond et al., 2007; Maes, 2018; Foley et al., 2005). NPP denotes the balance between gross biomass production during photosynthesis and plant respiration and represents a fundamental ecological process (Vitousek et al., 1986). NPP, and in particular NPP, which remains in agroecosystems after harvest (i.e., NPP$_{eco}$), directly contribute to a range of ESS. In a systematic review, Harrison et al. (2014) mapped 530 studies where linkages between specific biodiversity attributes and ESS are cited. Primary production, aboveground biomass, belowground biomass, and litter and crop residues are closely linked to the following ESS: mass flow regulation (49% of studies), atmospheric regulation (44%), pest regulation (21%), water purification (10%) and flow regulation (7%). Several studies have demonstrated the benefits of returning crop residues to soils (Carvalho

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et al., 2017; Blanco-Canqui and Lal, 2007; Lal, 2004; Bentsen et al., 2014; Lal, 2008) or cover crops which are left on fields after harvest (Schipanski et al., 2014; Wittwer et al., 2017; Blum and Swaran, 2004; Daryanto et al., 2018) for climate regulation through the formation of soil organic carbon (SOC) and improving the relation between SOC and N. Cover crops and crop residues also contribute to water retention as well as the slow passage of water (Lal, 2020) into deeper soil layers. Moreover, biomass being left on the field after harvest provides habitats and is thus central to biodiversity conservation (Franzluebbers, 2002). The species-energy hypothesis holds that energy availability in an ecosystem is positively related to species diversity (Wright, 1983), i.e., that there is a positive relationship between ecological productivity and species richness (Cusens et al., 2012). Thus, a reduction in energy availability in ecosystems by human activities (e.g., biomass harvest) is likely to impact the essential function to provide ESS (Harrison et al., 2014; Carvalho et al., 2017; Cherubin et al., 2018) and species and habitat diversity (Vitousek et al., 1986; Wright, 1990; Haberl et al., 2009; Hawkins et al., 2003; Brown, 2014; Gaston, 2000).

While NPP is an established indicator in ecosystem services literature, indicator frameworks that quantify the involved pressures on NPP have not yet been applied widely (Vačkář et al., 2016; Pan et al., 2014; Zhang et al., 2021; Haberl et al., 2014). The Human Appropriation of Net Primary Production (HANPP) framework (Haberl et al., 2013) applies a sociometabolic perspective on land systems and allows for the calculation of indicators that integrate ecological and socioeconomic perspectives on land use. It quantifies the amount of NPP appropriated by society by harvest as well as land conversions and races biomass flows from their ecosystem origin to the final consumption of biomass products. The HANPP framework quantifies the potential NPP in a region, i.e., the NPP that would prevail in ecosystems without human land use, and compares it with the actual prevailing NPP in used ecosystems. That comparison allows deriving the amount of NPP altered due to land-conversion.

Furthermore, it assesses the amount of biomass harvested or killed during harvest ($HANPP_{harv}$) and separately quantifies biomass flows that enter socioeconomic processes from those killed during harvest and remain on field (unused extraction of biomass). The amount of NPP that remains intact in ecosystems after harvest (NPP_{eco}) is inferred from these accounts. Thus, the HANPP framework allows to quantify the amount of NPP that remains in ecosystems after the supply of biomass-reliant provisioning services (the sum of NPP_{eco} and unused extraction). This flow is available for ecosystem processes, such as heterotrophic food webs or C-cycling. The process-based perspective of the HANPP framework is highly compatible with ESS frameworks, such as the Common International Classification of Ecosystem Services (CICES) framework (Potschin-Young et al., 2018; Haines-Young and Potschin, 2010; Plutzar et al., 2016; Haberl et al., 2014; Krausmann et al., 2013; Erb et al., 2013). CICES provides a five-level hierarchical structure to trace ESS from the origin towards their contribution to human well-being (Potschin-Young et al., 2018). In line with the HANPP framework, it applies a systemic and integrated perspective on ecosystem processes and alterations from primary ecosystem processes towards socioeconomic biomass utilization.

Livestock is a key component of agricultural and food systems and is central to the overall functioning of ecosystems (Dumont et al., 2013). It provides nutrient-dense food, albeit associated with considerable resource flows (Krausmann et al., 2008) and substantial environmental detriments (Steinfeld et al., 2006; Herrero et al., 2013). A particular area of concern is livestock's comparatively low efficiency in converting primary biomass (i.e., NPP) into edible biomass, as compared to direct human consumption of plant biomass (Godfray et al., 2018; Bowles et al., 2019). However, livestock also provides a means for harnessing primary productivity of land that is not or difficult to use for cropping. Under industrial agricultural conditions, however, the importance of livestock in harnessing marginal lands has clearly diminished (Gerber et al., 2010) and it has been estimated that livestock consumes, inter alia, one-third of global cereal production (Mottet et al., 2017). In the year 2000, livestock consumed about three-quarters of the entire global agricultural harvest and was responsible for approx. 70% of HANPP at the global level (Haberl et al., 2007; Krausmann et al., 2008). Tracing feed consumed by livestock back to primary feed and relating the corresponding animal products and feed quantities to ecosystem productivity in terms of NPP allows to assess the sociometabolic size of the livestock system through a material flow analysis (MFA) perspective (Domingues et al., 2019).

In line with ecosystem services frameworks, we quantify the utilized amount of biomass that is extracted or harvested from agroecosystems as (biotic) biomass-related provisioning ecosystem service (PESS) from agroecosystems (IPBES, 2019; Maes et al., 2016; Haines-Young and Potschin, 2018; SEEA, 2021). These comprise primary crops for food, feed, fibers and fuels from cropland as well as utilized crop residues and litter, and grass harvest from grasslands. However, parts of the killed biomass are not harvested, thus mediate or moderate the ambient environment and secure the long-term functioning of ecosystems and provision of ecosystem services (Sutherland et al., 2018). Biomass remaining in ecosystems after harvest and belowground NPP - denoted as "back-flows to nature" (Krausmann et al., 2008) - can thus be used as a proxy for the essential functioning (EF) of ecosystems to provide the four regulating services as described in Harrison et al. (2014). NPP remaining in ecosystems is also classified as a representative indicator in the IPBES Global assessment (see Chapter 2.2 Supplementary material, Brondizio et al., 2019) for ecosystem functioning.

In this study, we calculate HANPP components at a sub-national resolution for 220 sub-national regions (NUTS2 level; Nomenclature of Territorial Units for Statistics) in 25 European countries (24 countries of the EU and UK). We scrutinize the spatial patterns for provisioning ESS and the essential functioning of ecosystems and relate these flows to the potential NPP in ecosystems. We use the potential NPP as a measure of reference for our assessment and as an indicator for the natural ecosystem capacity to deliver ecosystem services, in line with (Brondizio et al., 2019; Potschin-Young et al., 2018). We further analyze the role of the livestock sector as a driver of HANPP on cropland and grassland in order to assess the embodied or "virtual" HANPP flows through livestock production (Erb et al., 2009b; Haberl et al., 2016; Haberl et al., 2012) and also relate these fluxes to potential NPP (NPP_{pot}).

We aim to find empirical evidence to answer the following research questions: What is the geographic pattern of land use intensity and efficiency in the provision of ESS in agroecosystems in the European Union at the NUTS2 level? What in particular is the role of livestock production as a driver of HANPP flows? What are the regional patterns of harvested biomass and biomass remaining in agroecosystems concerning ecosystem capacity in Europe, and how can they be characterized?

2. Methods

We compiled a comprehensive, consistent and systematic dataset of agricultural biomass flows and land use for feed, food, fuels and fibers production on the European NUTS2 level. We included 24 EU-27 countries (excluding Croatia, Cyprus and Malta due to missing data) and the UK. For simplicity, we use the term EU in the following when referring to all simulated countries. The reference year is 2012 because it is the most recent year for which all relevant input data are available. The dataset covers the entire agricultural production on cropland and grassland. Moreover, we utilize the HANPP framework (Krausmann et al., 2013) to calculate ecological productivities of agricultural areas and changes in net primary production on cropland and grasslands induced by cropping and livestock activities. Forests and non-agricultural land (urban and infrastructure areas, unproductive land, water bodies) are not considered in this study. Further details on data sources and calculation procedures are described in the following sections and in the Supplementary Information.

2.1. Data sources

Sub-national level data from the CAPRI (*Common Agricultural Policy Regional Impact*) modeling framework (Britz et al., 2011) are the main basis for all calculations (Data Source: CAPREG – 21.03.2019, see (Britz and Witzke, 2015; Kempen and Witzke, 2018). Cropland data for the year 2012 (harvested area, harvest, yields) was complemented with estimations on non-reported flows (e.g., stems, leaves, belowground biomass) from Krausmann et al. (2013). Grassland data from CAPRI was converted into distinct classes based on spatial patterns derived from Plutzar et al. (2016), who defined three grazing classes based on the level of grassland productivity (NPP) and land cover types (see Supplementary Information) Data on livestock feed was also derived from the CAPRI model. Biomass quantities were converted to dry matter units based on Krausmann et al. (2013).

2.2. HANPP framework and data

In the HANPP framework, three different forms of NPP are discerned: NPP_{pot} denotes the potential biomass flows in ecosystems that would prevail at a specific site in the absence of human land use under current climatic conditions. NPP_{act} is the actual NPP of current ecosystems. NPP_{act} can be smaller or larger than $NPP_{pot,}$ depending on land management. Lastly, NPP_{eco}, calculated as the difference between NPP_{act} and $HANPP_{harv}$, is the biomass remaining in the agroecosystems after harvest, which is available to all other heterotrophic food chains but humans. $HANPP_{harv}$ is defined as the sum of primary and secondary biomass removed (e.g., grain and straw) as well as biomass components that are killed in the course of harvest, i.e., roots (Erb et al., 2009a). The sum of unused crop residues (litter) and belowground biomass, i.e., unused harvest ($HANPP_{harv\_uue}$), are considered as back-flows to nature. Unused harvest comprises all biomass that is harvested but left on the field (e.g., straw), as well as cover crops, plowed into soils and green manure.

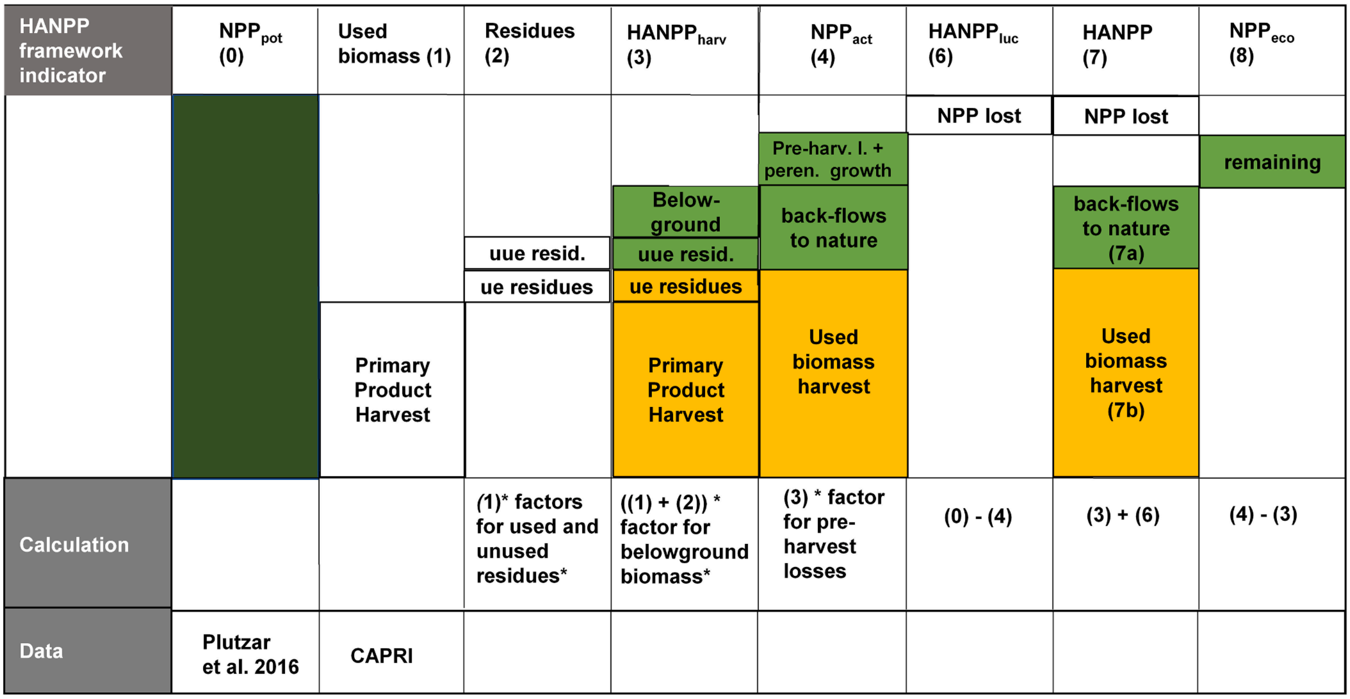
2.3. HANPP and $eHANPP_{lst}$ calculation

HANPP calculations follow the standard HANPP accounting approach based on Haberl et al. (2014) and are conducted for 220 NUTS2-regions. On cropland, as depicted in Table 1, $HANPP_{harv}$ and NPP_{act} have been extrapolated from CAPRI production data by applying factors from Krausmann et al. (2013). $HANPP_{luc}$ (productivity changes resulting from land conversion and land use), HANPP and NPP_{eco} have been obtained by applying basic arithmetic operations as derived from the HANPP framework concept. Consequently, on cropland with annual cultures, NPP_{eco} corresponds to pre-harvest losses, and on cropland with permanent cultures, NPP_{eco} additionally includes NPP allocated to plant growth (e.g., tree trunks). In the absence of better data and in line with Haberl et al. (2007) and Plutzar et al. (2016), we assumed actual NPP to be 20% lower than NPP_{pot} ($HANPP_{luc}$) for grasslands located on potential forest sites, in order to take the reduction of photosynthetic active layers caused by land conversion into account. Uncertainties related to NPP on grasslands are large, in particular at the global level, but less so for Europe (Fetzel et al., 2017). On pastures and meadows on natural grasslands, $HANPP_{luc}$ was assumed to be zero (Haberl et al., 2007). NPP_{pot} and NPP_{act} on fallow land are derived from Plutzar et al. (2016) and applied to cropland and grassland areas in 2012. Since no data for 2012 was available, we applied values for NPP_{pot} and NPP_{act} in gC/m^2 from 2006 to the land-use extent in the year 2012.

The calculation of HANPP embodied in livestock products ($eHANPP_{lst}$) follows the same approach as for HANPP but with additional assumptions. The basis for the $eHANPP_{lst}$ calculation is data on livestock feed consumption from cropland in a given region. However, crop-specific extrapolation from feed data is not as straightforward as cropland production since CAPRI reports feed categories that cannot be assigned to one primary product (e.g. feed rich protein and feed rich energy). We estimated the respective share of primary products in each category according to (Karlsson et al., 2021) and national feeding statistics to associate crop-related HANPP flows (see a more detailed

Table 1

HANPP framework, data sources and indicators used in this study for a consistent calculation of NPP flows on cropland. Colors indicate the ecosystem services relevant compartment within the HANPP framework, which are used in the remainder of this manuscript (dark green = ecosystem capacity, yellow = PESS, light green = EF). "*Pre.harv. l. + peren. growth*" = pre-harvest losses and perennial growth. Ue residues denote used (harvested) residues, unused (uue) residues are residues left on fields or returned to fields. The latter, together with belowground NPP on cropland, are denoted as "back-flows to nature". * factors derived from Krausmann et al. (2013). For abbreviations, see Supplementary Information.



HANPP framework indicator	NPP_{pot} (0)	Used biomass (1)	Residues (2)	$HANPP_{harv}$ (3)	NPP_{act} (4)	$HANPP_{luc}$ (6)	HANPP (7)	NPP_{eco} (8)
	🟩	Primary Product Harvest	uue resid. ue residues	Below-ground uue resid. ue residues Primary Product Harvest	Pre-harv. l. + peren. growth back-flows to nature Used biomass harvest	NPP lost	NPP lost back-flows to nature (7a) Used biomass harvest (7b)	remaining
Calculation			(1)* factors for used and unused residues*	((1) + (2)) * factor for belowground biomass*	(3) * factor for pre-harvest losses	(0) - (4)	(3) + (6)	(4) - (3)
Data	Plutzar et al. 2016	CAPRI						

explanation in the Supplementary Information). All output from grassland is exclusively associated with livestock feed, thus HANPP on grassland and HANPP associated with livestock feedstuff from grassland is assumed to be equal. NPP_{pot} refers to a virtual domestic land area required for livestock feed production. We also assumed domestic production efficiencies and applied region-specific yield data from CAPRI. If no yield values for a given crop and region are reported, we assumed average country yields. The calculation of $eHANPP_{lst}$ deviates from HANPP calculation in two further aspects: Firstly, we only include residues used by the livestock system such as straw and excluded unused residues. Secondly, no fallow land has been additionally assigned to virtual cropland for livestock feed, which results in a conservative $eHANPP_{lst}$ estimation. Overall, $eHANPP_{lst}$ assumes that the total supply of livestock feed is covered by agricultural biomass harvested on domestic (i.e., NUTS2) area. Although livestock systems are often supplied by national and international imports of feed resources, missing subnational trade data prohibited a more sophisticated approach. Therefore, $eHANPP_{lst}$ refers to a virtual area related to the feed demand of the domestic livestock system. The virtual domestic production of livestock feedstuff allows to relate the size of a region's livestock system to its primary production on crop- and grassland (HANPP) and the potential net primary production (NPP_{pot}).

2.4. *Provisioning ESS and ecosystem functioning proxies*

According to the CICES framework (Haines-Young and Potschin, 2018), we define used biomass harvest (7b in Table 1), consisting of primary and secondary biomass, as provisioning ecosystem services (PESS). $PESS_{\%}$ denotes the ratio of PESS to NPP_{pot}. We further define the sum of back-flows to nature and NPP_{eco} (7b and 8 in Table 1) as a proxy for ecosystem function (EF, see introduction), with $EF_{\%}$ denoting its ratio to NPP_{pot}. Table 2 provides examples of ESS which are related to the indicators developed in this study.

3. Results

Total annual agricultural output from 220 NUTS2 regions included in this study was 1.03 Gt of dry matter biomass (Gt dm/yr) from croplands and grasslands, and this agricultural production invoked 1.67 Gt dm/yr of HANPP flows (1.23 Gt dm/yr on cropland, and 0.44 Gt dm/yr on grassland). Agricultural HANPP as percent of NPP_{pot} ($HANPP_{\%}$) ranges between 14% and 86% on total agricultural land, with an EU average of 62%. This ratio is considerably higher on croplands at 83% across the EU than grasslands at 36%. Among NUTS2 regions, the heterogeneity of $HANPP_{\%}$ is smaller on croplands (where it ranges from 52% to more than 90%) than on grasslands (2% to more than 90%).

3.1. *HANPP intensity across NUTS2 regions*

Fig. 1 shows that in 95% of all analyzed regions, HANPP per area is higher on croplands than on grasslands, and while the intensity of grasslands is increasing with total HANPP intensity, the share of grasslands in total utilized agricultural area (UAA) shows an opposite trend to total HANPP intensity.

HANPP per unit of utilized agricultural area (UAA; red dots in Fig. 1) ranges from 147 to 1197 g dm/m^2/yr, with an average of 772 g dm/m^2/yr. Average HANPP on croplands is considerably higher than on grasslands, with 1007 versus 449 g dm/m^2/yr, respectively. However, data also shows a considerable variation among regions for croplands as well as grasslands (487–1368 g dm/m^2/yr and 23–1096 g dm/m^2/yr, respectively). Approximately 60% of all regions have higher HANPP intensities than the EU average. These regions cover 55% of the total UAA, which indicates that higher intensities are rather found in small NUTS regions. Additionally, the share of grasslands in total UAA decreases with increasing HANPP intensity, albeit individual regions with a high share of grasslands and high HANPP were found in France, the Netherlands, the British Islands, Germany and Austria.

3.2. *EU-wide patterns for biomass-related provisioning ecosystem services (PESS)*

Fig. 2a illustrates the total used biomass harvest per UAA on NUTS2 level. On average, 633 g dm/m^2/yr are harvested on croplands and 262 g dm/m^2/yr on grasslands. The average value for the total UAA is 469 g dm/m^2/yr. In Central Europe, the British Islands, and Ireland, the output is more than 600 g dm/m^2/yr of plant biomass in most regions (except in the Alps and Scotland), with a few regions harvesting more than 1000 g dm/m^2/yr. In Eastern Europe and Southern Europe, the output is generally lower, ranging from 200 to 500 g dm/m^2/yr.

It is thus not surprising that in most regions with high output per area, i.e., Northern France, Denmark, Germany and Ireland, $HANPP_{\%}$ is higher than 80% (Fig. 2b). $HANPP_{\%}$ is linked to the magnitude of agricultural output e.g., in the UK or in the North-West of France, but we also find high $HANPP_{\%}$ values in areas with relatively low agricultural output (e.g., NUTS2 regions in Poland or Italy), caused by a high $HANPP_{luc}$. $HANPP_{\%}$ is lowest in Spain, Southern France, Greece, and Alpine regions in Central Europe and in Northern Sweden; i.e., regions with warm (Mediterranean) climate or relatively low suitability for agricultural production. Additionally, perennial crop production causes lower $HANPP_{\%}$ than annual crops, leading to lower $HANPP_{\%}$ in regions

Table 2

Selected examples of ecosystem services that are related to the indicators developed in this study. Provisioning ESS relates to the HANPP sub-indicator 7b "used biomass harvest", and ecosystem functioning relates to 7a "back-flows to nature" + 8 "NPP_{eco}, remaining in the ecosystem (details see Table 1). Ecosystems services are derived from CICES v5.1 classification (Haines-Young and Potschin, 2018).

	Section	Division	Group	Class
Provisioning ecosystem services	Provisioning (Biotic)	Biomass	Cultivated terrestrial plants	Cultivated plants for human nutrition, for livestock, materials, energy by type
	Provisioning (Biotic)	Biomass	Reared animals	Animal products by type
Ecosystem functioning	Regulation & Maintenance (Biotic)	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events, atmospheric composition and conditions, Regulation of soil quality, pest and disease control, Water conditions	Control of erosion rates, buffering and attenuation of mass movement, water flow regulation, wind protection, seed dispersal, decomposition and fixing processes and their effect on soil quality

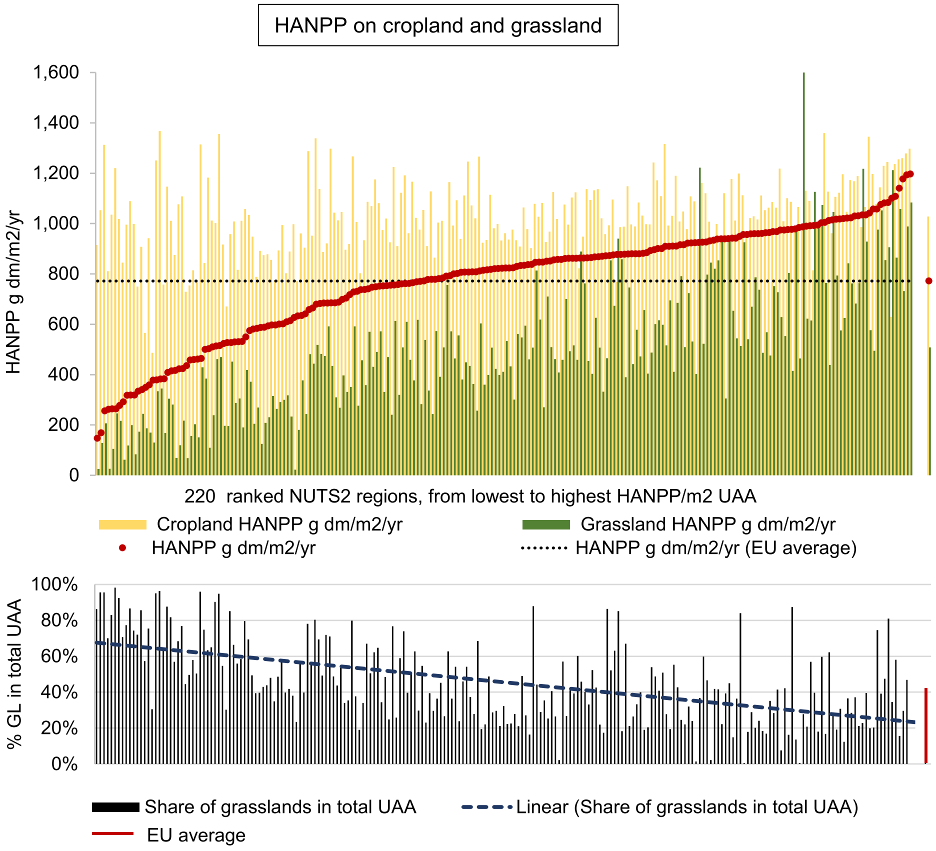


Fig. 1. HANPP on croplands and grasslands across 220 NUTS2 regions in the year 2012. Upper figure: Y-axis shows the area related HANPP on croplands (yellow) and grasslands (green) in g dm/m^2/yr per UAA (utilized agricultural area) of cropland and grassland area. Regions are grouped from lowest to highest agricultural (cropland and grassland) HANPP intensity in g dm/m^2/yr from left to right (red dots). The black dotted line shows EU average HANPP as g dm/m^2/yr. Lower figure: the black bars show the share of grasslands in total UAA per NUTS2 region (regions are again grouped from lowest to highest HANPP intensity in g dm/m^2/yr from left to right), and the dotted blue line represents the linear trend line across all regions. Separated bars at the very right side show the EU average.

with large perennials areas (e.g., Spain). Surprisingly, in contrast to their role as important agricultural producers, many NUTS2 regions in Belgium, Western Germany and Central and Southern France show HANPP$_{\%}$ values near the European average or below (Fig. 2b), which we discuss in the following section.

HANPP describes the combined effect of land use change (HANPP$_{luc}$) and agricultural harvest (HANPP$_{harv}$) on ecological biomass availability. In the EU, HANPP$_{harv}$ accounts for 80% and HANPP$_{luc}$ for the remainder of 20% of total HANPP. One-third of all regions (24% of EU UAA) show a negative HANPP$_{luc}$ (Fig. 2c), i.e., NPP$_{act}$ higher than NPP$_{pot}$. All NUTS2 regions of Netherlands and Denmark, 96% of Germany, and 88% in Belgium show negative HANPP$_{luc}$ values, which indicates that the productivity of agricultural land use exceeds the NPP$_{pot}$ at the respective sites. Note that caution is requested with regard to the interpretation of negative HANPP$_{luc}$. Although negative HANPP$_{luc}$ reduces total HANPP (the sum of HANPP$_{harv}$ and HANPP$_{luc}$) through a higher NPP$_{act}$, it must not be interpreted as an indication for reduced pressures on ecosystem functioning; it actually indicates substantial human modification of pristine ecosystems, i.e., intensively managed agroecosystems with high input intensity of, e.g., fertilizer or irrigation. (Emmerson et al., 2016; Egli et al., 2018; Rusch et al., 2016; Teixeira et al., 2019; Krausmann et al., 2013).

Fig. 2d relates the total used biomass harvest to total HANPP as an indicator for the environmental pressures of agroecosystems per output, sometimes denoted as "HANPP efficiency" (Fetzel et al., 2014, 2016; Gingrich et al., 2015). Regions in the South and East of Europe are comparably inefficient in terms of this indicator; hence, relatively high environmental pressures in terms of reduced ecosystem productivity are associated with each unit of used output. In contrast, efficient agroecosystems prevail in Northern France, the Benelux nations, and most parts of Germany, the UK and Lombardia (Italy). These regions largely correspond to those with a negative HANPP$_{luc}$. In Northern Europe and across the Mediterranean belt, comparably low shares of total HANPP are used as agricultural biomass (share of used biomass harvest in HANPP lower than 50%). In general, cropland efficiency is a major driver of total HANPP efficiency, whereas the coupling of grassland with HANPP efficiency is weaker ($r^2 = 0.95$ for total/cropland HANPP efficiency, vs 0.39 for total/grassland HANPP efficiency).

3.3. EU-wide patterns of the essential functioning of ecosystem services (EF)

Fig. 3a shows the relation of NPP$_{eco}$ and HANPP$_{harv\_uue}$ to NPP$_{pot}$ at the country level. We interpret this ratio as a proxy for the essential functioning of ecosystem services (EF). Across the whole European Union, 46% of NPP$_{pot}$ in agroecosystems (measured in dry matter mass flows) are contributing to secure ecosystem services. Throughout all regions, NPP$_{eco}$ represents the main contribution to EF. Unused harvested biomass is of limited significance in most countries. In general, values for EF$_{\%}$ range lower than 35% in Ireland, Denmark, Germany or the Czech Republic. Countries with the highest values are located in the Mediterranean region (e.g., Greece, Portugal and Spain). In these countries, the value is beyond 50% of NPP$_{pot}$. The contribution of backflows to nature in general decreases with increasing EF$_{\%}$, indicating that less of the available biomass on fields is directly harvested but left on fields.

The map in Fig. 3b provides information on the sub-national patterns of the essential functioning of ecosystem services (EF$_{\%}$). We find heterogeneous patterns not only between but also within individual countries. In 30% of all regions (34% of the EU's UAA), biomass quantities equivalent to more than 50% of the potential NPP remain in the agroecosystems after harvest. In 11% of regions (accounting for 8% of the considered UAA), this ratio is less than 30%. In all Spanish NUTS2 regions, biomass quantities corresponding to more than 50% of NPP$_{pot}$

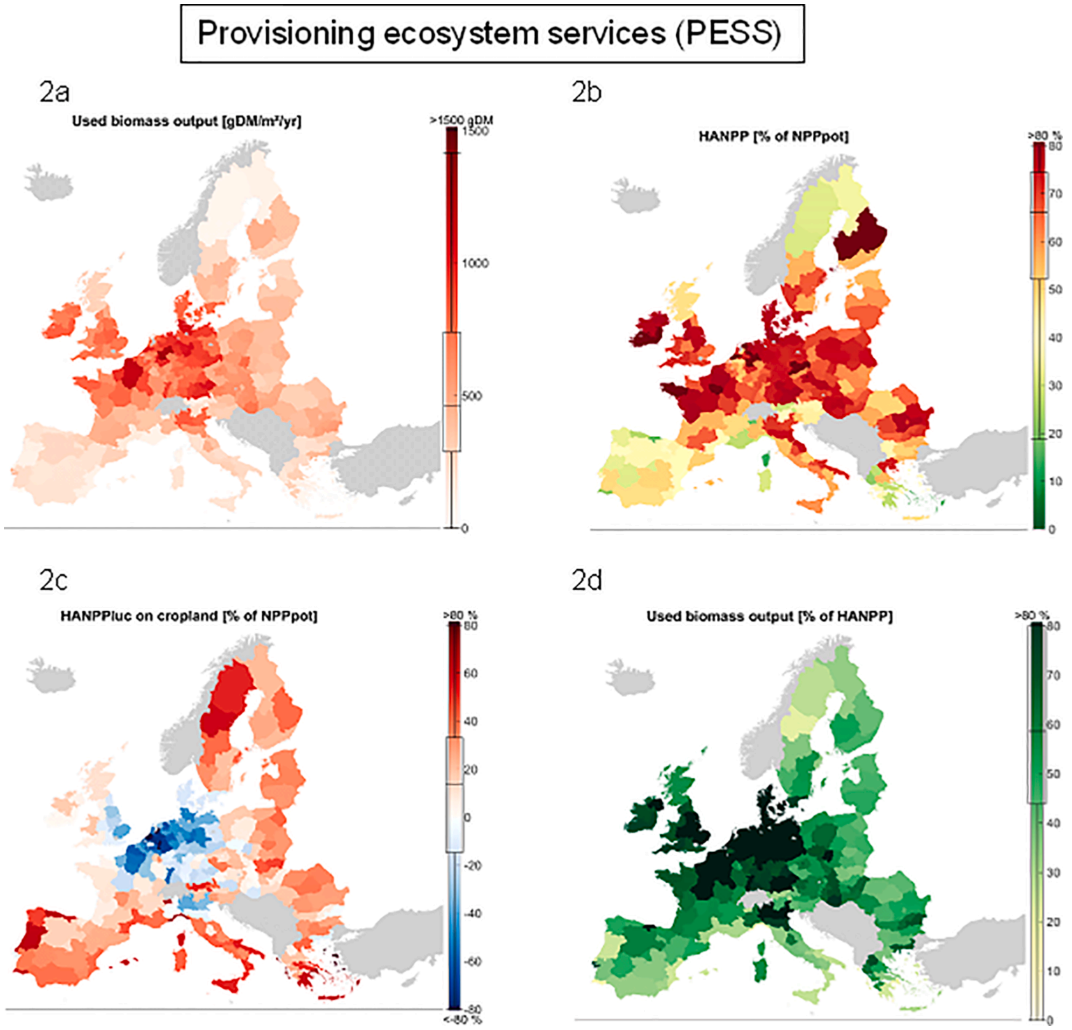


Fig. 2. Potential indicators for provisioning ecosystem services (PESS). Used biomass output, $HANPP_{luc}$ and HANPP. Fig. 2a shows a map for total used output/UAA in g dm/m^2/yr (PESS) for 220 NUTS2 regions, total human appropriation of net primary production ($HANPP_{\%}$) (Fig. 2b), $HANPP_{luc}$ on cropland in % of NPP_{pot} (Fig. 2c), and the share of used biomass / HANPP in % (Fig. 2d). Boxplots indicate minimum, Q1, median, Q3, and maximum values. See Supplementary Information for additional tables.

remain in agroecosystems after harvest. In Northern regions, as well as in Greece, Western Austria and Northern Sweden, the ratio typically exceeds 70%. Spain, Portugal, Greece and Austria are the only countries where no region displays a value below 40%, indicating either extensive land use systems or multifunctional grassland systems, i.e., agro-pastoralist systems (Malek and Verburg, 2017; Plieninger and Huntsinger, 2018). Throughout all other countries, there are NUTS2 regions with low values, sometimes even below 20%.

3.4. Embodied HANPP flows in livestock feed consumption

Total $eHANPP_{lst}$ in the EU slightly exceeds the total HANPP on domestic agricultural land (Fig. 4a). $eHANPP_{lst}$ is 1.75 Gt dm/yr on total agricultural land (1.29 Gt dm/yr on croplands), which is approx. 6% more than the total HANPP arising from domestic agricultural production for food, feed, fibers and fuels (see Fig. 4a). $eHANPP_{lst}$ from cereals (including harvested straw) is 12% higher than the corresponding HANPP, $eHANPP_{lst}$ for oil crops is more than two times larger than the domestic HANPP related to oil crops production. This result underlines the strong dependence of the EU livestock sector on feed imports, particularly oil crops. $eHANPP_{lst}$ of fodder products was lower than domestic HANPP, since a significant share of domestic fodder maize production is used for bioenergy production.

Fig. 4b shows HANPP on grasslands as percent of the NPP_{pot} on grassland – an indicator which is similar but not identical to grazing intensity (Petz et al., 2014; Erb et al., 2016), because here the reference quantity is NPP_{pot}, whereas for grazing intensity it is NPP_{act}. We find the highest pressures on grassland ecosystems in the Northern part of Central Europe, Southern Finland and the British Islands, regions with highly managed grasslands or low NPP_{pot} (Plutzar et al., 2016). HANPP/NPP_{pot} is lowest in Sweden, and Southern and Southwestern Europe, and around 30%–40% in most regions of Austria and Eastern Europe.

The ratio of $eHANPP_{lst}$ to the respective production output from livestock systems reveals vast differences between the various types of animal products (Fig. 4c). The figure further illustrates that the HANPP pressures from livestock production vary widely among NUTS2 regions. For one kg dm of animal product (across all product types and livestock groups), on average, 40 kg dm $eHANPP_{lst}$ on agricultural land within and outside the EU were necessary. Monogastric products (pork and poultry meat and eggs) show average values across the EU of 26 to 38 kg dm $eHANPP_{lst}$ per kg dm. We find similar patterns for the inner quartiles for monogastric production, i.e., 21–34 kg dm $eHANPP_{lst}$ per kg dm for poultry meat, with slightly higher ranges for egg and pork production (30–48 kg dm $eHANPP_{lst}$ per kg dm). For ruminants (i.e., beef cattle and cow milk), we find average vales of 28 kg dm $eHANPP_{lst}$ per kg dm for milk, and 125 kg dm $eHANPP_{lst}$ per kg dm for beef. The $eHANPP_{lst}$

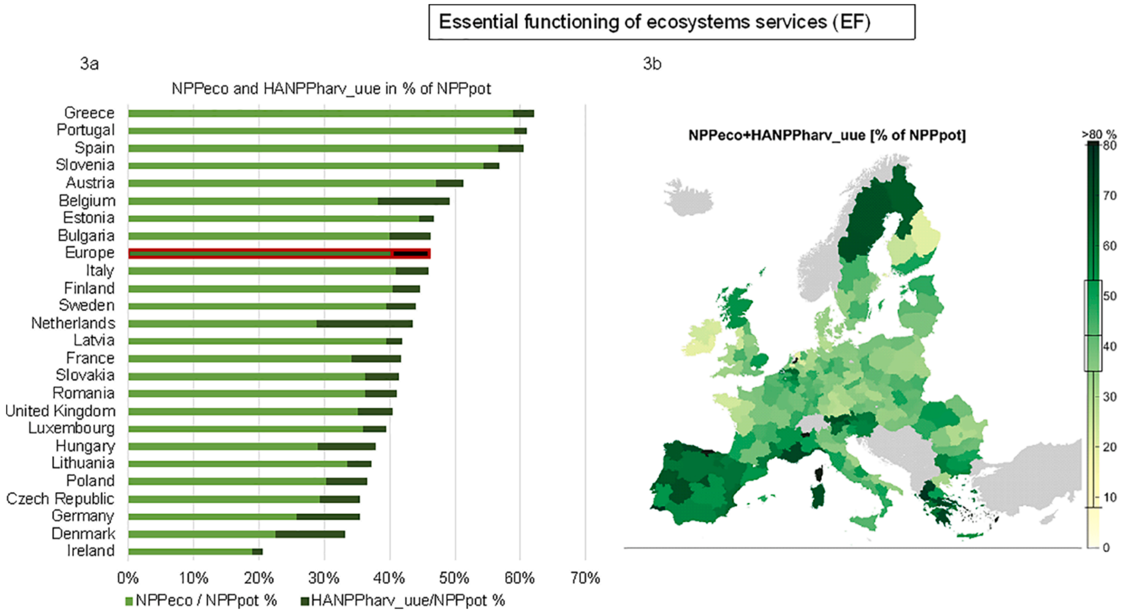


Fig. 3. Proxy for $EF_{\%}$, calculated as (NPP_{eco} + $HANPP_{harv\_uue}$) relative to NPP_{pot}. Fig. 3a shows stacked bar charts for 25 EU28 countries and EU average. Fig. 3b shows a map with the same ratios for 220 NUTS2 regions.

patterns for beef production are also much more heterogeneous, with 92–217 kg dm $eHANPP_{lst}$ per kg dm (inner quartile). Notwithstanding differences in nutritional values of the considered animal products, milk production is more efficient in terms of HANPP flows than all other animal products. However, there are also regions with strikingly low efficiency (>350 units dm per unit dm output).

Fig. 4d shows the relation of $eHANPP_{lst}$ to total agroecosystem capacity for each NUTS2 region. The map clearly illustrates the large heterogeneity in patterns of the sociometabolic weight of livestock in relation to the domestic capacity to host livestock, and consequently also the dependence on additional and foreign resources to host domestic livestock systems. Hot-spot regions where $eHANPP_{lst}$ is considerably higher than the total ecosystem capacity of current agroecosystems, reaching nearly double the size than the potential net-primary production exist in the Benelux countries, Northern Italy, Western France – typically regions with large livestock sectors. In every fourth region, $eHANPP_{lst}$ is larger than total capacity of current agroecosystems, in more than two-thirds it is higher than 50% of NPP_{pot}, while in less than 5% the value is below 20%. These results underline the dominant role of livestock systems for alterations in ecosystem flows in the European Union, and that in a considerable number of regions livestock systems mobilize resource flows that exceed net energy flows in ecosystems without any disturbance, clearly indicating high pressures on domestic ecosystems.

3.5. Mapping regional patterns of biomass-related provisioning ecosystem services and ecosystem functioning in the European Union

We now categorize all EU NUTS2 regions included in this analysis according to the dominant final destination of biomass flows in agroecosystems. Utilized biomass is used as a proxy for provisioning ecosystem services (PESS) and back-flows to nature and NPP_{eco} as a proxy for essential functioning of ecosystem services (EF). Mapping the amount of PESS against the available EF per unit of ecosystem capacity, i.e., NPP_{pot} ($PESS_{\%}$ vs. $EF_{\%}$), yields the following insights. Of the total 2,3 Mio km^2 agricultural land, 36% (0.77 Mio km^2) fall into the blue cluster with above-EU average provisioning and below-EU average essential functioning of ecosystem services – apparently regions with highly intensive agroecosystems, where special attention needs to be put on securing the long-term maintenance of ecosystem services. Such regions dominate in Central Europe, i.e., Northern France, Germany, the Benelux countries and Denmark, as well as in most parts of the United Kingdom and Ireland.

In contrast, regions with opposite characteristics (low $PESS_{\%}$, high $EF_{\%}$ - yellow cluster) cover 37% of total agricultural land. In these agroecosystems, relatively high shares of biomass are not used and remain on-site, which is beneficial for the essential functioning of ESS. This cluster consists of two dominant land use systems: Firstly, many regions across the South- and South-Eastern parts of Europe with a high share of perennial cropland, where a comparably larger share of NPP goes into stem and leaf biomass than in annual crops. Secondly, regions dominated by grassland, which is an indication that cropping activities are constrained by climatic and ecological conditions, and grasslands are one of the few options for agricultural activity.

The cluster with low $PESS_{\%}$ and low $EF_{\%}$ per unit of NPP_{pot} (red cluster) contains 0.43 million km^2 of UAA or nearly 20% of all agricultural land. It mainly includes regions in Eastern Europe as well as dry regions in Southern Europe. Here, high values of $HANPP_{luc}$ are an indication for massive human intervention into natural ecosystems through the conversion to agroecosystems, with high costs in terms of losses of NPP.

Regions with high $PESS_{\%}$ and high $EF_{\%}$ (green cluster) cover only 7.4% of total agricultural land use in the EU. They are located in Central Europe, i.e. Germany, the Netherlands, Belgium, and France, as well as individual regions in the UK and one region in Greece. In these regions, high ecosystem capacity is utilized to produce agricultural goods, but also high amounts of biomass remain after harvest, indicating a favorable pattern for all ESS included in this assessment.

The linear trend line across all NUTS2 regions shows the relation between biomass-related provisioning ESS and the essential functioning of ESS. Grasslands are the dominant land use within the yellow cluster, with 62% in total agricultural lands. If grasslands are intensified or converted into croplands, or if croplands (with high shares of permanent crops) are converted to annual crops, essential ecosystem functioning might be infringed. Additionally, plant breeding has increased the harvest index for higher yields without significant changes in total biomass production (Hay, 1995; Fan et al., 2017; Bentsen et al., 2014; Krausmann et al., 2013), leading to less biomass available to contribute to essential EF. However, at a certain degree of land use change, other factors, which are not considered in this study, play a more substantial

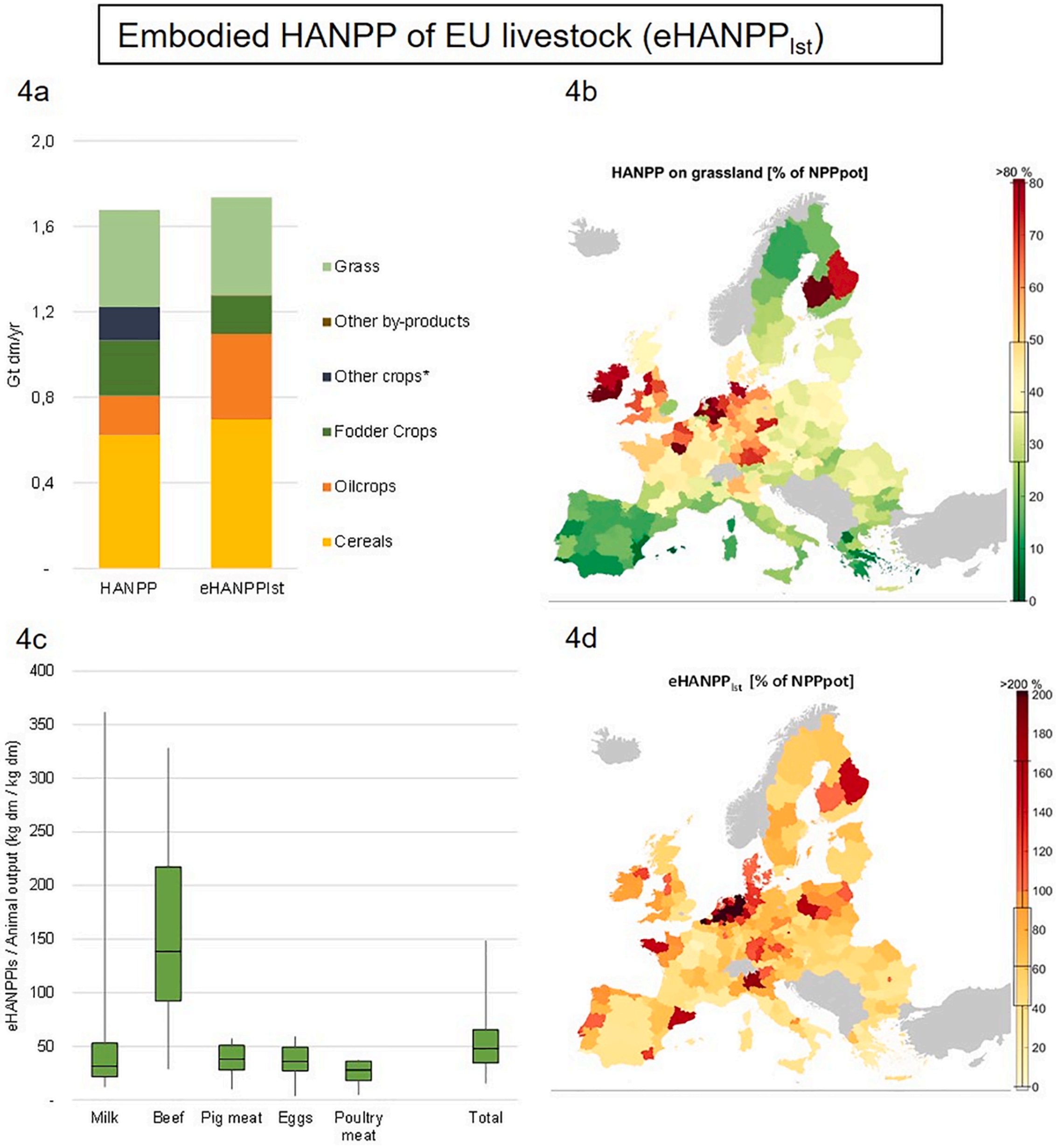


Fig. 4. Embodied HANPP of EU livestock in 2012. Fig. 4a shows a comparison of eHANPP$_{lst}$ with HANPP in Gt dm/yr. Note that straw is included in cereals. Fig. 4b shows HANPP$_{\%}$ (HANPP$_{harv}$/NPP$_{pot}$) on grasslands. Boxplots in Fig. 4c illustrate the ranges for the embodied HANPP per animal product on total agricultural land as eHANPP / animal output (kg dm / kg dm) among regions. “Total” refers to the aggregated data for each region and includes sheep and goat milk and meat, which are not shown separately. Fig. 4d shows eHANPP$_{lst}$ relative to total ecosystem capacity (NPP$_{pot}$) for each NUTS2 region.

role. Thus, the intensification or conversion of such agroecosystems needs to be done with caution in order to avoid declining EF while increasing provisioning services.

4. Discussion

European agroecosystems deliver enormous amounts of biomass, i.e., provisioning services, per unit area. In 2012, 469 g dm/m^2/yr (38% of NPP$_{pot}$) of used biomass was harvested on total agricultural land. We find that each unit of harvested biomass (dm) is associated with HANPP between 0.8 – 8.1 units dm across all regions and that especially regions across the Benelux countries provide large volumes of usable biomass harvest while also relatively large quantities of biomass remain in ecosystems after harvest. Nevertheless, the high biomass production is due to agricultural intensification, which itself exerts strong pressures on ecosystems (IPCC, 2019). NPP remaining in ecosystems after provisioning society with biomass is 563 g dm/m^2/yr or 46% of NPP$_{pot}$ on total agricultural land. On cropland, only 351 g dm/y^2/yr remain in ecosystems after harvest, while on grassland this value is considerable higher at 793 g dm/y^2/yr. These values correspond to 28% and 66% of NPP$_{pot}$, respectively. This is essential for the functioning of ecosystems, the source of many regulating ecosystem services and central for securing the long-term stability of provisioning ecosystem services (Brondizio et al., 2019; Haines-Young and Potschin, 2018; Harrison et al., 2014).

Livestock husbandry is a large consumer of provisioning ecosystem services and a major driver of pressures on ecosystem functioning. Thus, the role of livestock production for HANPP within and beyond EU borders requires more detailed scrutiny. Embodied HANPP from livestock production is an indirect proxy for the pressure of feed production on ecosystems, and results from this study underline the considerable pressure of the European livestock sector on ecosystems. We compared

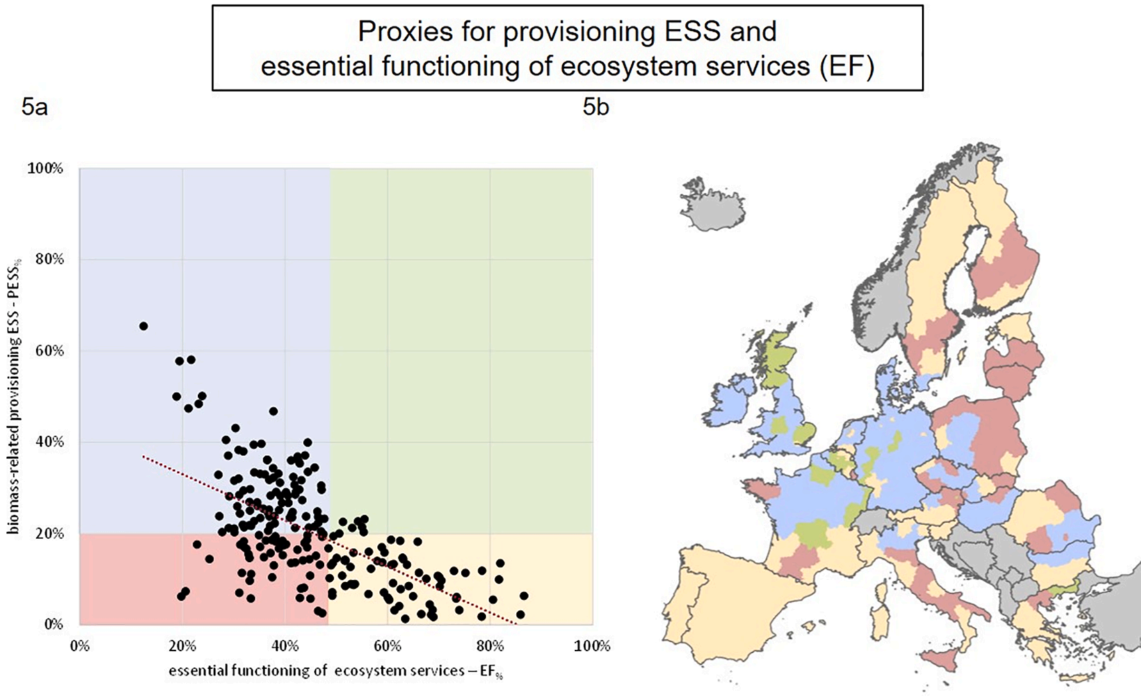


Fig. 5. Scatterplot showing $PESS_{\%}$ as used biomass harvest / NPP_{pot} in % (y-axis) and $EF_{\%}$ as (NPP_{eco} + back-flows to nature) / NPP_{pot} in % (x-axis). The central point in Fig. 5a is defined as the EU average (PESS = used biomass EU/ NPP_{pot} EU; EF = NPP_{eco} + $HANPP_{harv\_uue}$ EU/NPP_{pot} EU), with 20% for $PESS_{\%}$ and 44% for $EF_{\%}$. Dotted line represents the linear trend line with $r^2 = 0.39$. Clusters show high and low scores as follows: Green: high-high; red: low-low; yellow: low ($PESS_{\%}$) – high ($EF_{\%}$), blue: high ($PESS_{\%}$) - low ($EF_{\%}$). (Fig. 5a) and a map showing in which cluster regions fall (Fig. 5b).

the primary biomass flows which are mobilized for livestock feed to total ecosystem capacity and found that in a considerable share of regions, these flows exceed (>100%, 21% of regions) or massively exceed (>150%, 9% of regions) domestic NPP_{pot}. This indicates an externalization of ecosystem pressures related to feed imports (Fuchs et al., 2020; Karlsson et al., 2021). Embodied HANPP flows per product show that the low input–output efficiency is associated with high pressure on ecosystems per output, adding to previous studies on the low feed conversion efficiency of livestock (Herrero et al., 2013; de Vries et al., 2015; Shike, 2013; Van Zanten et al., 2016). We, therefore, add a novel contribution to the discussion of the sociometabolic size of livestock systems in relation to land and ecological boundaries through the integration of ecological productivities (Van Zanten et al., 2018; Mu et al., 2017; Domingues et al., 2019).

EU policies such as the Common Agricultural Policy (CAP) that aim at mitigating the impacts of agriculture on ecosystems need to specifically address livestock production. Ruminant livestock implicates a range of environmental costs (e.g., CH_4 emissions, excessive nitrogen loads and leakage), and a reduction of certain types of animal production is beneficial for both the environment and human health (Godfray et al., 2018; Westhoek et al., 2014). Nevertheless, extensively used grasslands have been proven to be central for the provision of ESS (Sala et al., 2000; McSherry and Ritchie, 2013; Öckinger and Smith, 2007; Tälle et al., 2016). Keeping extensive grasslands across the EU potentially appears as an efficient pathway to decrease overall pressures on agroecosystems.

In our analysis we encountered a number of intricacies, most of which are based on the surprisingly limited data availability for European agriculture. Data on livestock production are extremely scarce, especially when it comes to sub-national disaggregation, but also at the national level. This is surprising given the economic, social and environmental importance of livestock systems. While census data on livestock numbers and animal production is readily available and accessible (partly only at the country-level), hardly any comprehensive and consistent data for livestock feed production and utilization is available. Furthermore, no data on livestock production besides milk is available at the NUTS2 level. This was one reason why we had to resort to modeling results from the CAPRI model instead of primary statistical data. Another source of uncertainty is that we had to refer to agricultural NPP_{pot} data per unit area from the year 2006 for the HANPP calculation for the year 2012. While the introduced error cannot be quantified, one can suspect that the overall level of NPP_{pot} did not change substantially in this period due to relatively low changes of total agricultural land in the European Union (−3%) between 2006 and 2012 (Faostat, 2021). Thus, we assume that this uncertainty is not affecting the interpretation of our results presented here.

The embodied HANPP livestock calculation has intricacies that warrant caution in the interpretation of results. Firstly, we relate the $eHANPP_{lst}$ to the main animal product and ignore any purposes for which livestock is raised other than food production – leading to an overestimation of feed requirement per animal product where e.g. draft power or touristic use are predominant. Secondly, due to the lack of data, and because it was out of the scope of this paper, we calculated HANPP of livestock production with domestic land use factors where the livestock was raised, implying that all imported feedstuff is associated with the same HANPP as a domestically produced feedstuff. This is, of course, a simplification. If feedstuff were imported from regions with higher HANPP-efficiency, our results would be an overestimate. However, as many regions that export to Europe are characterized by lower HANPP efficiency (Roux et al., 2021), we conclude that our estimate is conservative and eHANPP of livestock might even be larger than quantified here. Nevertheless, due to the high regional heterogeneity and specialization of livestock systems, it is necessary to further develop more precise approaches to estimate the extent of HANPP embodied in sub-national livestock systems in the EU, in particular, because no sub-national trade-data is available. Concrete next steps are to develop consistent frameworks to measure the production against consumption in a given region in order to estimate net-trade volumes. According to the national trade patterns, these volumes can then be allocated to international trade partners (Kalt et al., 2021; Kastner et al., 2015) or by using multiregional I/O tables (Bruckner et al., 2019). Such approximation of the place of production, which is relevant for applying the HANPP framework, could serve as a first entry point for sub-national embodied HANPP flows.

Trade-offs between regulating and provisioning ESS are at the core of ecosystem services research (IPBES, 2019; Maes et al., 2016). In this study, we calculate proxy indicators for ESS, which are directly related to biomass-flows in agroecosystems. We utilize the usable output as a metric for provisioning ESS, the mass-flows of biomass remaining in agroecosystems after harvest as a proxy for the essential functioning of ESS, and assess the metabolic size of the livestock systems in relation to domestic ecosystem capacity. The biomass that remains in agroecosystems after harvest contributes to a range of regulating ESS such as mass flow and atmospheric regulation, and to a lesser extent pest and water flow regulation (Raudsepp-Hearne et al., 2010; Bronick and Lal, 2005; Harrison et al., 2014; Brondizio et al., 2019). Given data availability, the HANPP framework would furthermore allow assessing the impact of, for example, changing crop rotations that integrate catch crops, and which are essential to maintain regulating ESS such as soil stabilization, nitrogen fixation, or natural pest control (Schipanski et al., 2014; Wittwer et al., 2017; Hobbs et al., 2008). Overall, the indicators developed in this study should be integrated into broader ecosystem services (SEEA, 2021; IPBES, 2019) and trade-off assessments since they allow to establish consistent proxies for the ESS pressures and benefits of biomass flows from their origin towards their final usage (Power, 2010; Raudsepp-Hearne et al., 2010; Maes et al., 2016).

Agriculture in the European Union is at a crucial decision point, apparent in the increasing number of strategic policy documents addressing a green transformation (European Commission, 2019; European Commission, 2020a; European Commission, 2020b). Rapidly advancing climate change and irreversible ecosystem service loss (IPBES, 2019; IPCC, 2019) demand urgent action to reconcile the provision of agricultural goods with environmental, social and economic services. Pushing economies of scale and increasing large-scale agricultural and livestock production while keeping on spending EU agricultural subsidies not where they are most needed (Scown et al., 2020), and ignoring or outsourcing negative impacts is no more a viable solution for agriculture (Fuchs et al., 2020). In the light of our findings, addressing these issues must become a pivotal topic for policymaking.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2021.101344.

References

Bentsen, N.S., Felby, C., Thorsen, B.J., 2014. Agricultural residue production and potentials for energy and materials services. Prog. Energy Combust. Sci. 40, 59–73.

Blanco-Canqui, H., Lal, R., 2007. Soil and crop response to harvesting corn residues for biofuel production. Geoderma 141 (3-4), 355–362.

Blum, W.E.H., Swaran, H., 2004. Soils for sustaining global food production. J. Food Sci. 69 (2), crh37–crh42.

Bowles, N., Alexander, S., Hadjikakou, M., 2019. The livestock sector and planetary boundaries: a ‘limits to growth’ perspective with dietary implications. Ecol. Econ. 160 (C), 128–136.

Britz, W., Verburg, P.H., Leip, A., 2011. Modelling of land cover and agricultural change in Europe: Combining the CLUE and CAPRI-Spat approaches. Agric., Ecosyst. Environ. 142(1). Scaling methods in integrated assessment of agricultural systems: 40–50.

Britz, W., Witzke, P., 2015. CAPRI model documentation. https://www.capri-model.org/dokuwiki/doku.php?.

Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T., 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124 (1-2), 3–22.

Brown, J.H., 2014. Why are there so many species in the tropics? Ed. by Jens-Christian Svenning. J. Biogeogr. 41 (1), 8–22.

Bruckner, M., Wood, R., Moran, D., Kuschnig, N., Wieland, H., Maus, V., Börner, J., 2019. FABIO—the construction of the food and agriculture biomass input-output model. Environ. Sci. Technol. 53 (19), 11302–11312.

Carvalho, J.L.N., Hudiburg, T.W., Franco, H.C.J., DeLucia, E.H., 2017. Contribution of above- and belowground bioenergy crop residues to soil carbon. GCB Bioenergy 9 (8), 1333–1343.

Cherubin, M.R., Oliveira, D.M.da.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, Letícia.L., Morais, M.C., Satiro, L.S., Popin, G.V., Paiva, S.R.de., dos Santos, A.K.B., Vasconcelos, A.L.S.de., Melo, P.L.A.de., Cerri, C.E.P., Cerri, C.C., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. Scientia Agricola 75 (3), 255–272.

Costanza, R., d`Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O`Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1998. The value of ecosystem services: putting the issues in perspective. Ecol. Econ. 25 (1), 67–72.

Costanza, R., Fisher, B., Mulder, K., Liu, S., Christopher, T., 2007. Biodiversity and ecosystem services: A multi-scale empirical study of the relationship between species richness and net primary production. Ecol. Econ. 61 (2-3), 478–491.

Cusens, J., Wright, S.D., McBride, P.D., Gillman, L.N., 2012. What is the form of the productivity–animal-species-richness relationship? A critical review and meta-analysis. Ecology 93 (10), 2241–2252.

Daryanto, S., Fu, B., Wang, L., Jacinthe, P.-A., Zhao, W., 2018. Quantitative synthesis on the ecosystem services of cover crops. Earth Sci. Rev. 185, 357–373.

Domingues, J.P., Gameiro, A.H., Bonaudo, T., Tichit, M., Gabrielle, B., 2019. Exploring trade-offs among indicators of performance and environmental impact in livestock areas. Reg. Environ. Change 19 (7), 2089–2099.

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., Tichit, M., 2013. Prospects from agroecology and industrial ecology for animal production in the 21st century. Animal 7 (6), 1028–1043.

Egli, L., Meyer, C., Scherber, C., Kreft, H., Tscharntke, T., 2018. Winners and losers of national and global efforts to reconcile agricultural intensification and biodiversity conservation. Glob. Change Biol. 24 (5), 2212–2228.

Emmerson, M., M.B. Morales, J.J. Oñate, P. Batáry, F. Berendse, J. Liira, T. Aavik, et al. 2016. Chapter Two - How Agricultural Intensification Affects Biodiversity and Ecosystem Services. In Advances in Ecological Research, ed. by Alex J. Dumbrell, Rebecca L. Kordas, and Guy Woodward, 55:43–97. Large-Scale Ecology: Model Systems to Global Perspectives. Academic Press, January 1. http://www.sciencedirect.com/science/article/pii/S0065250416300204. Accessed October 23, 2019.

Erb, K.-H., Fetzel, T., Kastner, T., Kroisleitner, C., Lauk, C., Mayer, A., Niedertscheider, M., 2016. Livestock Grazing, the Neglected Land Use. In Social Ecology, ed. by Helmut Haberl, Marina Fischer-Kowalski, Fridolin Krausmann, and Verena Winiwarter, 295–313. Cham: Springer International Publishing. http://link.springer.com/10.1007/978-3-319-33326-7_13. Accessed July 26, 2016.

Erb, K.-H., Haberl, H., Jepsen, M.R., Kuemmerle, T., Lindner, M., Müller, D., Verburg, P. H., Reenberg, A., 2013. A conceptual framework for analysing and measuring land-use intensity. Curr. Opin. Environ. Sustain. 5(5). Human settlements and industrial systems: 464–470.

Erb, K.-H., Krausmann, F., Gaube, V., Gingrich, S., Bondeau, A., Fischer-Kowalski, M., Haberl, H.. 2009a. Analyzing the global human appropriation of net primary production — processes, trajectories, implications. An introduction. Ecol. Econ. 69 (2). Special Section: Analyzing the global human appropriation of net primary production – processes, trajectories, implications: 250–259.

Erb, K.-H., Krausmann, F., Lucht, W., Haberl, H., 2009b. Embodied HANPP: Mapping the spatial disconnect between global biomass production and consumption. Ecol. Econ. 69 (2), 328–334.

European Commission. 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal.

European Commission. 2020a. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-Friendly Food System.

European Commission. 2020b. EU Biodiversity Strategy for 2030 Bringing Nature Back into Our Lives.

Fan, J., McConkey, B., Janzen, H., Townley-Smith, L., Wang, H., 2017. Harvest index–yield relationship for estimating crop residue in cold continental climates. Field Crops Research 204, 153–157.

Faostat. 2021. FAOSTAT database. http://www.fao.org/faostat/en/.

Fetzel, T., Gradwohl, M., Erb, K.-H., 2014. Conversion, intensification, and abandonment: A human appropriation of net primary production approach to analyze historic land-use dynamics in New Zealand 1860–2005. Ecol. Econ. 97, 201–208.

Fetzel, T., Havlik, P., Herrero, M., Erb, K., 2017. Seasonality constraints to livestock grazing intensity. Glob. Change Biol. 23 (4), 1636–1647.

Fetzel, T., Niedertscheider, M., Haberl, H., Krausmann, F., Erb, K.-H., 2016. Patterns and changes of land use and land-use efficiency in Africa 1980–2005: an analysis based on the human appropriation of net primary production framework. Reg. Environ. Change 16 (5), 1507–1520.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., et al., 2005. Global consequences of land use. Science 309 (5734), 570–574.

Franzluebbers, A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res. 66(2). Conservation Tillage and Stratification of Soil Properties: 197–205.

Fuchs, R., Brown, C., Rounsevell, M., 2020. Europe's Green Deal offshores environmental damage to other nations. Nature 586 (7831), 671–673.

Gaston, K.J., 2000. Global patterns in biodiversity. Nature 405 (6783), 220–227.

Gerber, Pierre, Harold Mooney, Jeroen Dijkman, eds. 2010. Livestock in a Changing Landscape, Volume 2: Experiences and Regional Perspectives. Island Press.

Gingrich, S., Niedertscheider, M., Kastner, T., Haberl, H., Cosor, G., Krausmann, F., Kuemmerle, T., Müller, D., Reith-Musel, A., Jepsen, M.R., Vadineanu, A., Erb, K.-H., 2015. Exploring long-term trends in land use change and aboveground human appropriation of net primary production in nine European countries. Land Use Policy 47, 426–438.

Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. Science 361 (6399), eaam5324.

Haberl, H., Erb, K.-H., Krausmann, F., 2013. Global human appropriation of net primary production (HANPP). http://www.eoearth.org/view/article/51cbede37896bb431f694846.

Haberl, H., Erb, K.-H., Krausmann, F., 2014. Human appropriation of net primary production: patterns, trends, and planetary boundaries. Annu. Rev. Environ. Resour. 39 (1), 363–391.

Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc. Natl. Acad. Sci. 104 (31), 12942–12947.

Haberl, H., V. Gaube, R. Díaz-Delgado, K. Krauze, A. Neuner, J. Peterseil, C. Plutzar, S.J. Singh, and A. Vadineanu. 2009. Towards an integrated model of socioeconomic biodiversity drivers, pressures and impacts. A feasibility study based on three European long-term socio-ecological research platforms. Ecol. Econ. 68(6). Eco-efficiency: From technical optimisation to reflective sustainability analysis: 1797–1812.

Haberl, H., Kastner, T., Schaffartzik, A., Erb, K.-H., 2016. How Far Does the European Union Reach? Analyzing Embodied HANPP. In Social Ecology, ed. by Helmut Haberl, Marina Fischer-Kowalski, Fridolin Krausmann, and Verena Winiwarter, 349–360. Human-Environment Interactions 5. Springer International Publishing. http://link.springer.com/chapter/10.1007/978-3-319-33326-7_16. Accessed January 20, 2017.

Haberl, H., Steinberger, J.K., Plutzar, C., Erb, K.-H., Gaube, V., Gingrich, S., Krausmann, F., 2012. Natural and socioeconomic determinants of the embodied human appropriation of net primary production and its relation to other resource use indicators. Ecol. Ind. 23 (3), 222–231.

Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. In: Raffaelli, D.G., Frid, C.L.J. (Eds.), Ecosystem Ecology. Cambridge University Press, Cambridge, pp. 110–139 https://www.cambridge.org/core/product/identifier/CBO9780511750458A013/type/book_part. Accessed December 6, 2019.

Haines-Young, R., Potschin, M.B., 2018. Common international classification of ecosystem services (CICES) V5. 1 and guidance on the application of the revised structure. Nottingham: Fabis Consulting Ltd.

Harrison, P.A., Berry, P.M., Simpson, G., Haslett, J.R., Blicharska, M., Bucur, M., Dunford, R., Egoh, B., Garcia-Llorente, M., Geamănă, N., Geertsema, W., Lommelen, E., Meiresonne, L., Turkelboom, F., 2014. Linkages between biodiversity attributes and ecosystem services: a systematic review. Ecosyst. Serv. 9, 191–203.

Hawkins, B.A., Field, R., Cornell, H.V., Currie, D.J., Guégan, J.-F., Kaufman, D.M., Kerr, J.T., Mittelbach, G.G., Oberdorff, T., O'Brien, E.M., Porter, E.E., Turner, J.R.G., 2003. Energy, water, and broad-scale geographic patterns of species richness. Ecology 84 (12), 3105–3117.

Hay, R.K.M., 1995. Harvest index: a review of its use in plant breeding and crop physiology. Ann. Appl. Biol. 126 (1), 197–216.

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blummel, M., Weiss, F., Grace, D., Obersteiner, M., 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc. Natl. Acad. Sci. 110 (52), 20888–20893.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B: Biol. Sci. 363 (1491), 543–555.

IPBES. 2017. Report of the Plenary of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on the work of its fifth session. Bonn: IPBES. https://www.ipbes.net/sites/default/files/ipbes-5-15_en.pdf. Accessed September 9, 2017.

IPBES. 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services. Zenodo, November 25. https://zenodo.org/record/3553579. Accessed March 1, 2021.

IPCC. 2019. IPCC Special Report on Climate Change, Desertification, LandDegradation, Sustainable Land Management, Food Security, and Greenhouse gas fluxes in Terrestrial Ecosystems.

Kalt, G., Kaufmann, L., Kastner, T., Krausmann, F., 2021. Tracing Austria's biomass consumption to source countries: a product-level comparison between bioenergy, food and material. Ecol. Econ. 188, 107129.

Karlsson, J.O., Parodi, A., van Zanten, H.H.E., Hansson, P.-A., Röös, E., 2021. Halting European Union soybean feed imports favours ruminants over pigs and poultry. Nat. Food 2 (1), 38–46.

Kastner, T., Erb, K., Haberl, H., 2015. Global human appropriation of net primary production for biomass consumption in the European Union, 1986–2007. J. Ind. Ecol. 19 (5), 825–836.

Kempen, M., Witzke, P., 2018. Improvement of the stable release of the CAPRI model: Fertilizer and Feed allocation routines. Deliverable 3: Revised feed module for CAPRI. Specific contract No. Joint Research Centre 154208.X39.

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci.: 201211349.

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., Haberl, H., 2008. Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. Ecol. Econ. 65 (3), 471–487.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304 (5677), 1623–1627.

Lal, R. 2008. Crop residues as soil amendments and feedstock for bioethanol production. Waste Manage. 28(4). OECD Workshop – Soils and Waste Management: A Challenge to Climate Change: 747–758.

Lal, R., 2020. Regenerative agriculture for food and climate. J. Soil Water Conserv. 75 (5), 123A–124A.

Maes, J., 2018. Mapping and Assessment of Ecosystems and their Services: An analytical framework for ecosystem condition. Luxembourg: Publications Office of the European Union. https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/5th%20MAES%20report.pdf.

Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M.L., Barredo, J.I., Grizzetti, B., et al., 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosyst. Serv. 17, 14–23.

Malek, Žiga, Verburg, P., 2017. Mediterranean land systems: representing diversity and intensity of complex land systems in a dynamic region. Landscape Urban Plann. 165, 102–116.

McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Glob. Change Biol. 19 (5), 1347–1357.

MEA, ed. 2005. Ecosystems and human well-being: synthesis. Washington, DC: Island Press.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security 14, 1–8.

Mu, W., van Middelaar, C.E., Bloemhof, J.M., Engel, B., de Boer, I.J.M., 2017. Benchmarking the environmental performance of specialized milk production systems: selection of a set of indicators. Ecol. Ind. 72, 91–98.

Öckinger, E., Smith, H.G., 2007. Semi-natural grasslands as population sources for pollinating insects in agricultural landscapes. J. Appl. Ecol. 44 (1), 50–59.

Pan, Y., Wu, J., Xu, Z., 2014. Analysis of the tradeoffs between provisioning and regulating services from the perspective of varied share of net primary production in an alpine grassland ecosystem. Ecol. Complexity 17, 79–86.

Petz, K., Alkemade, R., Bakkenes, M., Schulp, C.J.E., van der Velde, M., Leemans, R., 2014. Mapping and modelling trade-offs and synergies between grazing intensity and ecosystem services in rangelands using global-scale datasets and models. Global Environ. Change 29, 223–234.

Plieninger, T., Huntsinger, L., 2018. Complex Rangeland Systems: Integrated Social-Ecological Approaches to Silvopastoralism. Rangeland Ecology & Management 71 (5). Integrated Social-Ecological Approaches to Silvopastoralism: 519–525.

Plutzar, C., Kroisleitner, C., Haberl, H., Fetzel, T., Bulgheroni, C., Beringer, T., Hostert, P., Kastner, T., Kuemmerle, T., Lauk, C., Levers, C., Lindner, M., Moser, D., Müller, D., Niedertscheider, M., Paracchini, M.L., Schaphoff, S., Verburg, P.H., Verkerk, P.J., Erb, K.-H., 2016. Changes in the spatial patterns of human appropriation of net primary production (HANPP) in Europe 1990–2006. Reg. Environ. Change 16 (5), 1225–1238.

Potschin-Young, M., Haines-Young, R., Görg, C., Heink, U., Jax, K., Schleyer, C., 2018. Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. Ecosystem Services 29. SI: Synthesizing OpenNESS: 428–440.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. B: Biol. Sci. 365 (1554), 2959–2971.

Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. 107 (11), 5242–5247.

Richmond, A., Kaufmann, R.K., Myneni, R.B., 2007. Valuing ecosystem services: a shadow price for net primary production. Ecol. Econ. 64 (2), 454–462. Special Section - Ecosystem Services and Agriculture.

Roux, N., Kastner, T., Erb, K.-H., Haberl, H., 2021. Does agricultural trade reduce pressure on land ecosystems? decomposing drivers of the embodied human appropriation of net primary production. Ecol. Econ. 181, 106915.

Rusch, A., Chaplin-Kramer, R., Gardiner, M.M., Hawro, V., Holland, J., Landis, D., Thies, C., Tscharntke, T., Weisser, W.W., Winqvist, C., Woltz, M., Bommarco, R., 2016. Agricultural landscape simplification reduces natural pest control: a quantitative synthesis. Agric. Ecosyst. Environ. 221, 198–204.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., 2000. Global biodiversity scenarios for the year 2100. Science 287 (5459), 1770–1774.

Schipanski, M.E., Barbercheck, M., Douglas, M.R., Finney, D.M., Haider, K., Kaye, J.P., Kemanian, A.R., Mortensen, D.A., Ryan, M.R., Tooker, J., White, C., 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric. Syst. 125, 12–22.

Scown, M.W., Brady, M.V., Nicholas, K.A., 2020. Billions in misspent EU agricultural subsidies could support the sustainable development goals. One Earth 3 (2), 237–250.

SEEA. 2021. System of Environmental-Economic Accounting—Ecosystem Accounting: Final Draft. Department of Economic and Social Affairs, Statistics Division, United Nations. https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA_Final_draft-E.pdf.

Shike, D.W. 2013. Beef Cattle Feed Efficiency. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?referer=http://iopscience.iop.org/article/10.1088/1748-9326/aaa273/meta&httpsredir=1&article=1027&context=driftlessconference. Accessed March 15, 2018.

Simoncini, R., Ring, I., Sandström, C., Albert, C., Kasymov, U., Arlettaz, R., 2019. Constraints and opportunities for mainstreaming biodiversity and ecosystem services in the EU's Common Agricultural Policy: Insights from the IPBES assessment for Europe and Central Asia. Land Use Policy 88, 104099. https://doi.org/10.1016/j.landusepol.2019.104099.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's Long Shadow: Environmental issues and options. Rome, Italy: FAO/LEAD. ftp://ftp.fao.org/docrep/fao/010/a0701e/a0701e.pdf.

Sutherland, I.J., Villamagna, A.M., Dallaire, C.O., Bennett, E.M., Chin, A.T.M., Yeung, A.C.Y., Lamothe, K.A., Tomscha, S.A., Cormier, R., 2018. Undervalued and under pressure: A plea for greater attention toward regulating ecosystem services. Ecol. Indic. 94. Landscape Indicators – Monitoring of Biodiversity and Ecosystem Services at Landscape Level: 23–32.

Tälle, M., Deák, B., Poschlod, P., Valkó, O., Westerberg, L., Milberg, P., 2016. Grazing vs. mowing: a meta-analysis of biodiversity benefits for grassland management. Agric. Ecosyst. Environ. 222, 200–212.

Teixeira, R.F.M., Barão, L., Morais, T.G., Domingos, T., 2019. "BalSim": a carbon, nitrogen and greenhouse gas mass balance model for pastures. Sustainability 11 (1), 53.

Vačkář, D., Harmáčková, Z.V., Kaňková, H., Stupková, K., 2016. Human transformation of ecosystems: comparing protected and unprotected areas with natural baselines. Ecol. Ind. 66, 321–328.

Van Zanten, H.H.E., M. Herrero, O.V. Hal, E. Röös, A. Muller, T. Garnett, P.J. Gerber, C. Schader, and I.J.M.D. Boer. 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biology online first. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14321. Accessed June 25, 2018.

van Zanten, H.H.E., Mollenhorst, H., Klootwijk, C.W., van Middelaar, C.E., de Boer, I.J.M., 2016. Global food supply: land use efficiency of livestock systems. Int. J. Life Cycle Assess. 21 (5), 747–758.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., Matson, P.A., 1986. Human appropriation of the products of photosynthesis. Bioscience 36 (6), 368–373.

de Vries, M., van Middelaar, C.E., de Boer, I.J.M., 2015. Comparing environmental impacts of beef production systems: a review of life cycle assessments. Livestock Sci. 178, 279–288.

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., Oenema, O., 2014. Food choices, health and environment: effects of cutting Europe's meat and dairy intake. Global Environ. Change 196–205.

Wittwer, R.A., Dorn, B., Jossi, W., van der Heijden, M.G.A., 2017. Cover crops support ecological intensification of arable cropping systems. Sci. Rep. 7 (1), 41911.

Wright, D.H., 1983. Species-energy theory: an extension of species-area theory. Oikos 41 (3), 496–506.

Wright, D.H., 1990. Human impacts on energy flow through natural ecosystems, and implications for species endangerment. Ambio 189–194.

Zhang, Y., Pan, Y., Li, M., Wang, Z., Wu, J., Zhang, X., Cao, Y., 2021. Impacts of human appropriation of net primary production on ecosystem regulating services in Tibet. Ecosyst. Serv. 47, 101231.