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Product-Specific human appropriation of net primary production in US counties

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ABSTRACT

Human appropriation of net primary production (HANPP) has been developed in the 21st century as an ecological indicator that may supersede ecological footprint due to its spatial specificity, precise measurement of land use intensity, and potential to be tied to trade in biomass-based products, thus enabling a consumption-based analysis. Fusing publicly available data sources, this paper presents a product-specific, county-level analysis of HANPP harvested from crops, timber and grazing in the conterminous United States in the years 1997, 2002, 2007 and 2012, the most recent dates for which all necessary data are available. Total HANPP(harvest) was 716–834 megatonnes (MT), including 514–615 MT from crops, 105–148 MT from timber and 64–76 MT grazed. Of this total, 432–512 MT, 60–66 percent, was a harvested commodity while the remainder was straw and forest slash; 83–84 percent was above-ground HANPP. Mean HANPP density varied from 92 – 107 $gCm^{-2}yr^{-1}$ in the years studied. With net primary production (NPP) varying from 558 – 610 $gCm^{-2}yr^{-1}$, this is 15–17 percent of NPP; NPP(ecological) thus varied from 466 – 577 $gCm^{-2}yr^{-1}$, 83–85 percent of NPP. The specific products with the largest proportions of HANPP were corn grain (26–32 %), soybeans (9–11 %), hardwood (6–10 %) and softwood (8–9 %) timber, grazing on private land (7–9 %), wheat (6–9 %), alfalfa (5–6 %) and aggregated minor crops (15–18 %). Among states, HANPP density varies from 7 $gCm^{-2}yr^{-1}$ in Nevada to 391 $gCm^{-2}yr^{-1}$ in Iowa and from 2 % of NPP in Massachusetts to 53 % in Iowa. Disaggregated analysis for 3101 counties shows even greater variation, from less than 1 to 726 $gCm^{-2}yr^{-1}$, and delineates regions carrying similar HANPP signatures. In the U.S. context, data availability and stoichiometry choices place only modest limitations on the accuracy of HANPP estimates making it a valuable ecological indicator for analyzing land use intensity, especially in agricultural ecosystems.

1. Introduction

A conceptual approach to studying “human appropriation of the products of photosynthesis” as a measure of the intensity of ecological impact through human uses of land was initiated by Vitousek et al. (1986). Further developed by the social ecology (Haberl et al., 2016) and social metabolism (Haberl et al., 2019) research programs, “human appropriation of net primary production” has emerged in the 21st century as a powerful approach to analyze human utilization of and impact upon ecosystems. Net primary production (NPP) is defined as gross primary production through photosynthesis minus respiration by autotrophs (Schlesinger and Bernhardt 2013). Zhang et al. (2009) found that NPP averages 52 percent of gross primary production globally but with large spatial variations among ecosystem types. NPP is the most widely used measure of the capacity of an ecosystem to build biomass and provide energy to heterotrophs. It is usually measured in accumulated mass of dry matter per unit area or, estimating 45 percent of this as the carbon content (Schlesinger and Bernhardt, 2013), carbon fixed in biomass per square meter annually ($gCm^{-2}yr^{-1}$). Geographical variations in NPP are great (Haberl et al., 2007; Schlesinger and Bernhardt, 2013), with production among terrestrial sites varying from zero on ice and impervious surfaces to a reported 1880 $gCm^{-2}yr^{-1}$ in managed

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cocoa farms in Ghana (Morel et al., 2019).

In the conceptualization used by the Millennium Ecosystem Assessment (2005) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (Diaz et al., 2019), NPP is a fundamental supporting ecosystem service. Global NPP represents, as much as any number could, the finiteness of the capacity of the biosphere to generate the energetic basis for all heterotrophs (Running, 2012). Nemani et al. (2003) report a mean global NPP value of 54.5 $PgCyr^{-1}$ and an increasing trend from 1982 to 1999 driven by CO_2 fertilization, nitrogen deposition, forest regrowth, and climate change. Yet Zhao and Running (2010) show that, due to drought, this trend was reversed after 2000 and Cao et al. (2022) project continuing declines in global NPP going forward due to intensifying drought. Thus, there are trade-offs in utilizing this finite planetary photosynthetic capacity among provisioning ecosystem services that harvest NPP for biomass products versus cultural and regulatory ecosystem services (Brauman et al., 2020; Canelas and Pereira, 2022) and non-domesticated species that utilize remaining NPP in place without harvesting it (Lorel et al., 2019, 2021). Yet a systematic analysis of the relationship between HANPP and ecosystem services is in its infancy (Mayer et al. 2021).

Definitions of human appropriation of NPP (HANPP) have varied as the concept has matured. While Vitousek et al. (1986) established a broad range of 4 to 58 percent of global terrestrial NPP, more rigorous and nuanced estimates of HANPP recognize that—through agriculture, forestry and other land uses (AFOLU)—humans remove or inhibit far more NPP than they directly use as biomass-based goods. Since the seminal work by Haberl et al. (2007), the definition of HANPP has solidified around the idea that humans impact NPP both by harvest of biomass through crop and wood production and livestock grazing, known as HANPP(harvest), and also by altering the NPP of the landscape, known as HANPP(land use). Thus, Haberl et al. (2007) measure HANPP as the difference between potential NPP in the absence of human land uses and NPP remaining after harvest, known as NPP(ecological), where:

NPP(potential) – NPP(actual) = HANPP(land use) (1).

NPP(actual) – NPP(ecological) = HANPP(harvest) (2).

NPP(potential) – NPP(ecological) = HANPP(total) (3).

HANPP(land use) + HANPP(harvest) = HANPP(total) (4).

Using this more refined definition of HANPP, Haberl et al. (2007) found human appropriation of NPP circa 2000 of 15.6 $PgCyr^{-1}$ or 23.8 percent of global terrestrial potential NPP of 65.5 $PgCyr^{-1}$ with an average density across all terrestrial environments of 111 $gCm^{-2}yr^{-1}$, which includes 63 $gCm^{-2}yr^{-1}$ for HANPP(harvest) and 48 $gCm^{-2}yr^{-1}$ for HANPP(land use). They calculated the mean global HANPP(harvest) onsite density as 296 $gCm^{-2}yr^{-1}$ for cropped, 41 $gCm^{-2}yr^{-1}$ for grazed, and 48 $gCm^{-2}yr^{-1}$ for forestry areas. Beyond appropriating NPP, human land uses have also been shown to halve the standing stock of biomass globally (Erb et al., 2018) and to double its turnover time (Erb et al., 2016) creating a global ecosystem of more rapidly cycled biomass. These major modifications of ecosystem structure have important consequences both ecologically and on the carbon cycle that controls climate change (IPCC, 2019), prompting a research program into 'natural climate solutions' (Griscom et al., 2017) that could partially reverse these ecological megatrends, while sequestering large quantities of atmospheric carbon. Fargione et al. (2018) show that 21 land-based interventions could sequester 0.9 to 1.6 $PgCO^2e$ per year in the U.S., offsetting 21 percent of net annual emissions.

While definable globally with reference to planetary limits (Rockstrom et al., 2009; Running, 2012), the study of HANPP is much more revealing of human dependence and impacts upon ecosystems at more highly resolved geographical scales. An increasing number of regional studies of HANPP show that population, moreso than affluence or technology (Jenkins et al. 2022), is placing increasing pressure on NPP. Abdi et al. (2014) found that, for 22 countries in the Sahel region of Africa, HANPP increased from 19 percent of NPP in 2000 to 41 percent in 2010 to meet demands for food, fuel and livestock feed. Chen et al. (2015) found that from 2001 to 2010, aboveground HANPP in China increased from 49.5 percent of NPP(potential) in 2001 to 57.8 percent in 2010. Grabher (2021) found that HANPP reached 63 percent of NPP (potential) in Ethiopia by 2013 with NPP(ecological) declining from about 400 gCm^2yr^{-1} in 1961 to 225 gCm^2yr^{-1} in 2013. In contrast, an abundance of studies focused on Europe, where the HANPP concept has flourished through work of the Institute of Social Ecology, show high, but slowly declining, HANPP with increasing efficiency as measured by HANPP(harvest) as a proportion of HANPP(total) (e.g., Gingrich et al., 2015).

Geographical variations in HANPP also show its value as an ecological indicator. Haberl et al. (2007) found HANPP to vary regionally from 35 $gCm^{-2}yr^{-1}$ in Northern Africa and Western Asia, where NPP is a low 70 $gCm^{-2}yr^{-1}$, to 311 $gCm^{-2}yr^{-1}$ in Eastern and Southeastern Europe. As a percentage of NPP(potential), HANPP(total) varies regionally from 11 percent in Australia and Oceania to 63 percent in Southern Asia. Site-specific values as high as 1300 $gCm^{-2}yr^{-1}$ have been measured in Bangladesh (Mahbub et al., 2019) and vary from less than −200 percent (negative values are possible when irrigation raises NPP (actual) above NPP(potential)) to over 80 percent of NPP. HANPP(harvest) varies from 4 percent of NPP(actual) in Central Asia and Russia to 56 percent in Southern Asia.

Recent work has refined HANPP measurement to finer spatial resolutions. Qin et al. (2021) used the 250 m resolution of MODIS NPP data to map HANPP in the Qilian Mountains of China. Paudel et al. (2021), in a corn belt county in the U.S., and Liu and Song (2022), in the Heihe River Basin in China, refined the analysis of HANPP to the 30 m pixel scale. These geographical patterns of HANPP are influenced by NPP available, population density, affluence, agro-technological status, and a location's role as an importer or exporter of biomass-based products (Krausmann et al., 2009).

North America stands out, however, as a region lacking systematic analysis of HANPP. In the few case studies available, O'Neill et al. (2007) showed that HANPP in Nova Scotia is 25 percent of NPP(potential); Andersen et al. (2015) showed that HANPP in a small watershed in South Carolina decreased from 35 percent in 1968 to 28 percent in 2011. Barton et al. (2020) found that HANPP(harvest) in the Great Lakes region of the U.S. averaged 45 percent of NPP and correlated negatively with landscape diversity and connectivity.

Global trends in HANPP also indicate planetary changes in land use intensity, a critical issue in environmental sustainability (Kastner et al., 2022). Krausmann et al. (2013) found that, from 1910 to 2005, global HANPP doubled from 6.9 to 14.8 $PgCyr^{-1}$, or from 13 to 25 percent of global terrestrial NPP, largely due to increases in crop yields achieved after 1950, a trend that is land sparing (Phalan et al., 2011). HANPP increased slower than population, thus decreasing HANPP per capita by nearly half, from 3.9 to 2.3 $tCyr^{-1}$ from 1910 to 2005 through large decreases in HANPP(land use) while maintaining HANPP(harvest) per capita. As measured by the HANPP(harvest) to HANPP(land use) ratio, the efficiency of agricultural land use has thus been increasing. HANPP per unit GDP decreased by 88 percent as industries not dependent upon biomass came to dominate economic production, indicating a decoupling of economic growth from increases in resource extraction (Zhou et al., 2018). The efficiency of resource utilization has been improving even as absolute quantities of resource extraction continue to increase, especially relative to fixed planetary or local ecological limits (e.g., see Haberl et al., 2019; McAfee, 2019). That is, decoupling in biomass harvest has been relative rather than absolute.

The ability to decrease HANPP per capita through these gains in agro-ecological efficiency is encouraging in the 21st century, which has also witnessed decelerating population growth. That is, it is possible to maintain or even decrease the proportion of NPP appropriated by humans going forward—so long as HANPP(harvest) per capita is not increased for energy production though biofuels or expanded meat production and crop yields continue to increase at a faster rate than population despite climate change. This strategy maintains NPP

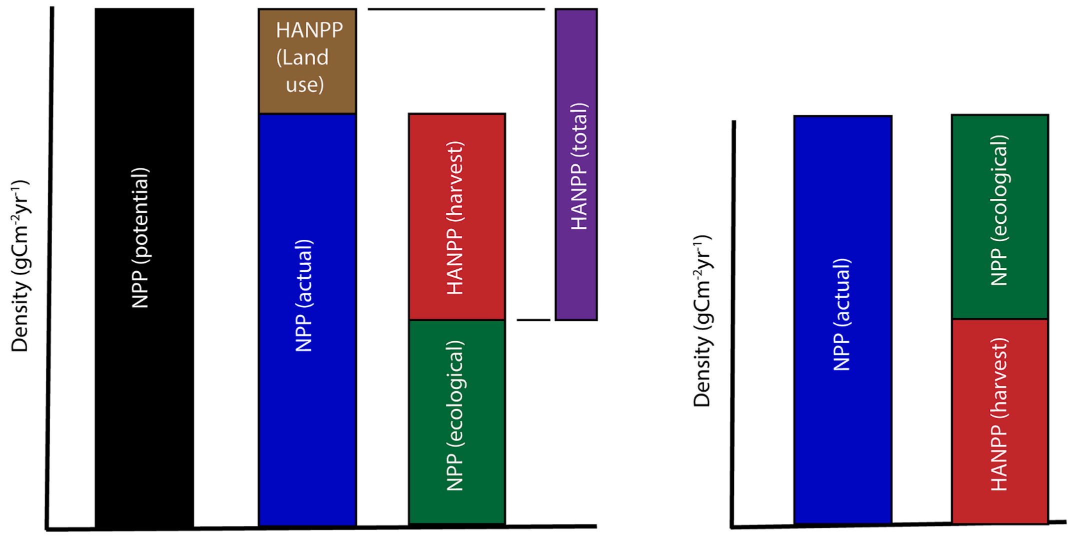

Fig. 1. Definition of HANPP. On the left is the definition of HANPP utilized by Haberl et al. (2007, 2014) that includes a modeled estimate of NPP(potential) and HANPP(land use) as NPP(potential) minus NPP(actual). On the right is the simplified definition of HANPP utilized in this study where NPP(potential) is excluded and NPP(ecological) is NPP(actual) minus HANPP(harvest).

(ecological), which is essential for biodiversity and cultural and regulatory ecosystem services, and thus sustainability.

The argument is thus strong that analyzing HANPP captures insights into the dynamics of nature-society interactions in general and human utilization of agricultural ecosystems in particular. It answers specific research questions applicable to specific places and time periods including: (1) How intensively do human land uses capture ecological material and energy flows? (2) How much ecological energy is left remaining for other species? (3) What is the allocation of ecological energy, for which NPP represents both a local and a planetary limit, among provisioning and other ecosystem services? HANPP measures the actual appropriation of NPP from spatially-specific ecosystems to social metabolism to produce specific consumable products. It can therefore be traced along supply chains as embodied HANPP from points of production to points of consumption (Kastner et al., 2011). This makes HANPP consistent with other well-established footprint measures. Carbon footprints are measured as the net radiative forcing effect of gaseous releases to the atmosphere. Water footprints are measured as the evapotranspiration or withdrawals induced by the production of a commodity. HANPP measures the photosynthetic energy made unavailable to ecosystems through human use of land. Like carbon and water footprints, HANPP can be calculated for an individual product or group of products, or for any defined geographical jurisdiction.

Amid this growing and insightful literature on HANPP, we address two missing elements—the paucity of North American case studies and product-specific studies at sub-national or mesoscales—while evaluating the value of HANPP as an ecological indicator. This paper studies appropriated NPP, the portion of it harvested, used and unused, above and belowground, in counties of the conterminous U.S. in 1997, 2002, 2007 and 2012 associated with harvests of specific crops and timber as well as livestock grazing. This product-specific, county-based approach at five-year intervals also facilitates subsequent analyses of trade and consumption of biomass products, thereby enabling an analysis of embodied HANPP, though that analysis is not pursued in the present paper.

2. Methods and calculations

2.1. HANPP definitional strategy

The definition of HANPP(land use) is the difference between potential and actual NPP (equation 1), yet the former is hypothetical and can only be simulated using ecosystem models such as Lund-Potsdam-Jena (Sitch et al., 2003) or the Carnegie-Ames-Stanford Approach (Potter et al., 1993). Different ecosystem models have been shown to generate quite different results with none of them achieving an accuracy within the bounds of flux tower measurement uncertainty (Schaefer et al., 2012). Moreover, Ellis et al. (2021) find that human activities have had a profound influence on ecosystem structure for at least 12,000 years, making the concept of NPP(potential) in the absence of humans quite hypothetical.

Second, while gross primary production can be directly measured using flux tower data, albeit on a sparce and unrepresentative spatial framework, NPP can only be estimated indirectly from remote sensing data. Our analysis of MODIS and Landsat, for example, yield NPP estimates that vary by an average of 19 percent. This leaves HANPP(land use) as conceptually inviting but, in practice, is a term that collects measurement error. Following Smil (2012), we measure HANPP(harvest) and compare it to NPP(actual), omitting NPP(potential) and thus HANPP(land use) from the analysis (Fig. 1). This aligns with equation (2) above.

Human 'appropriation' of ecological energy flows also brings to bear a definitional issue where, for example, in a crop field the yield of grain is clearly appropriated but the roots of annual crops and much of the straw or stover remain in place providing ecological energy to detritus cycles. Are these then "appropriated" by humans? Partitioning HANPP into above and below-ground and into economic yield and unused components, as we do here, enables calculating it under a variety of definitions.

2.2. Data Sources, spatial and temporal framework

To measure NPP, we aggregated 250 m resolution Moderate Resolution Image Spectroradiometer MODIS data for each county in 2002, 2007 and 2012. These NPP data are freely available since 2001 but are not available for 1997. The three primary means through which humans harvest NPP are crop production, timber cutting, and livestock grazing. Data availability on these three forms of HANPP(harvest) is the criterion used to identify the spatial framework and timeframe for the study. As a very small and declining component of HANPP in the U.S., use of wood for fuel is not included (Zhou et al., 2018), nor are forest fires because the human role is difficult to disentangle from 'natural' fires and the relationship between fires and the HANPP concept is not clear.

Critical data on harvests of crops and timber are available for the

Table 1
Stoichiometry for converting crop yield to HANPP for each crop studied using formula 5: NPP = (Economic yield * Dry fraction *Carbon content) / (Harvest index * % Shoot) ().

Crop	Dry frac-tion	Source	Car-bon con-tent	Source	% Shoot	Source	Harvest index	Source(s)
corn grain	0.845	4	0.45	12	0.85	11	1940: 0.35; linear interpolate to 2000: 0.53; >2000: 0.53	3,5
corn silage	0.35	10	0.45	12	0.85	11	1.0	
wheat	0.865	4	0.45	12	0.83	11	1940: 0.28; linear interpolate to 2000: 0.45; >2000: 0.45	3,5,6
soybeans	0.87	4	0.45	12	0.87	11	1940: 0.30; linear interpolate to 2000: 0.46; >2000: 0.46	3,5
alfalfa-hay	0.82	1	0.45	12	0.46	2	1.0	
cotton	0.935	13	0.45	12	0.86	8	1940: 0.35; linear interpolate to 1978: 0.47; >1978: 0.47	3,5,9
sorghum	0.88	7	0.45	12	0.86	11	1940: 0.34; linear interpolate to 2000: 0.47; >2000: 0.47	3,5

Sources:
1. Alberta Agriculture and Forestry, 2018.
2.Bolinger et al., 2002.
3. Evans, 1993.
4. Hellevang, 2018.
5. Johnson, et al., 2006.
6. Kumudini, et al., 2001.
7. McAlister, 2018.
8. McMichael and Quisenberry, 1991.
9. National Cotton Council, 1990.
10. Ontario Ministry of Agriculture, Food and Rural Affairs, 2018.
11. Prince et al., 2001.
12. Schlesinger and Bernhardt, 2013.
13. University of Arkansas Division of Agriculture, 2018.
adapted from Monfreda et al. 2008

3101 counties in the conterminous U.S., while grazing activity is best estimated at the county scale. Data on acres harvested and yields of major crops are available annually from the U.S. Department of Agriculture National Agricultural Statistics Service (USDA-NASS) Quick Stats; however, coverage of minor crops and the six New England states is incomplete. Timber production is available from the U.S. Department of Agriculture Forest Service (USFS) only at five-year intervals starting in 1997. USFS data for 2017 were incomplete at the time the study was conducted. For livestock grazing, analysis is dependent upon the USDA-NASS cattle inventory, which is available in the same five-year intervals. Therefore, this study is conducted at the county scale for the years 1997, 2002, 2007 and 2012.

2.3. Estimating HANPP (harvest) for crops

Crop production is the most intensive form of HANPP(harvest) in the U.S. and globally. In order to implement a detailed, bottom-up approach, we used yield data provided on a crop-specific basis for each county in each year by the U.S. Department of Agriculture (2019) and estimated similar data in the cases where these data are not available. The six New England states (CN, MA, ME, NH, RI, VT) lacked data on a crop-county-year specific basis. For these states we used the USDA-NASS Cropland Data Layer (USDA, 2012) to identify areas planted and utilized statewide average yields from neighboring New Jersey and New York. For Florida, crop yield data are missing for some counties in some years; we used the closest year where acreage and yield data are available for each county.

Monfreda et al. (2008) provides a formula for calculating the NPP harvested during crop production from data on economic yields.

HANPP(harvest) = (economic yield * dry fraction *carbon content) / (harvest index * % shoot) (5).

Where dry fraction is the proportion of yield remaining after moisture is driven off; carbon content is the proportion of dry fraction that is elemental carbon by mass; harvest index is the proportion of plant mass that is counted as yield; percent shoot is the proportion of the harvested plant that lies aboveground. The conversion (termed stoichiometry) from yield to NPP using this formula varies by crop. We therefore identified the leading crops grown in the U.S. from the USDA-NASS Cropland Data Layer. The ten high-acreage major crops for which USDA-NASS Quick Stats data (USDA, 2019) are most consistently available (corn grain and silage; winter, spring and durum wheat; alfalfa hay; pima and upland cotton; and sorghum) occupied 77 percent of cropland in 2012.

Table 1 provides the stoichiometry for each major crop with estimates derived from a variety of peer-reviewed and agricultural extension literature. Carbon content is set at 45 percent for all crops (Schlesinger and Bernhardt, 2013), while dry fraction varies from 82 to 94 percent for all crops except corn silage (35 percent). Percent shoot varies from 82 to 87 percent for all crops except perennial, deep-rooted alfalfa hay (46 percent). For corn silage and alfalfa hay, the harvest index is 1.0 because the entire plant is considered a product useable as livestock feed. For remaining crops, it varies from 44 to 53 percent (Table 1).

The Cropland Data Layer in 2012 was used to identify the acreage of minor crops in each county but data on yields and the stoichiometry of these numerous minor crops are not available. We therefore assumed that the on-site HANPP(harvest) density of minor crops is the national mean for major crops. We also assumed this to be constant for 1997, 2002, 2007 and 2012; CDL data became available for the entire conterminous U.S. in 2008.

The values provided in Table 1, as well as data on yields and acreage harvested from USDA-NASS to determine economic yield, were applied through equation 5 to calculate the NPP harvested for each crop in each county in each year studied. In this manner, three measures were derived: total carbon harvested in metric tonnes, on-site HANPP density and average HANPP density across the area of a county in $gCm^{-2}yr^{-1}$. These were further divided into used and unused portions as determined by the harvest index and above- and below-ground portions as determined by percent shoot. Formulas used to make these calculations are included in the Excel files available at the Mendeley Data repository (Mueller, et al. 2023).

Table 2
Stoichiometry for converting timber production into HANPP (harvest).

Wood type	Density (lb/ft^3)[1]	Dry Fraction[2]	Percent Shoot[4]	Carbon Content[3]
Softwood (gymnosperms)	31	0.75	0.79	0.45
Hardwood (angiosperms)	43	0.78	0.80	0.45

Sources:
[1] Cairns et al., 1997.
[2] Penn State University Extension, 2019.
[3] Schlesinger and Bernhardt, 2013.
[4] The wood database, 2019.

2.4. Estimating HANPP(harvest) for timber

Data on softwood and hardwood harvests, in cubic feet, for each U.S. county in the years 1997, 2002, 2007 and 2012 were obtained from the USDA Forest Service (2019). These data include timber products (roundwood) as well as “slash” (all removals minus roundwood) for the entire county. We derived HANPP(harvest) measures analogous to crops for both timber types for each county in each year: total metric tonnes of carbon and county-average density in $gCm^{-2}yr^{-1}$. On-site densities could not be calculated, however, because the data are not site-specific within the county. Equation (5) was adapted from crops to timber such that:

HANPP(timber harvest) = (all removals * dry fraction *carbon content) / (% shoot) (6).

Table 2 shows the values used in equation 6 for softwood and hardwood drawn from peer-reviewed and extension sources. Used portions were derived by substituting roundwood (cut timber that enters lumber and other markets) for all removals in equation 6, with unused portions as the remainder. Aboveground HANPP(harvest) was derived by removing “% shoot” from the equation with belowground as the remainder.

2.5. Estimating HANPP(harvest) for livestock grazing

Estimating HANPP(harvest) from livestock grazing is less straightforward, with quite different data sources for public and private lands. The USDA Forest Service (USFS) and the Bureau of Land Management (BLM) provide permits to ranchers in the form of animal-unit months (AUMs) appurtenant to allotments of land. AUMs are conceptually identical to HANPP(harvest) and are defined as the forage needed for a 1000-pound cow and her calf for one month. This is given as 26 lb of dry matter per day, which converts to 162 kgC of HANPP(harvest).

We applied this metric to data on AUMs authorized (which varies annually but never exceeds the amount permitted) provided by the USFS and BLM Permit Schedule Information Reports (US Department of Interior, 2019) to obtain measures of total metric tonnes of carbon and on-site densities in $gCm^{-2}yr^{-1}$ for each allotment in the most recent permit. Allotments were assigned to counties in proportion to the area that lies within each.

Livestock grazing on private lands is extensive yet lacks a straightforward data source like AUMs. It would be advantageous for USDA to publish data on the number of cattle grazing in each US county in the Cattle Inventory. In order to derive a relationship between grazing demand and the NPP of grassland/pasture resources in each county, the number of beef cattle (dairy cattle rarely graze in the U.S. in the 21st century) were drawn from the USDA-NASS Cattle Inventory conducted in 1997, 2002, 2007, and 2012. Each beef animal was assumed to require 12 AUMs per year or 1944 kgC from grazing. Lands categorized as grassland/pasture by the USDA-NASS Cropland Data Layer were identified and the NPP of these grassland/pasture areas was derived from LANDSAT data. In this way 30 m pixels could be matched between the two data sources. This allowed us to derive the total NPP of grassland/pasture in each county as the grazing resource.

In order to take advantage of regional variations in the proportion of the grazing resource that is appropriated through grazing, we assigned each county to one of the 20 USDA Land Resource Regions (LRRs) that overlay the 48 contiguous states (Fig. 2). The total AUMs from beef cattle were then compared to the total NPP of grassland/pasture in remaining counties in the LRR to derive a LRR-wide percentage of NPP harvested through grazing. This percentage was then applied to the NPP of grassland/pasture in each country in the LRR. Results show that the percentage of grassland/pasture NPP that is grazed varies from 4 to 19 percent among the 20 Land Resource Regions (Fig. 2).

Procedures followed to calculate HANPP(harvest) for crops, timber, and grazing from various sources of USDA data and to calculate NPP

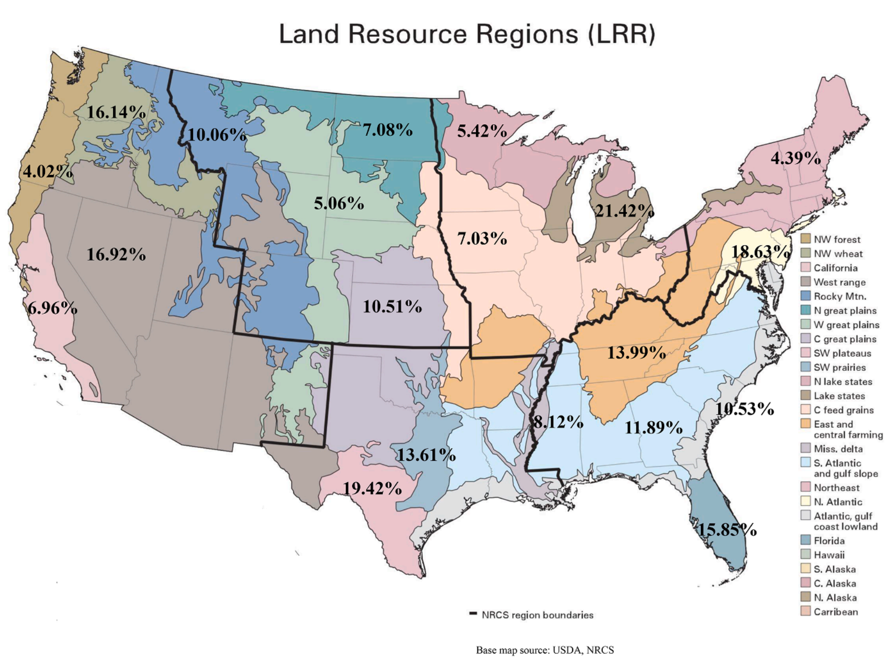

Fig. 2. Grazing HANPP in LRRs. Estimated percentages of grassland/pasture NPP consumed by livestock in each of the 20 USDA Land Resource Regions within the contiguous U.S. using data from USDA-NASS Cattle Inventory and Cropland Data Layer as well as Landsat data on NPP.

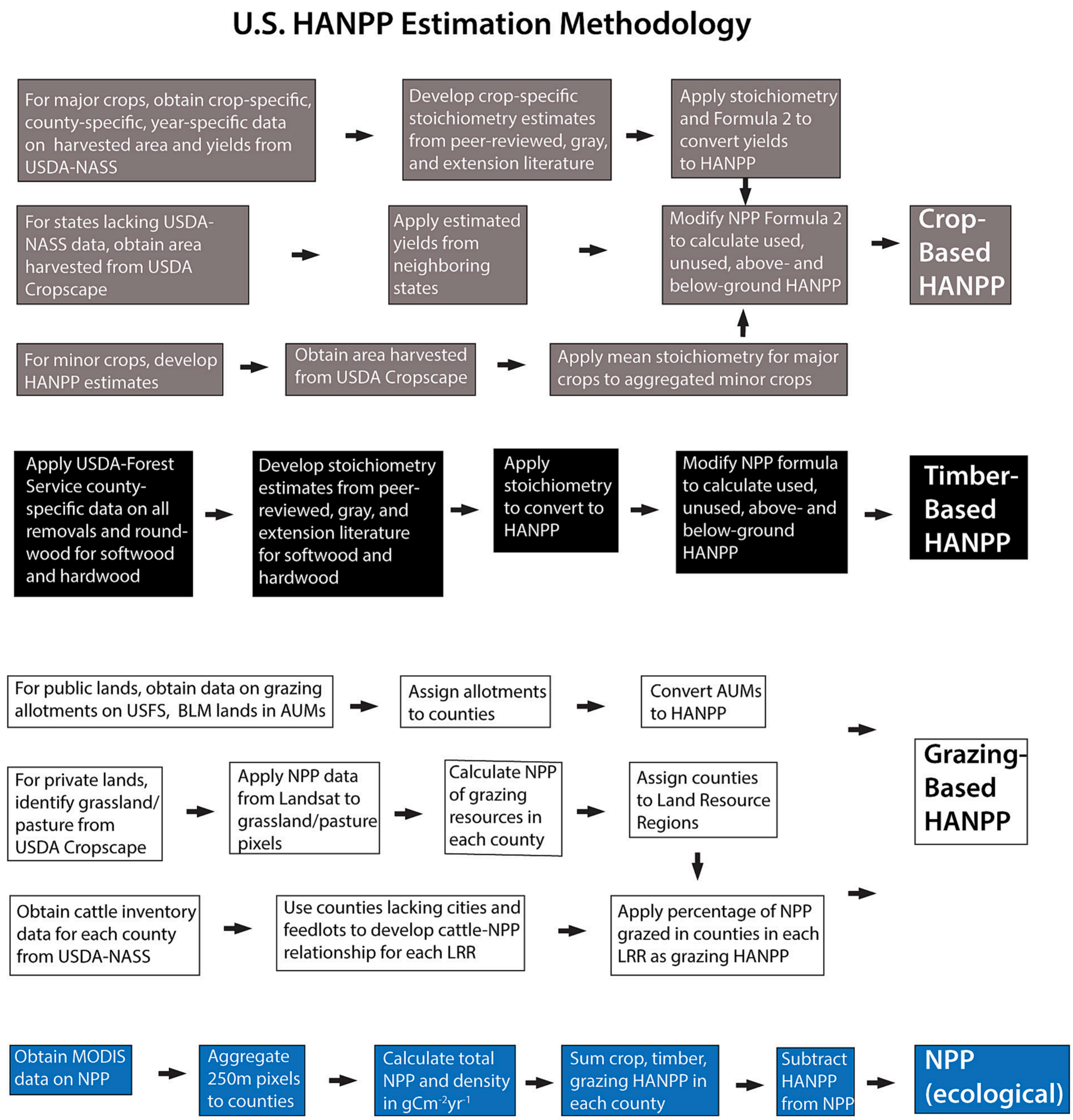

Fig. 3. Methodology Flow Chart. Procedures followed to calculate HANPP(harvest) for crops, timber and grazing and to calculate NPP (ecological) for each U. S. county.

(ecological) from NASA MODIS for each U.S. county in the 48 conterminous states are summarized in Fig. 3.

3. Results

Upon implementing the methods described above, for each of 16 products (11 crops, 2 timber, 3 grazing), for each of 3101 counties, across 4 time periods, this study generates results for kilotonnes C, county-wide and on-site densities, each partitioned into above- and below-ground and into used and unused components. The product of these permutations is about 3,000,000 measurements of HANPP. These results are provided in a Mendeley Data repository (Mueller et al., 2023). The primary county-based results are also provided to the reader in an interactive map provided in association with this paper. Here we present the results at the national and state level along with an analysis of the frequency distributions and primary patterns evident at the county level.

3.1. National totals and trends

We first report on-site and county-wide densities of NPP and HANPP (measured in $gCm^{-2}yr^{-1}$), which are best interpreted in an ecological perspective, and then quantities of used HANPP entering supply chains (measured in megatonnes per year), which provide an economic perspective. On-site densities are calculated from yields and the stoichiometries provided in Table 1 and equation 5. Corn grain has the highest HANPP(harvest) density at 597 $gCm^{-2}yr^{-1}$ followed by alfalfa hay at 503, winter wheat at 315, spring wheat at 306, soybeans at 285, sorghum at 218 and cotton at 68 $gCm^{-2}yr^{-1}$. The mean value for all major crops was 408 $gCm^{-2}yr^{-1}$ and this value was applied to minor crops that have data on area but lack data on yields or stoichiometry. Grazing on private land had a mean on-site density of 34 $gCm^{-2}yr^{-1}$. On-

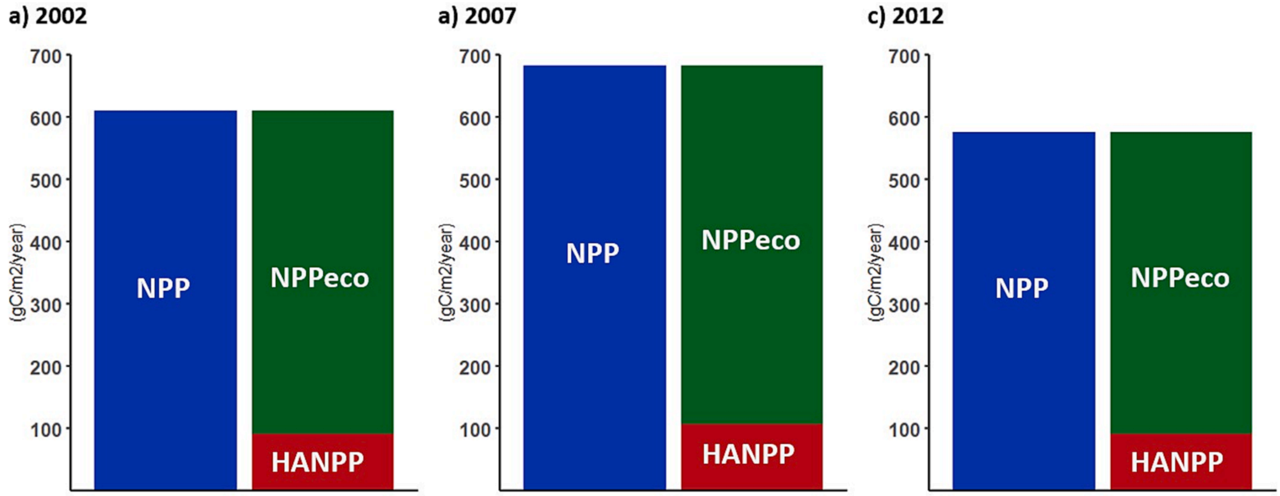

Fig. 4. Partition of NPP into NPPeco and HANPP. Trends in NPP, NPP(ecological) and HANPP(harvest) in the contiguous U.S. for (a) 2002, (b) 2007, (c) 2012. NPP data are not available for 1997.

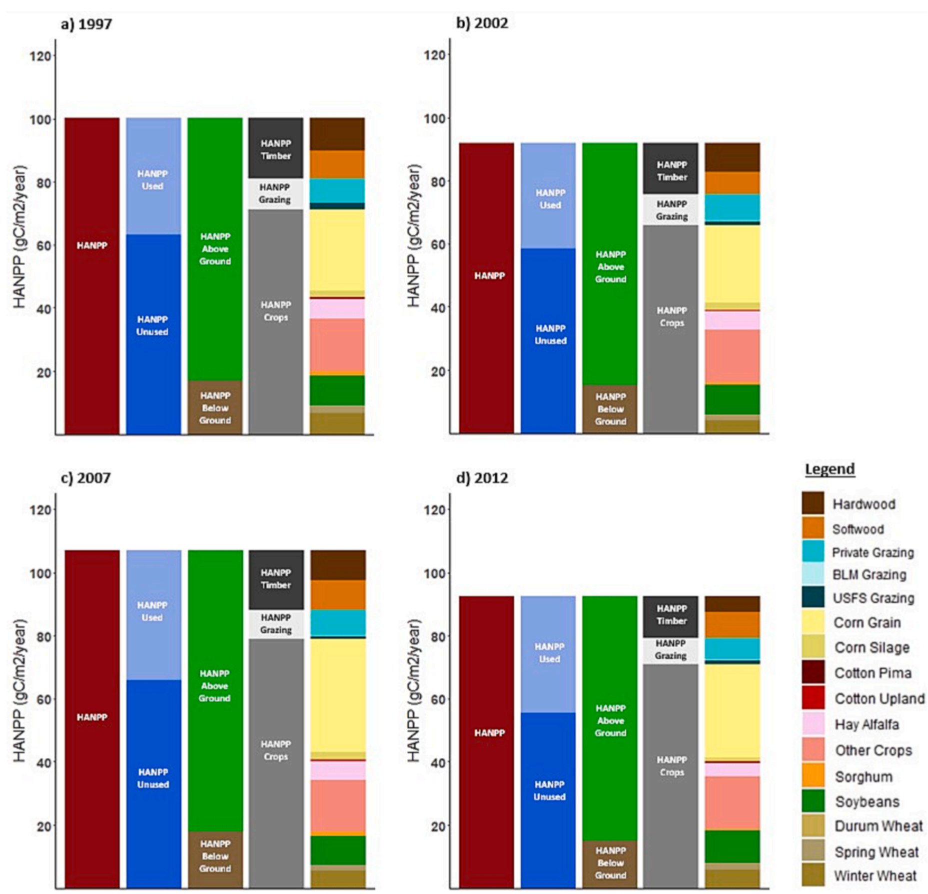

Fig. 5. National HANPP Signatures. Total HANPP(harvest) and its components: used and unused, above and below-ground, from crops, timber, and grazing, and by product for the contiguous U.S. in (a) 1997, (b) 2002, (c) 2007, (d) 2012.

site densities are not available for timber as noted above.

NPP varied from 558 in 2012 (a drought year) to 684 $gCm^{-2}yr^{-1}$ in 2007 (Fig. 4). The range of total HANPP (harvest) was 92–107 $gCm^{-2}yr^{-1}$ over the study period. This ranges from 15.1 to 16.7 percent of NPP among 2002, 2007 and 2012. NPP(ecological) thus varies from 83.3 to 84.9 percent of NPP and from 466 to 577 $gCm^{-2}yr^{-1}$ among 2002, 2007 and 2012 (Fig. 4).

The breakdown of HANPP(harvest) components for 1997, 2002, 2007 and 2012 with respect to used and unused, above- and below-ground, crop, grazing and timber and by specific product is shown in Fig. 4. This same stacked bar-chart scheme and color-coding is used for state and county-level breakdowns. Mean crop-based HANPP (harvest) density varied from 66 to 79 $gCm^{-2}yr^{-1}$; the values for timber are 13–19 $gCm^{-2}yr^{-1}$ and for grazing are 8–10 $gCm^{-2}yr^{-1}$.

Total HANPP was stable over the study period with a downward trend in timber and grazing-based HANPP balanced by increasing crop-

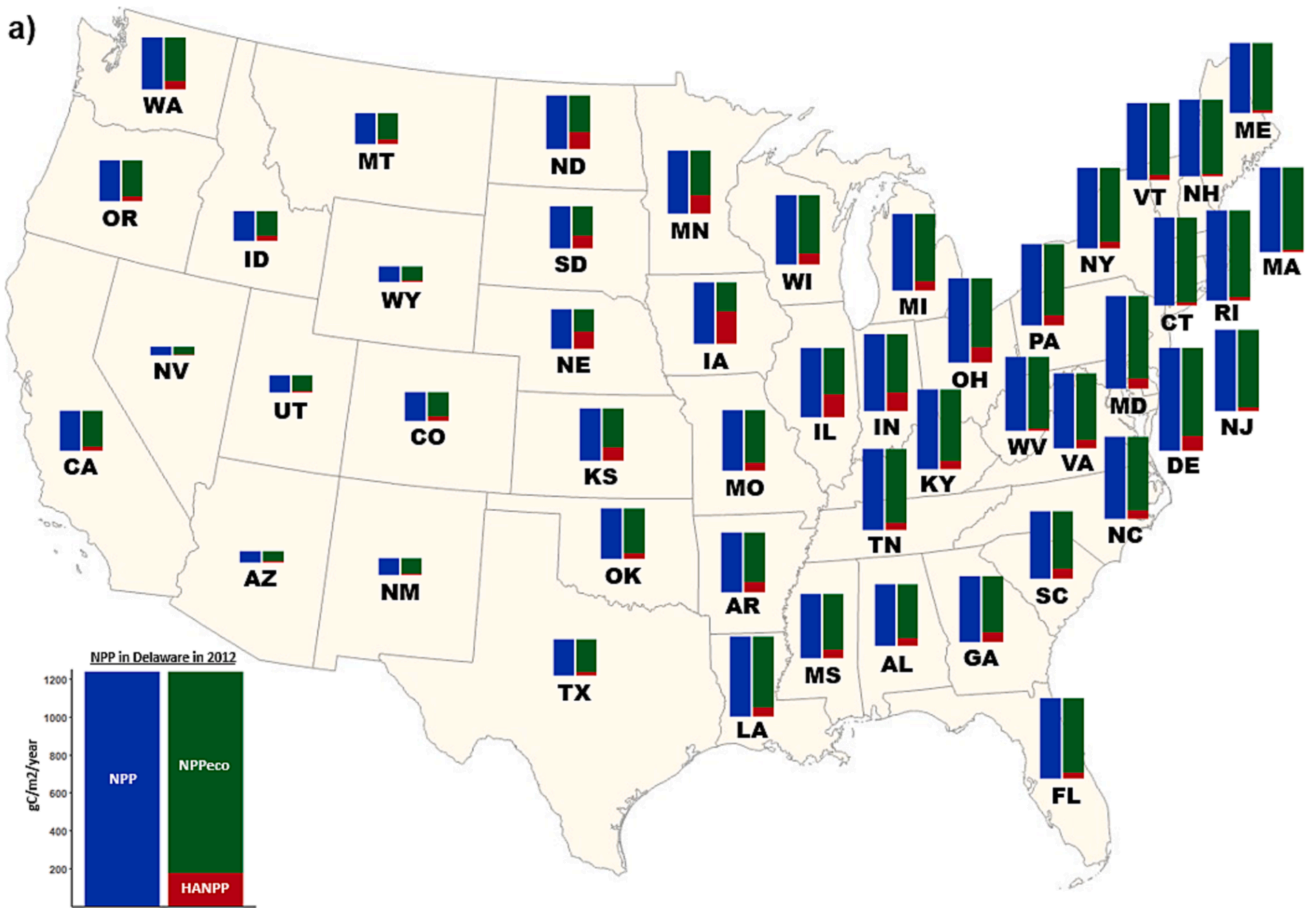

Fig. 6. Patterns of HANPP in U.S. States. Analysis of HANPP mean densities in 2012 by state (a) NPP (up to 1200 in $gCm^{-2}yr^{-1}$) and its partitioning into NPP (ecological), and total HANPP(harvest); (b) HANPP(harvest) signature for each state (up to 400 in $gCm^{-2}yr^{-1}$): used and unused, above- and below ground, timber, grazing and crops, and partitioned by specific crop. Individual state maps are scaled to the example bar chart in the lower left, which serves as a legend. See Fig. 5 for color-coding of individual products.

based HANPP borne of an increasing trend in yields. For example, mean corn yields increased at about one percent per year over the study period. Note that a severe drought significantly reduced crop yields in much of the conterminous U.S. in 2012; mean corn yield was 1.51 tonnes per hectare in 2011 and 1.62 in 2013, but only 1.26 in 2012 (USDA-NASS). Total HANPP varied from 719 to 834 $MTCyr^{-1}$ with no trend over the study period. Crops were the largest portion of HANPP(harvest), increasing from 71 to 76 percent of the total from 1997 to 2012. Timber declined from 19 to 15 percent of HANPP(harvest) and grazing varied from 9 to 11 percent.

The "used" portion of HANPP that enters supply chains as biomass-based products varied from 432 to 512 $MTCyr^{-1}$, including 54–58 percent of crop-based HANPP, 69–75 percent of timber HANPP and 100 percent of grazing HANPP (by definition). The proportion of total HANPP used declined from 66 to 60 percent as crops increased as a percentage of total HANPP. Used crops varied from 298 to 339 $MTCyr^{-1}$, increasing from 62 to 68 percent of total used HANPP; used timber declined from 113 to 74 $MTCyr^{-1}$ and from 23 to 17 percent of total used HANPP. Grazing declined from 76 to 64 $MTCyr^{-1}$, 14–16 percent of total used HANPP. The above-ground portion of HANPP was 83–84 percent of the total in each year (Fig. 5).

By product, corn grain generated 26–34 percent of all HANPP(harvest), with an increasing trend, followed by aggregated minor crops (15–18 percent), soybeans (9–11 percent), hardwood (6–10 percent with a decreasing trend), softwood (8–9 percent), grazing on private land (7–9 percent), alfalfa hay (5–6 percent) and winter wheat (5–7 percent) (Fig. 5).

3.2. State-Level aggregation

Aggregating county-based HANPP data by U.S. state allows for examination of spatial variations in HANPP and its components (Fig. 6). MODIS data show that NPP varies from 102 $gCm^{-2}yr^{-1}$ in arid Nevada to 1232 $gCm^{-2}yr^{-1}$ in Delaware (Fig. 6a). All 31 states east of Kansas City have mean NPP densities ranging from 713 to 1098 $gCm^{-2}yr^{-1}$. Six Great Plains (ND, KS, OK, SD, KS, TX) and three Pacific coast states (WA, OR, CA) share moderate NPP ranging from 413 to 650 $gCm^{-2}yr^{-1}$ while the eight Intermountain West states have water-limited NPP ranging from 102 to 368 $gCm^{-2}yr^{-1}$ (Fig. 6a).

Total HANPP(harvest) is highest in the heavily-cropped Midwestern states led by Iowa at 391 and Illinois at 279 $gCm^{-2}yr^{-1}$. For comparison, Baeza and Paruelo (2018) found mean HANPP(harvest) across the Rio de la Plata grasslands in Argentina, Brazil and Uruguay increased from 135 to 202 $gCm^{-2}yr^{-1}$ between 2001 and 2013 as grazed grasslands were converted to cropland. Four other Midwestern states (IN, MN, NE, ND) exceed 200 $gCm^{-2}yr^{-1}$ of total HANPP(harvest). Total HANPP(harvest) densities below 50 $gCm^{-2}yr^{-1}$ are found in the lightly harvested northeast (NJ, RI, CN, WV, NH, MA,) and arid Western states (TX, NM, UT, WY, AZ, NV), where low NPP limits HANPP. Thirty eastern states that are moderately harvested and nine Great Plains and Western states,

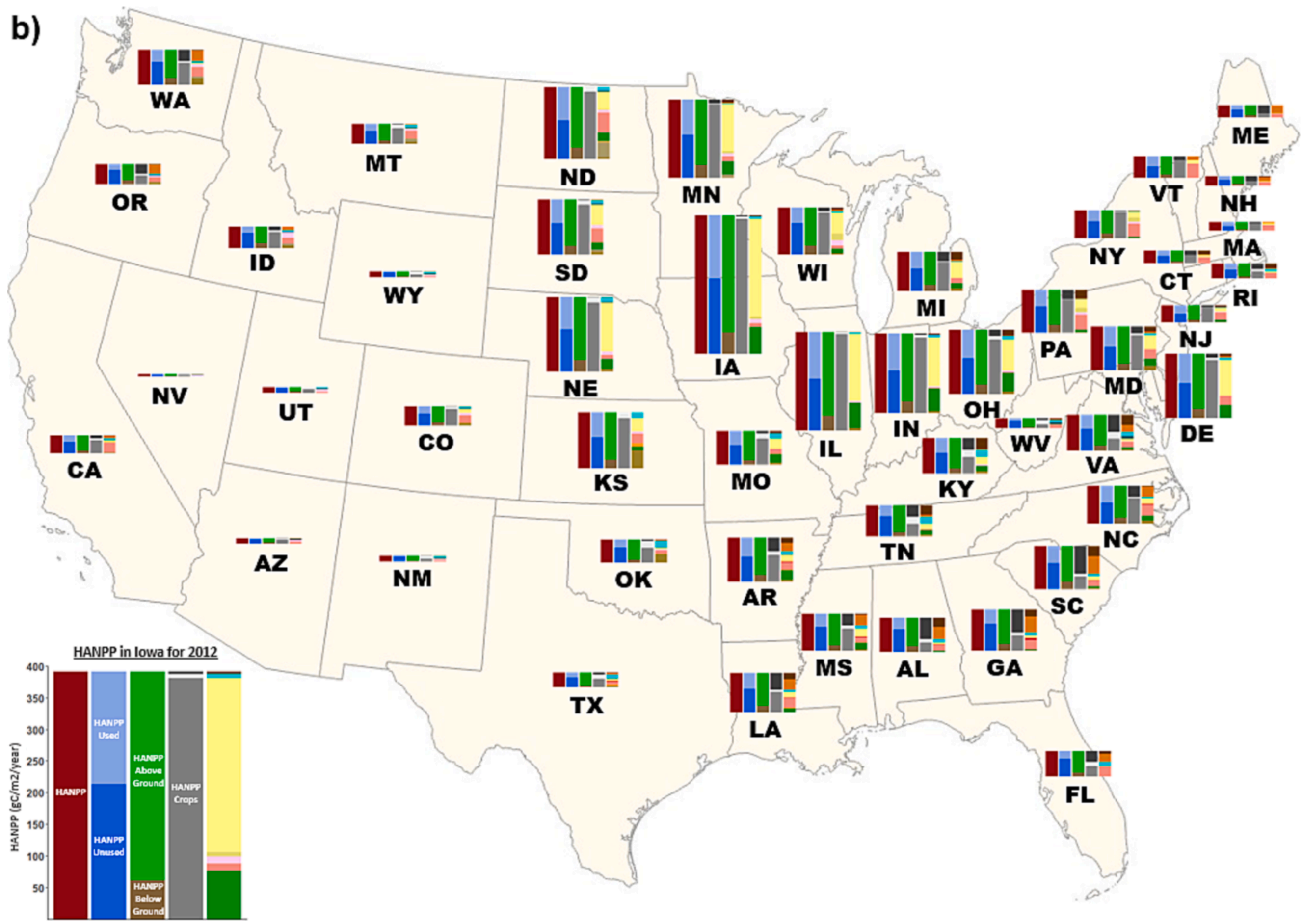

Fig. 6. (*continued*).

which have moderate levels of NPP, have intermediate levels of HANPP ranging from 50 to 200 $gCm^{-2}yr^{-1}$ (Fig. 6a).

Crops are the largest source of HANPP nationally and in 40 of the 48 states, led by Iowa at 381 $gCm^{-2}yr^{-1}$ and nine other Midwestern and Northern Plains (IL, IN, MN, NE, ND, OH, KS, SD, WI) states plus Delaware with over 100 $gCm^{-2}yr^{-1}$ crop-based HANPP. Crop-based HANPP

is highly variable among states, however, with a median value of 47 $gCm^{-2}yr^{-1}$. Timber is the highest HANPP(harvest) density in Oregon, two New England states (ME, NH) and five southeastern states (AL, FL, GA, SC, VA) led by South Carolina at 78 $gCm^{-2}yr^{-1}$. It is also highly variable with 22 states averaging less than 10 $gCm^{-2}yr^{-1}$. Grazing is the highest density form of HANPP in only two states (WV, WY) that have low levels of total HANPP. It is less variable among states than crops- and timber-based HANPP, peaking at only 20 $gCm^{-2}yr^{-1}$ in Kentucky (Fig. 6b).

Subtracting HANPP from NPP, eighteen lightly to moderately cropped eastern states (CN, DE, FL, KY, MA, MD, MI, NC, NH, NJ, NY, OH, PA, RI, TN, VT, WV) enjoy NPP(ecological) exceeding 800 $gCm^{-2}yr^{-1}$ (Fig. 6a) capped by Delaware at 1060 $gCm^{-2}yr^{-1}$. NPP(ecological) is lower in the Western states to the degree that precipitation limits NPP, ranging from 95 to 189 $gCm^{-2}yr^{-1}$ in five arid states (AZ, NM, NV, UT, WY). NPP(ecological) is also low in the heavily-cropped Midwestern states, such as Nebraska at 271 $gCm^{-2}yr^{-1}$, only 56 percent of NPP, and Iowa at 348 $gCm^{-2}yr^{-1}$ only 47 percent of NPP.

Fig. 6 (a and b) shows that each U.S. state has a distinctive overall HANPP signature with important regional patterns. Twelve Northeastern states (CN, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT, WV) have high-NPP, low-HANPP, and high NPP(ecological). Twelve southeastern states (AL, AR, FL, GA, KY, LA, MO, MS, NC, SC, TN, VA) have high NPP, moderate HANPP with timber and grazing as important as crops, and fairly high NPP (ecological). Seven Midwestern states (IA, IL, IN, MI, MN, OH, WI) have high NPP, high HANPP dominated by crops, and moderately low NPP(ecological). Six Great Plains states (KS, ND, NE, OK, SD, TX) have moderate NPP, moderately high HANPP dominated by crops and secondarily grazing, and low NPP(ecological). Eight Intermountain West states (AZ, CO, ID, MT, NM, NV, UT, WY) have low NPP, low HANPP with a substantial grazing component, and low NPP (ecological). Three West Coast states (CA, OR, WA) have complex environments that average out to moderate NPP, moderate HANPP with a mix of crops and timber, and moderate NPP(ecological). These HANPP signatures are even more unique and variable at the county scale to which we now turn.

3.3. County-Scale distributions

3.3.1. NPP, NPP(ecological) and total HANPP(harvest)

The spatial resolution of the dataset produced is best presented at the county scale, the spatial unit of analysis in which HANPP was calculated. Here we examine geographical patterns in the primary components of HANPP(harvest) in 2012 on a logarithmic scale to the base of 2 that best captures the range of densities from less than 2 to over 1024 (2^{10}) $gCm^{-2}yr^{-1}$. Over 2000 counties have NPP in the range 512–1024 $gCm^{-2}yr^{-1}$, with about 400 exceeding that mark (Fig. 7a). An additional 400 counties lie in the 256–512 $gCm^{-2}yr^{-1}$ range in semi-arid portions of the western U.S. A small number of arid southwestern counties form a tail at lower levels in the 64–128 $gCm^{-2}yr^{-1}$ range with a few large arid counties in Wyoming and the Mohave Desert of southeastern CA in the

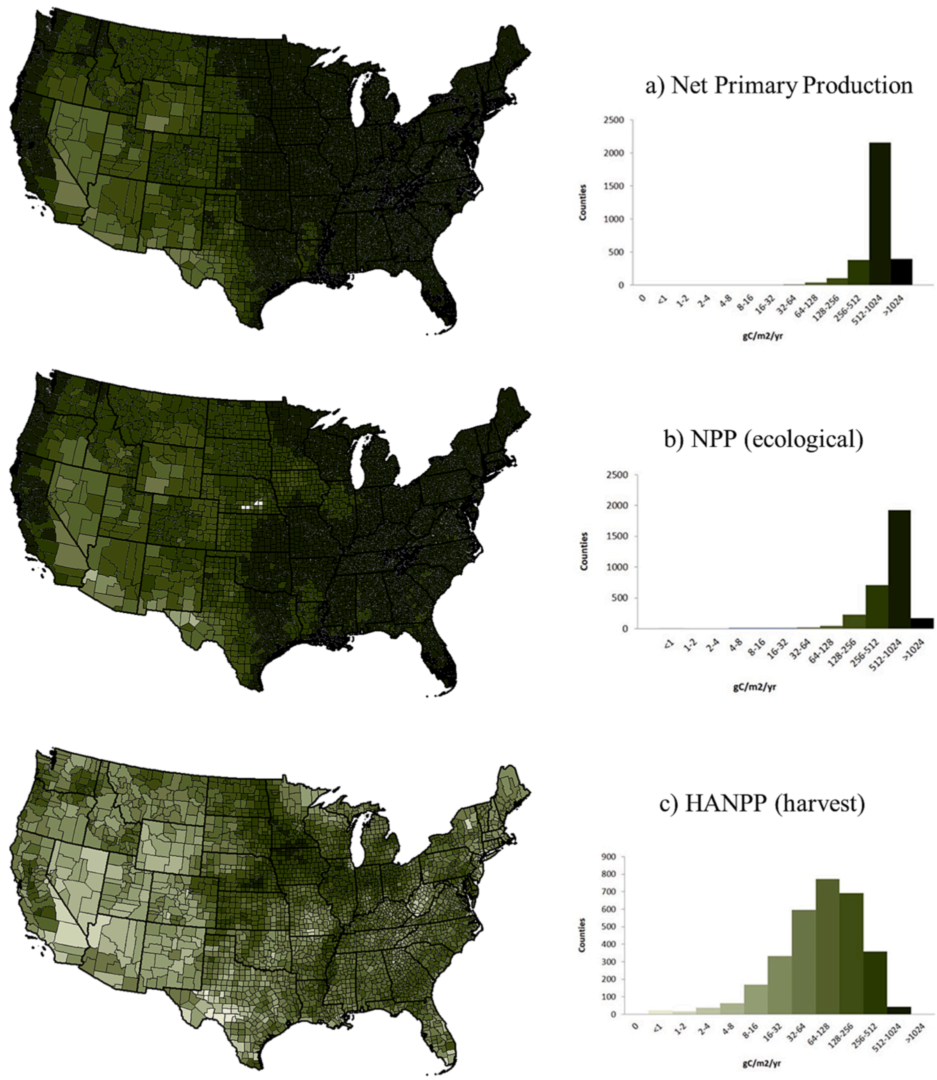

Fig. 7. County-Based Partition of NPP into NPPeco and HANPP. Geographic distribution (left) and frequency distribution among counties (right) of (a) NPP, (b) NPP (ecological) and (c) Total HANPP(harvest) on a common logarithmic scale.

lowest 32–64 $gCm^{-2}yr^{-1}$ range.

Total HANPP(harvest) among counties has a broad log-normal distribution with a mode in the 64–128 $gCm^{-2}yr^{-1}$ range (Fig. 7c). HANPP exceeds 512 $gCm^{-2}yr^{-1}$ in 43 counties in the most productive portions of the corn belt, in irrigated southeast Nebraska and straddling the Iowa-Minnesota border, where crops are rainfed. About 400 counties, mostly in the Corn Belt, exceed 256 $gCm^{-2}yr^{-1}$. At the low end, about 300 counties have total HANPP(harvest) below 16 $gCm^{-2}yr^{-1}$; these are scattered from the arid southwest, where NPP is limiting, to protected areas in many western and northeastern counties where most lands are either in protected status or are largely forested and not being harvested for timber.

NPP(ecological) has a median value of 643 $gCm^{-2}yr^{-1}$; it exceeds 1024 $gCm^{-2}yr^{-1}$ in 185 counties scattered in the eastern U.S. (Fig. 7b). It is also in the high 512–1024 $gCm^{-2}yr^{-1}$ range in about 2000 counties lying in a broad section of the eastern U.S. from Maine to eastern Minnesota and Texas, except where crop production is intensive. These counties reflect important trends in U.S. land use history where forest cleared for agriculture in the 19th century returned to forest through agricultural abandonment and ecological succession in the early 20th (Ramankutty et al. 2010) and currently harbor large and growing stocks of carbon (Nave et al. 2018). The lowest measures of NPP(ecological) are found both in the lowest-NPP arid portions of the western U.S. and in the most intensively cropped portions of the Corn Belt in Iowa and Nebraska.

3.3.2. *HANPP(harvest) from Crops, timber and grazing*

Breaking HANPP (harvest) into its crop, timber and grazing components (see below) yields more distinct regional variations and interpretations. U.S. counties fall within the entire range of intensities for crop-based HANPP (Fig. 8a) capped at 712 $gCm^{-2}yr^{-1}$ with about 36 counties exceeding 512 $gCm^{-2}yr^{-1}$ in the most productive portions of the corn belt. Over 800 counties with crop HANPP above 128 $gCm^{-2}yr^{-1}$ delineate the primary U.S. crop belts. At the low end, nearly half of all U. S. counties have crop HANPP below 32 $gCm^{-2}yr^{-1}$, including most.

of New England, the steepest portions of the Appalachians, the infertile Ozark plateau, and nearly all of the western third of the county with the exception of the irrigated areas noted above. As these patterns show, HANPP is a useful indicator of overall agricultural intensity.

Timber-based HANPP has a lower density distribution than crop-based HANPP (Fig. 8b), capped at 383 $gCm^{-2}yr^{-1}$. It is concentrated in regions with high NPP but steep slopes or soils that are unsuitable for crop production—the northwest and the southeast, with about 50 counties in these two regions exceeding timber-based HANPP of 128 $gCm^{-2}yr^{-1}$. Other regions with high timber-based HANPP(harvest) include the Olympic. Coast and Cascade ranges of Oregon and

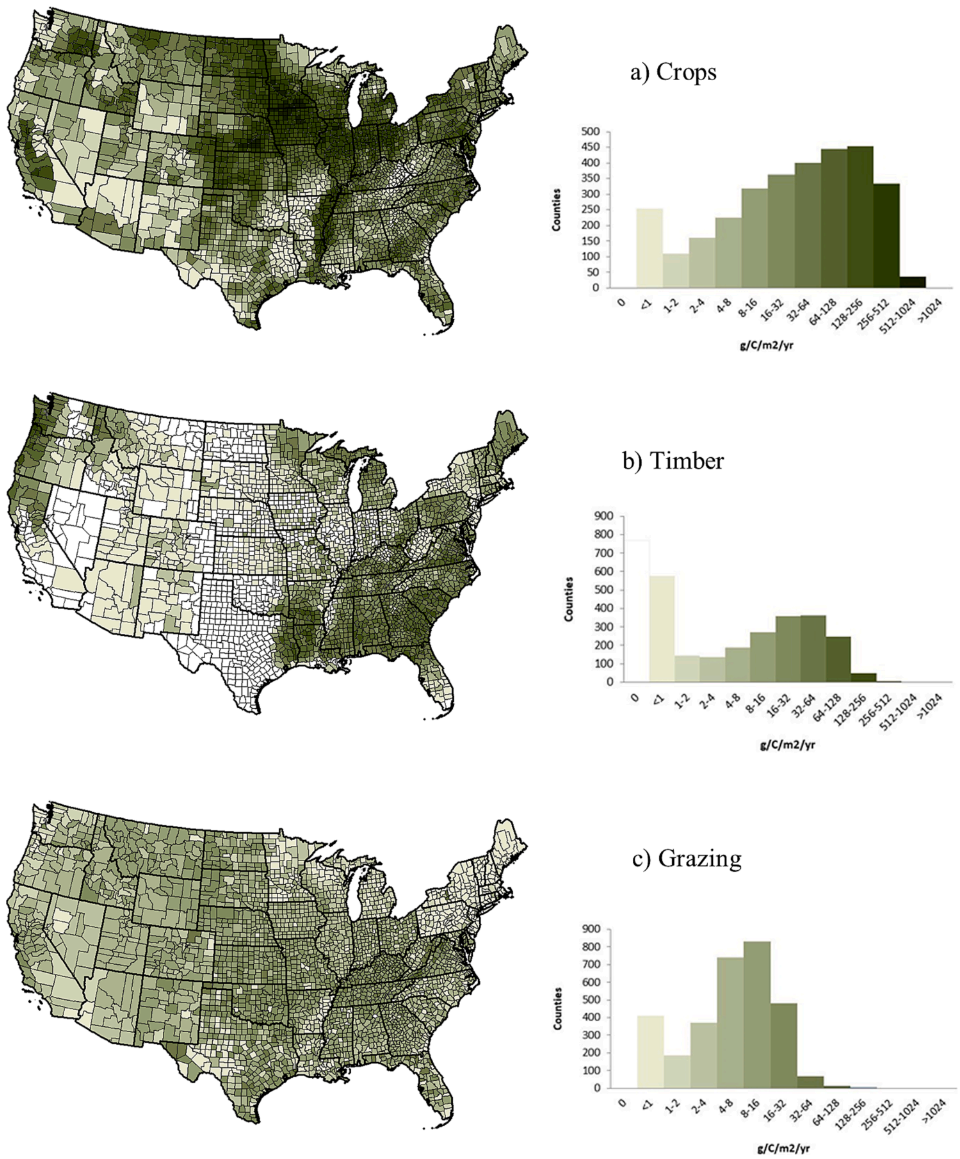

Fig. 8. Crop, Timber, and Grazing HANPP Densities in US Counties. Geographic distribution (left) and frequency distribution among counties (right) of HANPP derived from (a) crops, (b) timber, and (c) grazing on a common logarithmic scale.

Washington, followed by Maine, Pennsylvania and the counties surrounding Lake Superior.

Grazing-based HANPP is distributed log-normally through the lower levels of HANPP intensity with a maximum of only 136 $gCm^{-2}yr^{-1}$ and a mode at 8–16 $gCm^{-2}yr^{-1}$; about half of U.S. counties lie in the range 4–16 $gCm^{-2}yr^{-1}$, yet only a few urban counties lack grazing HANPP entirely (Fig. 8c). Widespread and extensive on lands not suitable for crop production, grazing is common on semi-arid lands, both federally owned rangelands of the western U.S. and privately owned grasslands in the Great Plains. It is also widespread on less fertile, moderately sloped privately-owned lands of the east.

3.3.3. Mass of HANPP(harvest) entering supply chains from U.S. Counties

While quantifying HANPP as a density provides valuable insights on land use intensity from an ecological perspective, quantifying volumes of HANPP provides an economic perspective on products entering supply chains from individual counties. This is especially the case for "used" HANPP that is calculated by multiplying HANPP(harvest) by the harvest index for crops (see Table 1) or by using data on Roundwood for timber. Of the 432 MT of crop and wood biomass products produced in the U.S. in 2012, corn grain provided 121 MT, minor crops 62, softwood 50, soybeans 37, alfalfa 33, hardwood 24, winter wheat 20, corn silage 11, and spring wheat 7 MT, respectively. Used HANPP(harvest) exceeded one MT in 50 counties in 2012, led by Fresno County California at nearly-two MT, yet the median value is a more modest 147 kilotonnes and every county produced some used HANPP (Fig. 9). When and where consumed, usually in cities, these products generate embodied HANPP (eHANPP) that can be traced back through supply chains to the county of production.

4. Discussion

4.1. Comparison to previous studies of HANPP

This study calculates HANPP(harvest) as 15–17 percent of NPP in the conterminous U.S. in 2002, 2007 and 2012 with a density of 92–107 $gCm^{-2}yr^{-1}$. This compares to Haberl et al. (2007) who calculated HANPP (harvest) as 14 percent of NPP in Northern America (circa 2000) with a density of 96 $gCm^{-2}yr^{-1}$. We calculate mean on-site HANPP(harvest) densities for crops at 408 $gCm^{-2}yr^{-1}$ and for grazing at 34 $gCm^{-2}yr^{-1}$

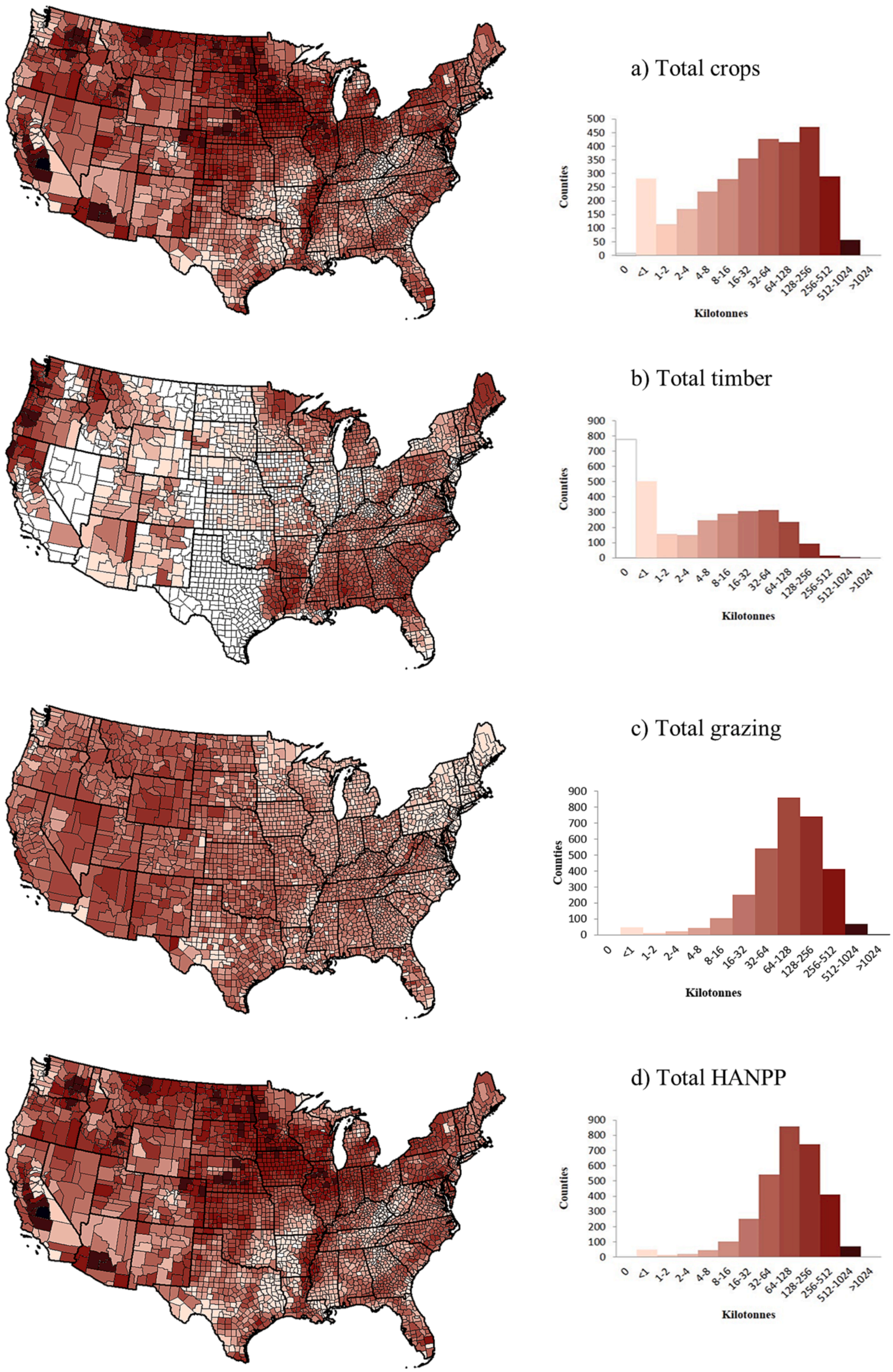

Fig. 9. Crop, Timber and Grazing HANPP Mass from US Counties. Geographic distribution and frequency distributions among counties of used HANPP(harvested) in 2012 in kilotonnes entering supply chains for: (a) crops, (b) timber, (c) grazing, and (d) total HANPP.

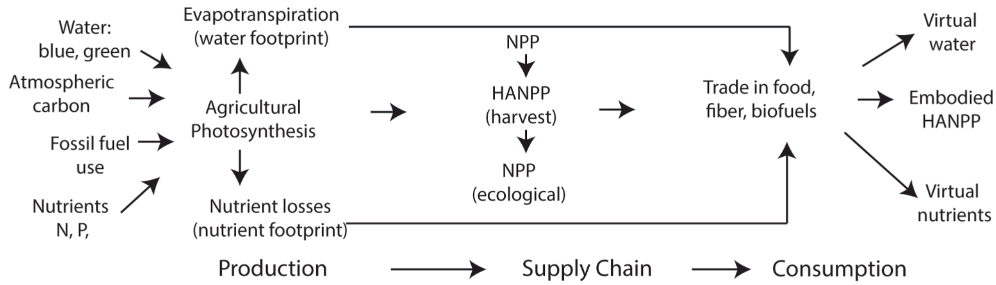

Fig. 10. Functional relationships among HANPP, eHANPP and other footprints.

compared to the circa-2000 global average of 296 $gCm^{-2}yr^{-1}$ for crops and 41 $gCm^{-2}yr^{-1}$ for grazing reported by Haberl et al. (2007). This reflects a developed-country agro-ecological system where technological advances and high inputs have raised crop yields while overgrazing of livestock is regulated. In comparison, Huang et al. (2018) report for Central Asia a similar mean on-site HANPP grazing density of 47 $gCm^{-2}yr^{-1}$ but 34 percent of grassland NPP compared to 4–19 percent among US Land Resources Regions. Huang et al. (2020) report for Xinjiang an increase from 38 $gCm^{-2}yr^{-1}$ in 1979 to 88 $gCm^{-2}yr^{-1}$ in 2012, reaching 51 percent of NPP (potential).

Comparing our results to other studies highlights that the United States is well-endowed in agro-ecological resources. The mean NPP of 577 $gCm^{-2}yr^{-1}$ in 2012 exceeds the world average of about 400 $gCm^{-2}yr^{-1}$ and NPP per capita of over 14 tonnes Cyr^{-1} in 2012 compares to a global average of 7.86 tonnes Cyr^{-1}. For this reason, the U.S. harvests a lower proportion of NPP than many countries with lower NPP per capita.

Total HANPP(harvest) in the U.S. was calculated here as 716–834 $MTCyr^{-1}$ per year with no clear trend, yet the population of the contiguous U.S. grew from 271 to 312 million over that period implying that HANPP per capita may have declined by 13 percent. This is a gain in agro-ecological efficiency, though without reducing strain on broad ecological limits on NPP such as laid out by Running (2012). These efficiencies were largely gained in the timber and grazing sectors, where total HANPP (harvest) is declining, as compared to crops where ongoing increases in yields are generating increasing HANPP without expanding area planted to crops, which was stable at 130–135 million hectares from 1997 to 2012. These are all positive trends consistent with the land sparing approach to conservation (Phalan et al., 2011). We should note, however, that this study does not measure imports and exports of biomass products which have an important bearing on footprints from a consumption standpoint.

4.2. Limitations of this study of HANPP

This study is of course bound by the data sources upon which it relies, all of which have margins of error. As discussed above, NPP data are modeled rather than measured and errors can be substantial (Heinsch et al., 2006). These uncertainties bear directly on calculations of NPP (ecological). Data used to measure HANPP(harvest) are only as accurate as (1) the yield data provided by USDA on crops and timber harvests and BLM and USFS on Animal Unit Months, and (2) the stoichiometries presented in Tables 1 and 2. For HANPP from livestock grazing on private land, for which no direct sources of data are available, additional uncertainties are embedded in the indirect methodology developed. These include calculating grazed HANPP from the USDA-NASS Cattle Inventory using the assumption that each animal utilizes 12 AUMs and aggregating the grassland/pasture NPP-grazing demand relationship for each LRR.

4.3. Directions for further research

This study provides a solid building-block for further research on consumption of biomass-based products from U.S. ecosystems. Three areas where next steps would be most fruitful are: (1) the cascade of footprints that are initiated by harvesting of crops, timber and grazing lands, (2) the effect of HANPP, combined with this footprint cascade, on ecosystem services, and (3) a consumption-based or embodied HANPP approach that specifically identifies teleconnections between HANPP and eHANPP.

Fig. 10 embeds HANPP within a larger system of production, supply chains, and consumption of biomass-based products. HANPP production is closely tied to blue (withdrawals, especially for irrigation) and green (transpiration from rainfed crops) water, nitrogen and phosphorus footprints, and carbon exchanges with the atmosphere that make this production possible. In this way, HANPP lies at the heart of a modernized ecological footprint indicator that includes not only NPP, but H_2O, N, P and C as well.

Further analysis could test hypotheses that HANPP or its associated footprints are negatively associated with a variety of cultural and regulatory ecosystem services. In the obverse, it can be hypothesized that NPP(ecological) is positively associated with provision of cultural and regulatory ecosystem services.

Finally, integrating the HANPP production data provided here with consumed or embodied HANPP is an important next step in this research program on HANPP in the U.S. Over 90 percent of biomass-based products are traded among counties but are not traded internationally (Rushforth and Ruddell, 2018; Lant et al., 2019). Capturing this dynamic mesoscale trade in HANPP and eHANPP would elucidate the ecological interdependencies among U.S. places and further our understanding of urban metabolism and land-based teleconnections (Seto et al., 2012). Urban areas are dependent upon rural areas for their provisioning ecosystem services and the footprints identified above thus constitute environmental load displacement (Hornburg, 2009). If these displacements place either party at a disadvantage, then the issue of ecologically unequal exchange is raised (Givens et al., 2019). Thus, a spatially and temporally detailed study of integrated ecological footprints exchanged among places through trade in biomass-based products would considerably improve our understanding of socio-ecological metabolism in a manner that has practical implications for environmental justice as well as environmental sustainability.

5. Conclusions

As an ecological indicator, HANPP is straightforward to apply and understand, applicable in a scientifically rigorous, quantitative manner to most land use issues, sensitive to changes and geographical variations in land use intensity, and applicable at scales from a pixel to a planet (Paudel et al. 2021). The data presented above represent the most intensive study of HANPP(harvest) in the United States conducted to date. Based upon reliable sources of publicly available data on specific biomass products at the county scale, it also contributes to a more granular understanding of HANPP as an ecological indicator. Given the positive attributes of HANPP, a continuous monitoring of HANPP, such as on a 5-year basis, would be a valuable assessment constituting a modernized ecological footprint.

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.

Data availability

Data are available at:Mendeley Data, V1, doi: 10.17632/ksyd2cr9cr.2

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