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Allocation of U.S. Biomass Production to Food, Feed, Fiber, Fuel and Exports

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Abstract: This paper analyzes the end uses—food, feed, fiber, fuel, and exports—of biomass production in the U.S. in 1997, 2002, 2007, and 2012. They are also analyzed at the state level in 2012. Biomass production is measured as human appropriation of net primary production (HANPP), an ecological footprint measured as carbon fixed through photosynthesis, derived from data on crop, timber and grazing yields. HANPP was allocated to end uses using publicly available sources from the U.S. Department of Agriculture and internet-based sources publishing data on agricultural trade. HANPP was 717–834 megatons (MT) of carbon per year, which comprised 515–615 MT of crop-based, 105–149 MT timber-based, and 64–76 MT of grazed HANPP. Livestock feed commanded the largest proportion, but decreased from 395 (50%) to 305 MT (42%) of all HANPP and 320 to 240 MT (58–44%) of crop-based HANPP. The proportion allocated to exports was stable at 118–141 MT (17–18%) of total HANPP and 112–133 MT (21–23%) of crop-based HANPP. Biofiber decreased from 141 MT (18%) to 97 MT (13%) of all HANPP. Biofuel increased strongly from 11 MT to 98 MT, from 1% to 14% of all HANPP and 2% to 18% of crop-based HANPP, surpassing food and biofiber by 2012. Direct food commanded 89–105 MT, the lowest proportion at 12–13% of all HANPP, and 17–18% of crop-based HANPP. The highly fertile Midwest and the drought-prone Intermountain West stand out as regions where a very small percentage of biomass is allocated to direct human food. The high proportions of biomass production allocated to nonfood uses is consistent with the tragedy of ecosystem services and commodification of nature frameworks. Reducing these proportions presents opportunities for improving ecosystem services, food security, and human well-being.

Keywords: allocation of biomass; biofuels; commodification of nature; ecosystem services; human appropriation of net primary production; United States

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1. Introduction

1.1. U.S. Biomass Production in the Context of Agricultural Sustainability and Food Security

Production of biomass-based products derived from ecological productivity—crops, timber, and grazing—is a central concern for environmental sustainability because the trade-offs between environmental pressures and the contributions to human well-being from consumption of biomass products vary markedly among product types and their end uses. While the global rate of population growth is slowing, rising incomes have been associated with higher rates of meat consumption, driving estimates that food production will need to rise 60–120% over the period 2005–2050 [1]. Efforts to reach that goal, however, may entail such enormous trade-offs to environmental sustainability that the efficacy of pursuing it must be questioned. Expansion of cropland area to meet growing biomass demands in the late 20th century occurred largely by converting tropical forests that had harbored high rates of biodiversity and contributed greatly to carbon storage and other ecosystem services [2].

Large-scale production of biofuels intensifies these trade-offs, reducing the level of environmental sustainability or human well-being that could otherwise be achieved. Biofuel programs not only increase food prices—to the detriment of human well-being—they drive the conversion of forests to marginal croplands, thus releasing more carbon to the atmosphere than they save by replacing fossil fuels [3,4]. By 2010, 6% of global crop production was allocated to biofuels, a fourfold increase from 2000, yet biofuels provided only 2.7% of transportation fuel [1]. Expansion of global cropland area at the expense of tropical forest can only be avoided if biofuel production is abandoned [5]. While increasing crop yields has been the primary trend sparing land from expanded crop production and thus limiting environmental pressures from growing exponentially [6], climate change is already imposing a cost on crop yields through excessive heat and changes in precipitation patterns [7–9]. Additionally, worsening supply chain disruptions threaten the transportation of food from surplus to deficit regions [10].

Recent overviews of the environmental impacts or footprints of agricultural intensification are revealing steep environmental costs that can only be justified by improving human well-being. In 2010, the global food system was responsible for 5.2 billion tons of greenhouse gas emissions (12% of the total), occupied 12.6 million km^2 of cropland (an area larger than Europe), and dominated all other uses of freshwater (1810 km^3), applied nitrogen (104 million tons) and applied phosphorus (18 million tons) [11]. Animal products, including the feed produced for them, had disproportionate effects, accounting for over 70% of greenhouse gas emissions from food production, making dietary changes the most effective strategy for reducing environmental pressures going forward. Livestock production is the largest use of land globally, accounting for three-fourths of agricultural land area [1], and animal-based products have substantially higher footprints than plant-based products as measured by water, carbon or nutrient footprints. Among animal products, the environmental costs of beef production entail 28 times more land, 11 times more irrigation water, 6 times more reactive nitrogen and 5 times more greenhouse gas emissions than other forms of animal-based calories such as pork, poultry, dairy and eggs [12]. Globally, shifting crop production from feed, fuel and other uses could produce calories sufficient to feed about 4 billion people. More moderately, shifting from beef to dairy and eggs could feed an additional 815 million people and shifting livestock feed from beef to pork and chicken could feed an additional 357 million [1].

There is clearly a trade-off between meeting basic human needs and minimizing the environmental costs of producing biomass products. Because of this, the higher the proportion of biomass production that is devoted to direct food production—the allocation that contributes most to human well-being—the lower the environmental cost of meeting human nutritional needs as populations continue to climb until at least the mid-21st century. It is within this context that we focus here on the production and allocation of biomass products in the United States, a country that enjoys a substantial surplus agricultural production potential relative to its population's needs and therefore plays a large role in mediating the trade-offs between environmental pressures and contributions to human well-being from biomass production globally. In identifying "leverage points for improving global food security and the environment," West et al. [13] showed that 26% of global harvested calories that are not eaten by humans derive from U.S. crop production—19% attributable to maize (corn) alone—a "diet gap" capable of feeding 760 million people. By weight, U.S. crop production circa 2000 was allocated 37% to food compared to a global average of 67%. Measured by calories, the U.S. allocated 27% to food compared to a global average of 55%. Measured as protein, the U.S. food allocation was 14% compared to a global average of 40% [1]. Thus, incremental shifts in biomass production from livestock feed and biofuels toward food, especially in the U.S., may have substantial potential benefits for global food security and environmental sustainability going forward.

While the objective of maximizing human well-being with minimal environmental impact [14] can be defended on normative grounds, production and allocation of biomass production is not necessarily determined by that objective empirically. There is thus a need to identify social scientific concepts that help explain empirical outcomes in biomass production and allocation. Below, we offer two—the tragedy of ecosystem services [15,16] and the commodification of nature [17]—with human appropriation of net primary production (HANPP) as an ecological indicator that is well suited to examine both.

1.2. HANPP and the Tragedy of Ecosystem Services

Net primary production (NPP), the biosphere's capacity to generate ecological energy through net photosynthesis of plant respiration, is an even more fundamental planetary limit [18] than those identified by Rockstrom et al. [19] against which human appropriation must be budgeted. Since Vitousek's et al. [20] seminal paper on "human appropriation of the products of photosynthesis," robust literature [21,22] has developed on the renamed "human appropriation of net primary production" (HANPP), a metric that captures the extent to which human use of land consumes NPP, whether globally or locally (Figure 1). Calculating HANPP facilitates the calculation of NPP (ecological) as NPP remaining after harvest for utilization by undomesticated species. Consistent with the identification of land use intensification as the leading driving force of biodiversity loss by the seminal IPBES study [23], HANPP has been associated with a negative effect on biodiversity [24,25]. As an ecological footprint indicator, HANPP initiates a domino effect of related footprints in the form of blue water (for irrigation), green water (for rain-fed crops), nitrogen and phosphorus (through fertilization) and carbon (through fossil fuel use, methane and nitrous oxide releases from agriculture and net changes in stored carbon inherent in converting land to agricultural uses).

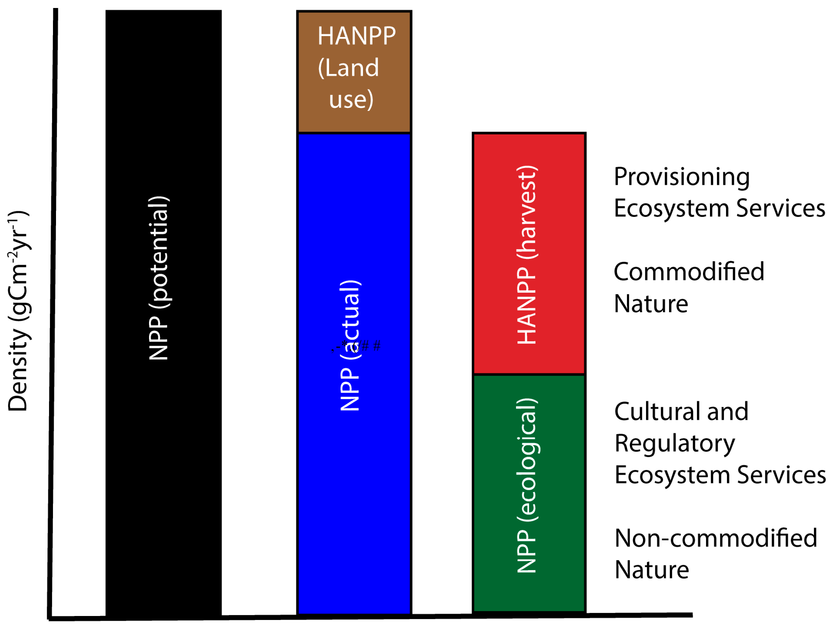

Figure 1. Conceptual definition of HANPP, partitioning NPP into a harvested component and NPP (ecological).

The Millennium Ecosystem Assessment [26] usefully categorized ecosystem services, (often referred to as nature's contributions to people) into provisioning, cultural, and regulatory, with supporting services that make the other three possible. HANPP (harvest) relates to the concept of provisioning ecosystem services (Figure 1), and like the latter, involves trade-offs with cultural and regulating ecosystem services, some of which (soil formation, regulation of the water cycle, pollination, pest control, denitrification) are pre-requisites for harvesting NPP. The ecological intensification paradigm, for example, identifies the regulatory ecosystem services that are limiting factors in agricultural production [27]. HANPP (land use) is human-induced changes in NPP, usually a decrease through urbanization or infrastructure development or various forms of land degradation, such as deforestation, desertification, soil erosion and human-induced fire. HANPP (harvest) is the capture of NPP, which in the U.S. almost always comprises marketed commodities such as crops, livestock and timber. This can be thought of conceptually as an ecological–economic production-possibility frontier for the allocation of NPP (Figure 2), where marketed provisioning services or HANPP (harvest) on the y-axis forms a convex trade-off with non-marketed supporting and regulatory services (x-axis) [28].

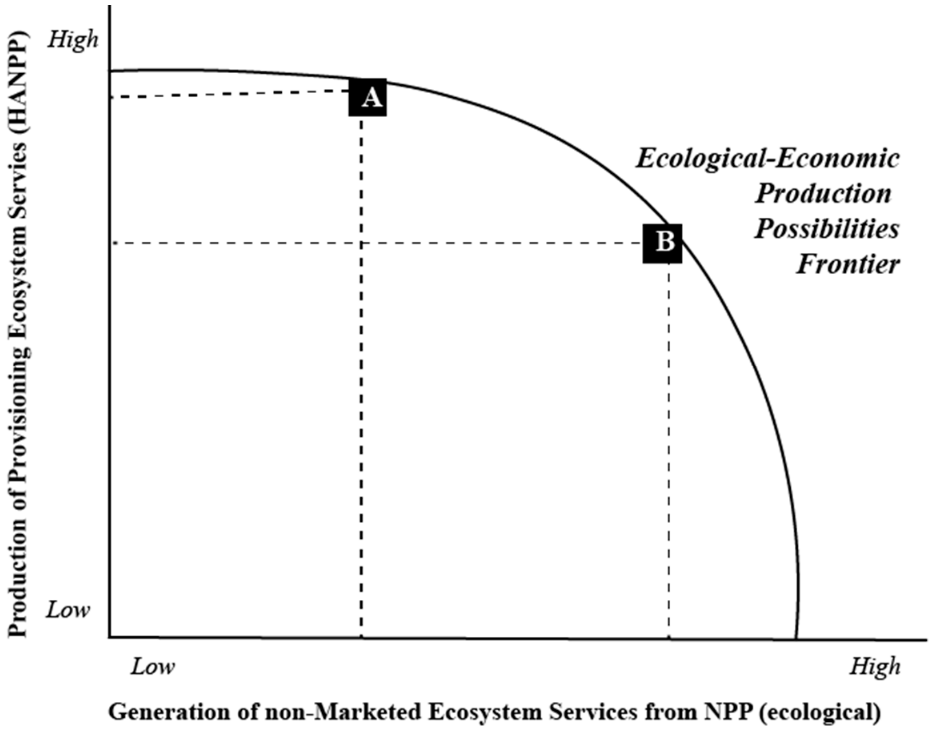

Figure 2. An ecological–economic production-possibility frontier where marketed provisioning ecosystem services trade-off against non-marketed supporting and regulatory ecosystem services (Adapted with permission from [28], 2013, Elsevier).

A "tragedy of ecosystem services" occurs, particularly in the U.S. economic [15] and legal systems [16], because supporting and regulatory ecosystem services are nonexcludable—they benefit all people within a specific geographical area whether they have paid for them or not, generating an incentive to free ride. Most ecosystem services are also nonrival—many can simultaneously receive benefits because it does not require competitive consumption. In contrast, marketed provisioning services (i.e., HANPP) are private goods that are excludable (only those who pay for them benefit) and rival (consumption by one prevents benefits to another). Markets thus reward the production of HANPP in the form of prices paid for biomass-based commodities such as crops, livestock and lumber, but this reward is often missing for nonexcludable ecosystem services that are derived from NPP (ecological). Because of this, without public programs to promote them, private landowners often lack an economic incentive to produce ecosystem services derived from NPP (ecological), and instead devote land, water and other resources to the production of marketable biomass commodities, increasing HANPP and decreasing NPP (ecological). This dynamic is reinforced in U.S. common law, where individuals do not have legal standing to protect the ecosystem services upon which they rely if they are generated by surrounding lands owned by others [16].

Responding to these market signals, private landowners are driven toward point A on the ecological–economic production-possibility frontier (Figure 2), where HANPP is high and NPP (ecological) is low, rather than point B, where HANPP is lower and NPP (ecological) is higher. If the trade-off along the ecological–economic production-possibility frontier is convex, as theory assumes, point B more likely represents optimal ecological–economic performance. Thus, the tragedy of ecosystem services dynamics hypothesizes that HANPP exceeds the level that would maximize human well-being with minimal environmental impact.

1.3. HANPP and the Commodification of Nature

The clear division of ecological productivity, measured as NPP, into a "human-appropriated" portion (HANPP) and NPP "remaining" for nondomestic species (NPP ecological) affords using the HANPP framework to examine the commodification of nature described by critical geographers, political ecologists and others [29]. Haberl et al. [22] refer to HANPP as a measure of the extent to which terrestrial ecosystems have been "colonized" by human activities. Castree [17] details (a) privatization (the assignment of property rights), (b) alienability (the separation of commodities from their sellers), (c) individuation (removal of the commodity from its supporting context), (d) abstraction (individual products as a generic form of the category of commodity to which they belong), (e) valuation (assignment of exchange value or price), and (f) displacement (temporally and spatially) as key elements in the process of commodifying nature. While in subsistence-oriented and traditional agricultural systems, the presence of these six elements is nuanced, in the U.S. context, it is clear that each holds when crops or roundwood are harvested and sold, as well as when pasture is grazed by livestock that are subsequently sold.

The context for commodification also matters, including what aspects of nature are commodified and to what extent. It is important to consider the material and ethical outcomes of commodification of nature as a capital accumulation strategy [17]. Commodity systems and the commodification of nature are processes that fundamentally shape humans' relationships with ecological systems [30]. HANPP as an ecological indicator quantifies and reveals the choices made to commoditize nature, turning ecological productivity into goods for sale in the market in response to market demands, rather than converting it for human food production or leaving it uncommodified to provide public ecological services through NPP (ecological). Furthermore, in quantifying land use choices, HANPP demonstrates the market logic that deprioritizes choices directed at improving human well-being or preserving ecosystem health. Applying and integrating [31] and [32], Ciplet [33] describes how the market system incentivizes exchange value at the expense of use values that would benefit communities and society more broadly. Although commodification is the norm under the current political economic regime of neoliberalism, it is anti-ecological [31,32].

Polanyi [32] theorizes society as moving in a double movement from one in which society is embedded in the market and market logic dominates to one in which society moves away from the idea of a self-regulating market and instead, via the state, subordinates the market to larger societal needs and goals. In fact, both circumstances require state action to produce such very different situations. Disembedding the market from society and giving too much power to the self-regulating market "implies a stark utopia. Such an institution could not exist for any length of time without annihilating the human and natural substance of society" (32:3). HANPP quantifies these choices and facilitates consideration of the material and moral outcomes of the processes driving the appropriation of net primary production. This allows for the identification of issues and opportunities for decommodification [32]. In this framework, ecological productivity represents a supporting ecosystem service that can be commodified to facilitate capitalist accumulation, to various degrees in various geographical and ecological contexts, by converting it to HANPP.

Globally, this is a process with profound effects on the fundamental elements of ecosystems. From 1910 to 2005, HANPP doubled from 6.9 to 14.8 billion tons of carbon per year or from 13% to 25% of global terrestrial NPP [34]. In the process, the global carbon stock was halved, releasing vast quantities of carbon to the atmosphere, with a doubling of the turnover time of the terrestrial carbon pool [35]. Rather than changes in land use areas, it is increases in land use intensity that are the key issue for environmental sustainability [36]. Thus, by rigorously categorizing ecological productivity into appropriated (HANPP) and unappropriated (NPP (ecological)) components, HANPP emerges as a clear and straightforward indicator of the "commodification of nature," especially in the context of agricultural land use and commercial forestry.

1.4. Research Questions and Objectives

This paper builds upon the work of Paudel et al. [37] that quantified human appropriation of net primary production (HANPP) harvested from each U.S. county derived from the production of specific crop, timber and livestock grazing products in the years 1997, 2002, 2007 and 2012. These dates correspond to data available from the U.S. Department of Agriculture that are used to calculate HANPP at the time the paper was written. We here calculate the quantities and proportions of biomass production in the U.S. that are allocated to direct human food, livestock feed, biofiber, biofuel and exports, delineating trends over the period 1997–2012. We focus on the following research questions. (1) How are biomass harvests, measured as HANPP, allocated in the U.S. among diverse end uses: direct food, livestock feed, biofiber, biofuel and exports? (2) How has this changed in the 1997–2012 time frame? (3) How does allocation vary geographically among U.S. states (focusing on data from 2012) to delineate regions where specific allocation issues emerge? (4) How do social dynamics account for the large volumes of less essential or substitutable biomass harvests allocated to nonfood uses, such as biofuel and livestock feed?

2. Materials and Methods

2.1. Sources of HANPP

The three primary means through which humans harvest NPP are crop production, timber cutting, and livestock grazing. Table 1 provides a summary of data on HANPP derived in 1997, 2002, 2007 and 2012 in the U.S. from primary biomass products. Similar data by U.S. state in 2012 are shown in Appendix A. For derivation of these data, see [37].

Table 1. U.S. HANPP in megatons (MT) and as a percentage of total HANPP. These values are derived from specific products in 1997, 2002, 2007, 2012.

Product	1997		2002		2007		2012	
	MT	**%**	**MT**	**%**	**MT**	**%**	**MT**	**%**
Grazing	76	0.097	76	0.106	72	0.086	64	0.089
Timber								
Softwood	79	0.101	72	0.101	73	0.088	41	0.057
Hardwood	69	0.088	55	0.077	76	0.091	64	0.089
Crops								
Corn Grain	201	0.257	192	0.268	279	0.355	229	0.317
Corn Silage	16	0.020	17	0.024	18	0.022	11	0.015
Winter Wheat	53	0.068	32	0.045	42	0.05	45	0.062
Spring Wheat	18	0.023	13	0.018	15	0.018	17	0.024
Soybeans	73	0.093	73	0.102	71	0.085	80	0.111
Alfalfa Hay	50	0.064	45	0.063	45	0.054	33	0.046
Cotton	4	0.005	4	0.006	4	0.005	4	0.006
Sorghum	12	0.015	8	0.011	11	0.013	6	0.008
Minor Crops	128	0.164	128	0.179	128	0.153	128	0.177
Total	781		716		834		722	

Source of data: [37].

2.2. Allocation of HANPP

Methods for determining the proportions of HANPP (harvest) shown in Table 1 and Appendix A that are allocated to food, feed, fiber, fuel and exports are based on data tables provided by the USDA Economic Research Service and other internet-based sources that gather and disseminate agricultural data. The *Feed Grains Data: Yearbook Tables* [38] account for the supply (beginning stocks, production, imports) and disappearance (food, alcohol and industrial use, seed use, feed and residual use) in the U.S. and exports of specific crops (e.g., corn, sorghum, hay) from the U.S. on a quarterly basis. Similar data were obtained from the *Oil Crops Yearbook* [39] for soybeans and other oil seeds. These national-level data were used to calculate proportions of each crop or timber source shown in Table 1 that were allocated to each of these five uses. These data are not broken down by state or county, and thus the proportions calculated are for the entire U.S. and vary by year. Allocation of crops and other products in each state was thus assumed to follow national trends. Additional data on use of corn and sorghum as biofuels were obtained from U.S. Bioenergy Statistics [40]. Data on exports were also obtained from the USDA's industrial U.S. roundwood imports and exports 2006–2018 [41] and U.S. cotton exports 1990–2019 [42]. In addition, we defined HANPP consumed through livestock grazing as being allocated entirely to feed. Corn silage and hay were similarly defined as feed. Timber and cotton production not exported were allocated entirely to fiber.

In addition to the 8 major crops shown in Table 1, we aggregated data for an additional 28 minor crops. Together, these 36 crops cover 99% of U.S. crop acreage. The area devoted to each crop in each state was derived from the USDA NASS cropland data layer (CDL). As CDL coverage for the entire conterminous U.S. began in 2008, we used area in each state in 2012 with an HANPP density of 408 $gcm^{-2}yr^{-1}$, the mean for major crops derived in [37]. Allocations to food, feed, fiber, fuel and exports for minor crops were derived from internet-based sources as shown in Appendix B. These include the USDA publications cited above, the Agricultural Marketing Resource Center, Statista, and Salina Wamucii, an end-to-end platform for sourcing food and agricultural produce from cooperatives.

These data were used to generate a national-level allocation of individual crops, timber sources and livestock grazing for 1997, 2002, 2007 and 2012. These allocations were then multiplied by the mass of HANPP harvested through each product identified in Table 1 to generate national estimates of the volume and proportion of HANPP allocated to each of the five uses considered—food, feed, fiber, fuel and exports—for 1997, 2002, 2007 and 2012. For 2012, they were also multiplied by the HANPP totals in Appendix A to derive state-by-state allocations of biomass production.

3. Results

3.1. National Trends in Allocation of Biomass Products

Table 2 provides the proportions of each major source of HANPP harvested in the U.S. that were allocated to food, livestock feed, biofiber, biofuel and exports in 1997, 2002, 2007 and 2012. For several of these products, such as hardwood and softwood timber, soybeans and wheat, allocations were stable over time, yet other commodities show important shifts in allocation over the study period. The largest shifts are the proportion of cotton exported increasing from 45% to 81% and the proportion of corn grain and sorghum allocated to biofuel increasing from 5% to 40% and 0 to 34%, respectively.

Multiplying the percentage allocations to food, feed, fiber, fuel and exports by HANPP volumes from Table 1 yields mass allocations of biomass to the five uses considered. From 1997 to 2012, the highest proportion of HANPP (harvest) was allocated to livestock feed, though this proportion decreased in the 2002–2012 period from 52% to 42% (Figure 3a, Table S1). Volumetrically, it varied from 396 MT in 1997 to 305 MT in 2012, yet the latter was a year of severe drought, so a trend cannot be determined. Exports were the second-highest allocation throughout, varying from 118 MT (16.5%) to 141 MT (17.6%). The proportion allocated to biofuel grew exponentially from 11 MT (1.4%) in 1997 to 98 MT (13.6%) in 2012 to become the third-highest allocation of HANPP. During the same period, biofiber decreased from 141 MT (18.0%) in 1997 to 97 MT (13.4%) in 2012 as timber harvests declined. Direct food varied only from 95 MT (12.4%) to 105 MT (13.2%) in the four time periods, yet by 2012 commanded the lowest proportion of the five allocations of total HANPP.

Table 2. Proportions of specific major crops, timber products and livestock grazing allocated to food, livestock feed, biofiber, biofuel and exports in 1997, 2002, 2007 and 2012.

Allocation	Food	Feed	Fiber	Fuel	Exports	Food	Feed	Fiber	Fuel	Exports
Source			**1997**					**2002**		
Grazing	0	1	0	0	0	0	1	0	0	0
Timber										
Softwood	0	0	0.904	0	0.096	0	0	0.941	0	0.059
Hardwood	0	0	0.965	0	0.035	0	0	0.954	0	0.046
Crops										
Corn grain	0	0.600	0	0.049	0.204	0.138	0.596	0	0.072	0.194
Corn silage	0	1	0	0	0	0	1	0	0	0
Soybeans	0	0.629	0	0.001	0.182	0.186	0.629	0	0.001	0.185
Winter wheat	0	0.051	0	0	0.430	0.432	0.106	0	0	0.462
Spring wheat	0	0.051	0	0	0.481	0.530	0.050	0	0	0.42
Alfalfa hay	0	1	0	0	0	0	1	0	0	0
Cotton	0	0	0.552	0	0.448	0	0	0.395	0	0.605
Sorghum	0	0.674	0	0	0.268	0.047	0.465	0	0	0.489
Minor crops [1]	0	0.516	0.001	0.005	0.161	0.318	0.516	0.001	0.005	0.161
		2007						**2012**		
Grazing	0	1	0	0	0	0	1	0	0	0
Timber										
Softwood	0	0	0.935	0	0.065	0	0	0.889	0	0.111
Hardwood	0	0	0.952	0	0.048	0	0	0.945	0	0.055
Crops										
Corn grain	0	0.494	0	0.189	0.190	0.115	0.361	0	0.401	0.123
Corn silage	0	1	0	0	0	0	1	0	0	0
Soybeans	0	0.624	0	0.026	0.182	0.150	0.598	0	0.048	0.205
Winter wheat	0	0.097	0	0	0.433	0.420	0.109	0	0	0.471
Spring wheat	1	0	0	0	0.493	0.500	0	0	0	0.5
Alfalfa hay	0	1	0	0	0	0	1	0	0	0
Cotton	0	0	0.194	0	0.806	0	0	0.190	0	0.810
Sorghum	0	0.363	0	0.095	0.492	0.050	0.317	0	0.344	0.289
Minor crops [1]	0.318	1	0.001	0.005	0.161	0.318	0.516	0.001	0.005	0.161

[1] See Appendix B.

For crops, livestock feed commanded the majority of HANPP, 298–320 MT in the 1997–2007 period, but had declined to 240 MT and 43.5% of crop-based HANPP by 2012 (Figure 3b, Table S1). Exports, the second-largest allocation of crops, remained stable at 112 to 133 MT (21.3–22.5%). Allocation of crops to direct food remained stable at 89–105 MT, 17–18% of the total. Biofuel increased from 11 to 98 MT, 1.9% to 17.8% of crop-based HANPP, surpassing food in 2012. Biofiber is a minor use of crop-based HANPP. Thus, the major trend for crops is a shift to biofuels, largely at the expense of livestock feed.

The largest single source of HANPP in the U.S. is corn grain at 191–280 MT (Figure 3c, Table S1), 25–36% of all HANPP, with an increasing trend if the 2012 drought is taken into account (Table 1). It has also seen a large shift in allocation to biofuels, increasing from 10 to 92 MT (5–40%) in the 1997–2012 period. This has come at the expense of exports (declining from 20% to 12%), food (declining from 15% to 12%) and especially livestock feed (declining from 60% to 36%). This reallocation of corn grain, a crop with an enormously high (597 $\mathrm{gcm^{-2}yr^{-1}}$ in 2012) and increasing HANPP density [37], drives a large part of the trends for overall utilization of biomass products in the U.S.

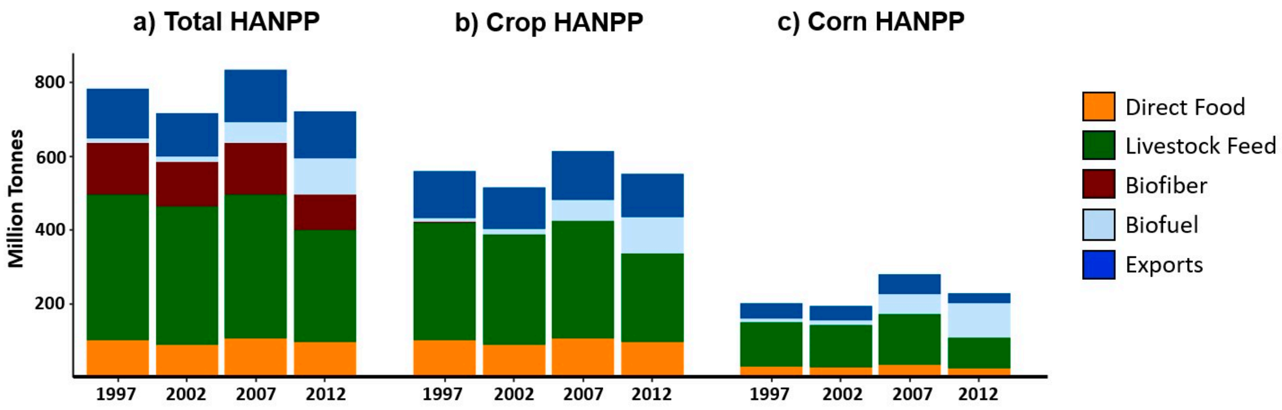

Figure 3. U.S. HANPP allocations in tons in 1997, 2002, 2007 and 2012 allocated to human food, livestock feed, biofiber, biofuel and exports for (**a**–**c**).

3.2. Geographic Patterns among U.S. States

Analyzed only for 2012, allocations of HANPP (harvest) (Figure 4a, Table S2) and crop-based HANPP (Figure 4b, Table S3) show substantial geographical differences among the 48 conterminous U.S. states. Total HANPP, while affected by the area of states, is highest in the Midwestern states, led by Iowa, Illinois, Minnesota and Nebraska at over 40 MT, followed by North Dakota, South Dakota and Kansas at about 30 MT. In contrast, HANPP is less than 4 MT in 10 small New England and Mid-Atlantic states as well as the five arid western states of Arizona, Nevada, New Mexico, Utah and Wyoming.

Allocations of total HANPP among states also show strong regional patterns (Figure 4a, Table S2). Livestock feed, 40.8% of national HANPP, was the leading allocation in 36 of the 48 states led by the same five arid states with 84–96% of HANPP allocated to livestock feed. It is also the leading allocation in all the high-HANPP states of the Midwest identified above. Biofiber, predominantly timber harvests at 14.4% of national HANPP, is the highest allocation of HANPP in 11 states in the northeast, northwest, and southeast, and the majority allocation in five states (Alabama, Georgia, Maine, Oregon, South Carolina).

In only one state (California) is food the highest allocation (29%), while 29 states allocated less than 10% of HANPP to food compared to the national mean of 13.2%. While biofuel was nowhere the leading allocation, five Midwestern states allocated more than one-fourth of HANPP to biofuels, led by Iowa at 30%. North Dakota and Iowa had the highest exports, at nearly 10 MT, and Kansas, exporting 28% of HANPP, yet in no state are exports the leading allocation of HANPP.

Allocation of crop-based HANPP among states also shows clear geographical patterns (Figure 4b, Table S3). In 2012, livestock feed commanded 42%, exports 22%, fuel 20%, food 16% and fiber less than 1% of crop-based HANPP in the U.S. Livestock feed was the leading allocation of crop-based HANPP in 38 states, with eight exceeding 80%, led by arid Nevada and Utah at 98% and 96%, respectively. Exports led allocation of crops for four contiguous south-central states (Arkansas, Kansas, Oklahoma, Texas). Food was the leading allocation of crops in six dispersed states, three where specialty crops are dominant, (California, Georgia, and especially Florida, at 73% of crop-based HANPP) and three states where wheat is dominant (Montana, North Dakota and Washington). Biofuel was not the leading allocation in any state; however, eight Midwestern states plus Texas and Delaware allocated more than 20% of crops to produce biofuel.

The U.S. Midwest, one of the best-endowed agricultural regions in the world, is characterized by high volumes of HANPP allocated predominantly to livestock feed, exports, and increasingly biofuels, with less than 10% allocation to food, except where wheat is dominant. On the most productive agricultural land in the corn belt states of Indiana, Illinois and Iowa, less than 10% of total or crop-based HANPP was allocated to food and 68–74% was allocated to livestock feed or biofuels.

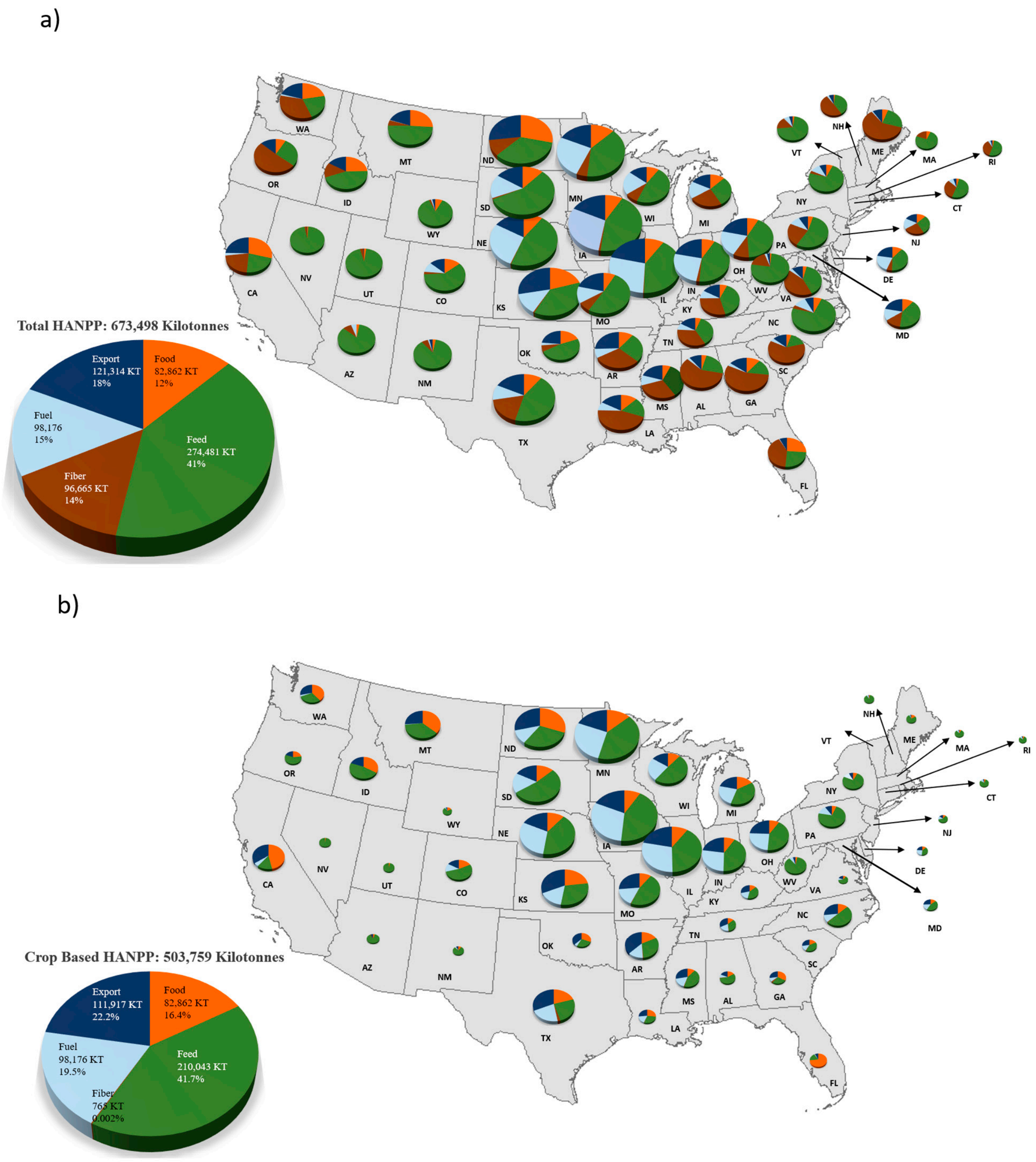

Figure 4. Geographic distribution among the 48 contiguous states in 2012 in (**a**) total HANPP (harvest) and (**b**) crop-based HANPP and the proportions allocated to human food, livestock feed, biofiber, biofuel and exports.

Less crop-intensive states also allocate most HANPP to livestock in the form of grazing or hay, including the arid Intermountain West, where water scarcity has been increasing and irrigation of livestock feed is severely impacting aquatic ecosystems [43]. Only a few states allocate substantial portions of HANPP to food, including important specialty crop areas of Florida and California.

4. Discussion

Over the 1997–2012 study period, the proportion of U.S. HANPP allocated to food production is shown here to be consistently low: 12–13% of all HANPP and 17–18% for all crops (compared to a global average of 67%). The proportion allocated to livestock feed was high (44% declining to 40%) and the proportion allocated to biofuels was rapidly increasing (from 1.4 to 14% of all HANPP, 1.9 to 18% of all crops), to exceed food by 2012.

We interpret these U.S. trends in the utilization of ecological productivity, which diverges considerably from global trends, attributable to a critical geographical factor (the U.S. is relatively well endowed agroecologically compared to most countries) while examining two social scientific explanations of how that favorable endowment is employed (the tragedy of ecosystem services and the commodification of nature).

The U.S population enjoys net primary production, the NPP in HANPP, per capita of over 14 tons of carbon per year (in 2012) compared to a global average of 8 tons [37]. Moreover, this NPP is more accessible than in many countries because none of it is in the form of tropical forest [18]. These favorable circumstances provide the U.S. with surplus potentially harvestable ecological productivity compared to countries that must press hard against their national resource base to meet domestic food demands. Compared to the U.S., many countries evidence HANPP as a high proportion of NPP, most HANPP being allocated to direct food, or substantial net imports of food that access ecological productivity beyond a country's borders. Given this high potential, the U.S. is harvesting NPP whenever and wherever there is the potential to convert it into a biomass commodity for which sufficient demand can be generated, even as demand among products shifts over time (e.g., biofuels partially replacing biofiber and livestock feed).

Despite trade-offs in non-provisioning ecosystem services, the rapid rise of biofuels in the 21st century illustrates the drive to pursue conversion of potentially harvestable NPP into a marketable commodity, even as demand for other bulk biomass-based commodities declines. In 2012, the 40% of corn allocated to ethanol produced about 4% of the energy in liquid fuels used for transportation (6% of volume at 65% of energy density) from about 2.2% of the NPP of the U.S. While technological progress for development of cellulosic biofuels has stagnated [44], there is a possibility that ever-larger proportions of NPP could be converted to transportation fuel. Over half of the NPP of the U.S. would be required to meet all liquid transportation fuel demands.

As a key ecological footprint metric, measuring HANPP empirically illuminates how the tragedy of ecosystem services and the commodification of nature dynamics drive a high rate of U.S. biomass-based commodity production. Especially in the uniquely valuable agricultural region of the U.S. Midwest, HANPP (harvest) is dominated by products that contribute less directly to human well-being or are more substitutable than direct food, whether consumed domestically or through exports to a world that is struggling to meet food demands in the face of rising incomes, supply chain insecurity and climate change. The tragedy of ecosystem services provides an explanation for why the trade-offs to nonmarketed cultural, regulatory, and supporting ecosystem services are largely ignored when provisioning ecosystem services (e.g., HANPP) are expanded. This is also the case when an opportunity to reduce HANPP, and thus improve those ecosystem services, is presented through technological changes, such as the reduced need for paper, changing consumer preferences or increases in crop yields borne of biotechnology. These trade-offs are ineffectively communicated through market signals that largely determine rural land uses in the U.S. [15].

The commodification-of-nature framework clearly and cleanly demarcates net primary production into a portion that facilitates capitalist accumulation, HANPP, and a portion that does not—NPP (ecological). The U.S. agroecological system engages a favorable endowment of ecological productivity per capita by pushing the boundary of the appropriation of NPP through commodification wherever this is practical and potentially profitable. For example, high per capita consumption of livestock-based products, especially beef, that convert NPP into usable food very inefficiently [12] generates demand for the conversion of NPP into HANPP. Biofuels do this in an even more direct and potentially limitless manner while driving up food prices [45]. From a public policy perspective, these circumstances are reinforced by subsidization of crop production in the form of price supports and biofuel programs that set production targets, provide subsidies and raise protectionist barriers against imports, such as of Brazilian ethanol derived from sugarcane. While HANPP allows us to examine the commodification of nature and change over time, these outcomes are not necessarily "natural". The state plays a role in creating policies that facilitate the commodification of nature to the detriment of ecosystem health and human well-being. This means that the possibility exists that the state could play a different role.

The analysis above suggests that a shift to ecosystem services-oriented subsidies would instead counteract the tragedy of ecosystem services and the commodification of nature and result in reduced HANPP and increased NPP (ecological). The Conservation Reserve Program is an example: it had an enrollment of 11.9 to 14.9 million hectares during the 1997–2012 study period, but only 8.9 million in 2020, the lowest total since the initial ramp-up of the program in the late 1980s [46]. Going forward, financial credits for increasing the terrestrial carbon pool to offset greenhouse gas emissions would simultaneously improve ecosystem service generation in agricultural and forestry landscapes by directly investing in NPP (ecological).

This study provides a solid building block for further research on the effects of HANPP on ecosystem services and the impact consumption of biomass-based products has upon them. Further analysis could test hypotheses that HANPP is negatively associated with a variety of cultural (e.g., recreational visitation) and regulatory ecosystem services (e.g., carbon storage, denitrification, hydrological moderation, soil formation, pollinator habitat), as well as biodiversity. By teleconnection through supply chain sources of production of food, feed, fiber, fuel and biomass exports with locations where they are consumed, it is possible to measure the displacement of environmental loads [47] associated with consumption of biomass-based products such as biofuels or beef. Such an analysis raises further issues of distributive environmental justice best captured by the concept of ecologically unequal exchange [48].

5. Conclusions

Humans cannot survive without consuming biomass-based products, especially in the form of plant-based food, and a modest allocation for animal-based food and biofiber can improve human well-being. Yet the largest allocations of biomass in the U.S., especially from the enormously fertile Midwest and the increasingly drought-stricken Intermountain West, are for livestock feed and biofuels, where commodification of NPP is an option selected when other options are possible. Options for utilizing the country's abundant ecological productivity include fostering NPP (ecological) for the maintenance of biodiversity and delivery of supporting, cultural, and regulatory ecosystem services, including those that maintain future agricultural productivity through ecological intensification. Options for the delivery of food include dietary shifts and increasing food exports to other nations where it would increase human well-being. Options for energy include reducing pressure on ecological productivity by forgoing the subsidization and tariff protection of biofuel programs.

Overcoming the tragedy of ecosystem services and slowing or reversing the commodification of nature—by reducing human appropriation of NPP for biofuels and continuing the downward trend in allocation of NPP to livestock feed and biofiber—thus represents the best opportunity to improve food security and maintain the ecosystem services that underlie agricultural and environmental sustainability. Consistently with the conclusions of other prominent studies [1,11,13], such changes in allocation of U.S. agroecological resources would have beneficial effects for human well-being, both domestically and, if reallocated to exports, globally. Bringing to bear HANPP as an ecological indicator in combination with the tragedy of ecosystem services and commodification of nature frameworks clarifies the socioecological dynamics that are generating suboptimal empirical outcomes in the allocation of agroecological resources in the U.S.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land12030695/s1. Table S1. Tons and proportions of total HANPP and HANPP from crops in 1997, 2002, 2007 and 2012 derived from livestock grazing, timber, and crops allocated to human food, livestock feed, biofiber, biofuel and exports for (a) all HANPP, (b) all crops, and (c) corn grain. These data are graphed in Figure 3. Table S2. Mass (in kilotons) and proportions of total HANPP allocated to food, feed, fiber fuel and exports by U.S. state in 2012. The item with the highest proportion in each state is italicized. These data are mapped in Figure 4a. Table S3. Mass (in kilotons) and proportions of crop-based HANPP allocated to food, feed, fiber fuel and exports by U.S. state in 2012. The item with the highest proportion in each state is italicized. These data are mapped in Figure 4b.

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Appendix A

Table A1. HANPP in megatons (MT) in 48 contiguous states in 2012 for specific products. Source of data: [37].

State	Grazing	Soft Wood	Hard Wood	Corn Grain	Corn Silage	Soybean	Winter Wheat	Spring Wheat	Alfalfa Hay	Cotton	Sorghum	Minor Crops	Total
Arizona	1	0.3	0	0	0	0	0	0	1.7	0.1	0	1.6	4.7
Arkansas	1	3.2	2.1	2.6	0	3.6	0.7	0	0	0.2	0.3	2.9	16.9
California	2	3.4	0	0.7	2	0	0.7	0	0	0.1	0	11.6	20.7
Colorado	2	0	0.1	2.8	0	0	1.9	0	1.8	0	0.1	6	14.9
Connecticut	0	0	0.1	0.1	0	0	0	0	0	0	0	0.2	0.5
Delaware	0	0	0	0.5	0	0.2	0	0	0	0	0	0.1	0.9
Florida	2	3.3	1.2	0.1	0	0	0	0	0	0	0	4.3	10.8
Georgia	1	7	2.9	1.2	0	0.2	0.3	0	0	0.7	0	4.2	17.8
Idaho	1	2.1	0	0	0	0	1.7	1.1	3.3	0	0	3.6	13.1
Illinois	1	0	0.1	27.6	0	10.2	1.1	0	0.7	0	0	0.1	40.8
Indiana	1	0	0.3	12.8	0	5.9	0.5	0	0.5	0	0	0.2	21.1
Iowa	1	0	0.5	40.2	0.9	11.2	0	0	1.7	0	0	1.6	57
Kansas	3	0	0.2	8	0	2.3	10.8	0	1.3	0	1.9	5.7	33.7
Kentucky	2	0.1	3.3	2.2	0	1.5	0.8	0	0.4	0	0	0	10.5
Louisiana	1	3.8	2.2	2	0	1.4	0	0	0	0.1	0.3	3.4	13.6
Maine	0	1.9	0	0.1	0	0	0	0	0	0	0	0.9	2.9
Maryland	0.2	0.1	0.4	1	0	0.5	0.3	0	0	0	0	0.7	3.2
Massachusetts	0	0.1	0	0.1	0	0	0	0	0	0	0	0.4	0.5
Michigan	0	0.8	3.2	6.7	0	2.3	1.2	0	0	0	0	2.2	16.7
Minnesota	0	0.6	1.8	29.4	1.2	8.1	0	2.1	2	0	0	3.3	48.8
Mississippi	1	3.7	0.3	2.8	0	2.3	0.5	0	0	0.2	0.1	1.8	12.9
Missouri	3	0.1	1.2	5.3	0	4.2	1.1	0	0.1	0.2	0.1	2.3	17.2
Montana	4	0.9	0	0.1	0.2	0	2.4	2.7	2.4	0	0	8.5	21.4
Nebraska	3	0	0.1	27.7	0	5.5	1.5	0	1.9	0	0.1	2.4	42.1
Nevada	1	0	0	0	0	0	0	0	0.8	0	0	0.2	1.9
New Hampshire	0	0.3	0.1	0	0	0	0	0	0	0	0	0.3	0.7
New Jersey	0	0	0.1	0.2	0	0.1	0	0	0	0	0	0.4	1
New Mexico	2	0.3	0	0.1	0.3	0	0	0	0.8	0	0	1.3	5.3
New York	0	0.3	0	2	1.5	0.4	0.1	0	0.7	0	0	4.7	9.9
North Carolina	0.5	4	0.2	2.1	0	1.7	1.2	0	0	0.3	0	3.9	13.4
North Dakota	2.4	0	0	9.1	0.4	4.3	1.2	7.3	1.5	0	0	10.3	37.4
Ohio	1.1	0.1	1.8	9.4	0	5.5	0.9	0	0.4	0	0	0.3	19.4
Oklahoma	3.5	0.4	0.5	0.7	0	0.1	4.4	0	0.4	0	0.1	1.9	11.9
Oregon	1	6.5	0.4	0	0	0	1.5	0.1	1.3	0	0	3.6	14.5
Pennsylvania	0.1	0.2	2.8	2.8	1.5	0.7	0.2	0	0.8	0	0	5.1	14.2
Rhode Island	0	0	0	0	0	0	0	0	0	0	0	0	0.1
South Carolina	0.6	4	2.3	0.8	0	0.3	0.3	0	0	0.1	0	1.3	9.8
South Dakota	2.6	0.2	0	11.5	0	3.8	1.6	1.2	1.8	0	0.1	8	30.8

Table A1. *Cont.*

State	Grazing	Soft Wood	Hard Wood	Corn Grain	Corn Silage	Soybean	Winter Wheat	Spring Wheat	Alfalfa Hay	Cotton	Sorghum	Minor Crops	Total
Tennessee	2.1	0.7	2.9	1.7	0	1.2	0.6	0	0	0.2	0	0.1	9.5
Texas	7.8	3	1.6	4.1	0	0.1	2.7	0	0	1.1	2.6	5.8	28.6
Utah	1.2	0.1	0	0	0	0	0	0	1.6	0	0	0.7	3.7
Vermont	0	0.3	0	0	0	0	0	0	0	0	0	1	1.5
Virginia	1.9	2.1	2.9	0.7	0	0.5	0.4	0	0.1	0	0	1.8	10.4
Washington	0.8	5.3	0.4	0.5	0	0	3.3	0.8	1.5	0	0	4.8	17.4
West Virginia	0.8	0.1	0.3	0.1	0	0	0	0	0	0	0	0.6	1.8
Wisconsin	0.6	0.6	0.9	8.5	2.8	1.9	1.5	0	2.2	0	0	1.3	19.3
Wyoming	2.1	0.1	0	0.1	0	0	0.1	0	1.1	0	0	0.7	4.1
Total	64.4	64.5	40.8	229.3	10.7	80.5	44.7	15.3	32.9	3.6	5.5	128.2	722.2

Source of data: [37].

Appendix B

Table A2. Proportion of HANPP from minor crops allocated to food, livestock feed, biofiber, biofuel and exports in 2012. Together with major crops, these sum to 99% of U.S. cropland area in 2012.

Minor Crop	Area (km^2)	Food	Feed	Fiber	Fuel	Exports	Reference
Non-alfalfa hay	96,646	0	1	0	0	0	Same as alfalfa
W.Wheat-Soybeans	21,493	0.210	0.310	0	0.024	0.456	Mean of two crops
Barley	11,543	0.650	0.200	0	0	0.150	[49]
Rice	10,812	0.500	0	0	0	0.500	[50]
Dry Beans	7055	0.667	0	0	0	0.333	[51]
Canola	6883	0.40	0	0	0	0.600	[39]
Peanuts	6708	0.830	0	0	0	0.170	[39]
Sunflower	6455	0.860	0	0	0	0.140	[39]
Oats	5201	0.316	0.670	0	0	0.014	[52]
Sugar beets	5011	1	0	0	0	0	[49]
Almonds	4676	0.300	0	0	0	0.700	[53]
Grapes	4600	0.975	0	0	0	0.025	[54]
Potatoes	4385	0.850	0	0	0	0.150	[55]
Sugarcane	4155	1	0	0	0	0	[54]
Oranges	4125	0.924	0	0	0	0.076	[56]
Peas	3133	1	0	0	0	0	[57]
Millet	1852	0	0.874	0	0	0.126	[54]
Rye	1835	0	1	0	0	0	[58]
Apples	1798	0.700	0	0	0	0.300	[59]
W.Wheat-Corn	1625	0.268	0.235	0	0.2	0.297	Mean of two crops
Pecans	1613	0.700	0	0	0	0.300	[60]
Lentils	1572	0.380	0	0	0	0.620	[57]
W.Wheat-Sorghum	1562	0.235	213	0	0.172	0.380	Mean of two crops
Tomatoes	1431	0.840	0	0	0	0.160	[61]
Walnuts	1382	0.300	0	0	0	0.700	[62]
W.Wheat-Cotton	1312	0.210	0.055	0.095	0	0.640	Mean of two crops
Sweet Corn	1220	0.960	0	0	0	0.04	[54]
Flaxseed	1150	0	0.766	0	0	0.234	[39]
Total	221,233	0.318	0.516	0.001	0.005	0.161	

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