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Bioenergy Potential of the United States Constrained by Satellite Observations of Existing Productivity

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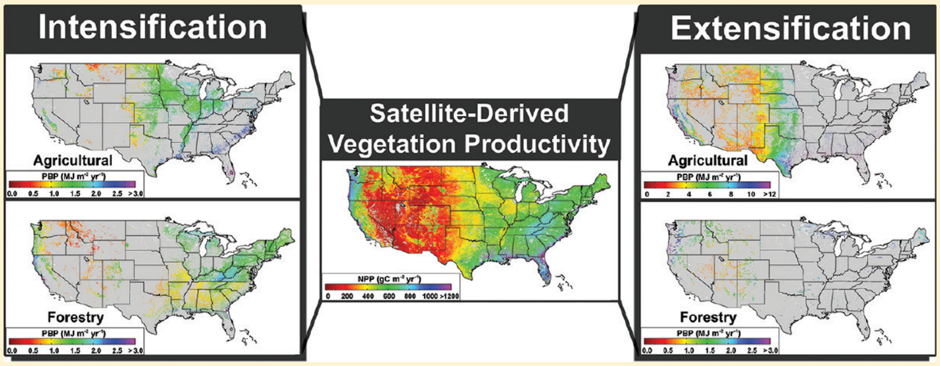
S *Supporting Information*



ABSTRACT: United States (U.S.) energy policy includes an expectation that bioenergy will be a substantial future energy source. In particular, the Energy Independence and Security Act of 2007 (EISA) aims to increase annual U.S. biofuel (secondary bioenergy) production by more than 3-fold, from 40 to 136 billion liters ethanol, which implies an even larger increase in biomass demand (primary energy), from roughly 2.9 to 7.4 EJ yr^{-1}. However, our understanding of many of the factors used to establish such energy targets is far from complete, introducing signifcant uncertainty into the feasibility of current estimates of bioenergy potential. Here, we utilized satellite-derived net primary productivity (NPP) data—measured for every 1 km^2 of the 7.2 million km^2 of vegetated land in the conterminous U.S.—to estimate primary bioenergy potential (PBP). Our results indicate that PBP of the conterminous U.S. ranges from roughly 5.9 to 22.2 EJ yr^{-1}, depending on land use. The low end of this range represents the potential when harvesting residues only, while the high end would require an annual biomass harvest over an area more than three times current U.S. agricultural extent. While EISA energy targets are theoretically achievable, we show that meeting these targets utilizing current technology would require either an 80% displacement of current crop harvest or the conversion of 60% of rangeland productivity. Accordingly, realistically constrained estimates of bioenergy potential are critical for effective incorporation of bioenergy into the national energy portfolio.

INTRODUCTION

Concerns about energy security and rising greenhouse gas (GHG) emissions continue to stimulate an unprecedented increase in the utilization of biomass as a source of renewable energy (bioenergy).[1] The United States (U.S.) leads this current bioenergy trend, producing 40 billion liters of ethanol (secondary bioenergy) in 2009, approximately half of the world's total ethanol supply.[1] Current renewable energy policy, namely the Energy Independence and Security Act of 2007 (EISA), has established even more ambitious secondary bioenergy targets for the U.S., stipulating a domestic ethanol production of 136 billion liters by 2022.[2]

Yet, these bioenergy targets are largely derived from highly uncertain estimates of future bioenergy potential, commonly based on implicit assumptions regarding relatively unresolved, complex factors such as yield potential, land availability, and energy conversion technology.[3−7] In fact, evidence indicates that previous evaluations have generally overestimated bioenergy potential, suggesting that bioenergy policy targets based on these previous evaluations could be unrealistic.[3−7] For instance, a number of previous evaluations have simply applied crop-specific maximum yield values across all land considered available for bioenergy cultivation.[8−10] Applying maximum yield values across spatial scales without adequate consideration of biophysical factors (e.g., temperature and precipitation), has been documented to overestimate bioenergy potentials by more than 100% in particular cases.[7] Despite these findings, policy-oriented studies that utilize this methodology are still being published, and have

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the potential to adversely influence the success of energy policy.[8−10]

Constraining estimates of primary bioenergy potential (PBP) represents a significant step forward in our ability to define realistic future energy targets. Here, we utilized 1-km^2 net primary productivity (NPP) values—estimated from satellite data [Earth Observing System (EOS), Moderate Resolution Imaging Spectroradiometer (MODIS) data]—as an upper-envelope constraint on PBP of the conterminous U.S.[11−13] MODIS NPP integrates global climatic data (e.g., temperature and precipitation), as well as remotely sensed vegetation dynamics [e.g., Fraction of Photosynthetically Active Radiation (FPAR) and Leaf Area Index (LAI) data], providing quantitative estimates of current terrestrial biomass growth capacity for every 1 km^2 of vegetated land.[11−13] This approach differs from multiple previous efforts[8−10] in that the utilization of satellite-derived spatial data removes the need for extrapolation of plot-level bioenergy yield potentials.

NPP is influenced by a number of factors including vegetation type, soil type, climate, and human management. However, it has been shown that over relatively large areas, average agricultural productivity is significantly lower than that of the natural vegetation it replaced.[14−17] Even when considering human management factors that can offset or reverse this trend (e.g., fertilization and especially irrigation), the conversion of natural vegetation to agriculture generally elicits relative declines in productivity.[14−17] For example, Haberl et al.[17] documented that, despite widespread utilization of the most advanced human management practices, agricultural productivity across the U.S. was still generally less than the natural potential. Since bioenergy cultivation is subject to similar agriculturally based human management practices, we applied this logic and utilized MODIS NPP as an upper-envelope constraint on yield potential.[5,6] We also accounted for currently unavailable resources by applying constraints that included current rates of harvest (i.e., agricultural and forestry harvest) and unavailable landcover (i.e., protected areas, pastureland, wetland, and low productivity regions). Finally, we compared our resulting PBP estimates with current U.S. secondary bioenergy targets by applying well-known secondary-to-primary bioenergy conversion factors. Ultimately, our goal was to constrain estimates of PBP for the conterminous U.S. utilizing MODIS NPP as the most geographically explicit measure of the current terrestrial growth capacity in an effort to evaluate the feasibility of current U.S. bioenergy policy.

■ MATERIALS AND METHODS

Landcover Classification. We utilized a composite 1-km^2 landcover classification scheme for the conterminous U.S. that combined National Landcover[18] and Global Human Footprint[18] data (Figure 1). Relevant landcover classes were separated into “managed” or “remote” utilizing a human footprint index of 10%, meaning remote lands represent the 10% most inaccessible land while managed lands represent the 90% most accessible land in the U.S.[19] We also defined “unavailable land” to include protected areas, pastureland, wetland, and low productivity regions (Supporting Information Figure S1). Protected areas were defined as land under strict protection including nature reserves and national parks, which we considered unavailable for bioenergy production based on current policy.[20] Pasturelands were defined as areas specifically managed for livestock grazing, while wetlands were defined as areas periodically saturated or covered with water, according to National Landcover Data.[18] We classified pastures and wetlands as unavailable due to the many negative trade-offs associated with conversion of these landcover types.[3−6] Finally, low-productivity regions were defined as areas with annual productivity less than 150 gC m^{-2} yr^{-1}, the threshold at which harvest energy requirements exceed potential energy output.[21]

MODIS GPP/NPP Algorithm. We utilized the MODIS GPP/NPP algorithm[11−13] to calculate 1-km^2 MODIS NPP from 2000 through 2006 for the conterminous U.S. (Figure 1). Biome-specific vegetation parameters were mapped utilizing 11 biome types that corresponded well with our NLCD-based landcover classification.[11−13] Remotely sensed vegetation property dynamic inputs included collection 5 (C5), 8-day composite, 1-km^2 Fraction of Photosynthetically Active Radiation (FPAR) and Leaf Area Index (LAI) data collected from the MODIS sensor.[11−13] Accompanying quality assessment fields were utilized to fill data gaps in the 8-day temporal MODIS FPAR/LAI caused by cloudiness.[11−13] Daily data obtained from the Data Assimilation Office (DAO) served as the meteorological input required to drive the algorithm.[11−13] A more detailed description and validation of the MODIS GPP/NPP algorithm can be found in Zhao et al.[13]

Agricultural and Forestry Harvest. Agricultural and forestry harvest was assumed to occur only on cropland and managed forestlands, respectively (Figure 1). We partitioned harvest into four relevant harvest pools: (1) total harvest (H_{TL}) or the total amount of nonliving biomass following harvest; (2) recovered harvest (H_{RC}) or the fraction of H_{TL} recovered during harvest; (3) harvest losses (H_{LS}) or the fraction of H_{TL} remaining in the field following harvest; or (4) harvest residues (H_{RS}) or the fraction of H_{LS} recoverable without impacting natural nutrient cycling (primary residues, e.g., felled branches), plus the fraction of H_{RC} that is ultimately remaining following processing (secondary residues, e.g., sawdust). Harvest pools were estimated regionally (SI Figure S2) at a spatial resolution of 1-km^2 according to eqs 1−4

$$H_{TL} = \sum_{i=1}^{n} NPP_i \times r_{ag} \times r_{hv} \tag{1}$$

where r_{ag} and r_{hv} represent literature-derived aboveground NPP and total harvest ratios, respectively. For agricultural harvest, we utilized aboveground NPP (r_{ag}) and total harvest (r_{hv}) ratios of 0.83 (range: 0.80−0.85) and 1.00 (range: 1.00−1.00), respectively (SI Table S1). These values represent the average for the three dominant U.S. crop types (i.e., maize, soybean, and wheat), which account for roughly 70% of total agricultural area.[22−24] Due to substantial regional variability regarding forest C allocation and harvest rates, r_{ag} and r_{hv} were estimated regionally (SI Figure S2) according to literature-derived aboveground NPP ratios[25] and average harvest volume data[26] (SI Table S2). H_{TL} was calculated as the sum of all vegetated pixels (n). H_{RC}, H_{LS}, and H_{RS} were estimated as proportional to H_{TL} according to eqs 2−4

$$H_{RC} = \sum_{i=1}^{n} (H_{TL_i} \times r_{rc} \times (1 - r_{rs2})) \tag{2}$$

$$H_{LS} = \sum_{i=1}^{n} (H_{TL_i} \times (1 - r_{rc}) \times (1 - r_{rs1})) \tag{3}$$

$$H_{RS} = \sum_{i=1}^{n} (H_{TL_i} \times (1 - r_{rc}) \times r_{rs1} + H_{TL_i} \times r_{rc} \times r_{rs2}) \tag{4}$$

where r_{rc}, r_{rs1}, and r_{rs2} represent literature-derived ratios describing H_{TL} recovered, H_{LS} recoverable without impacting nutrient cycling

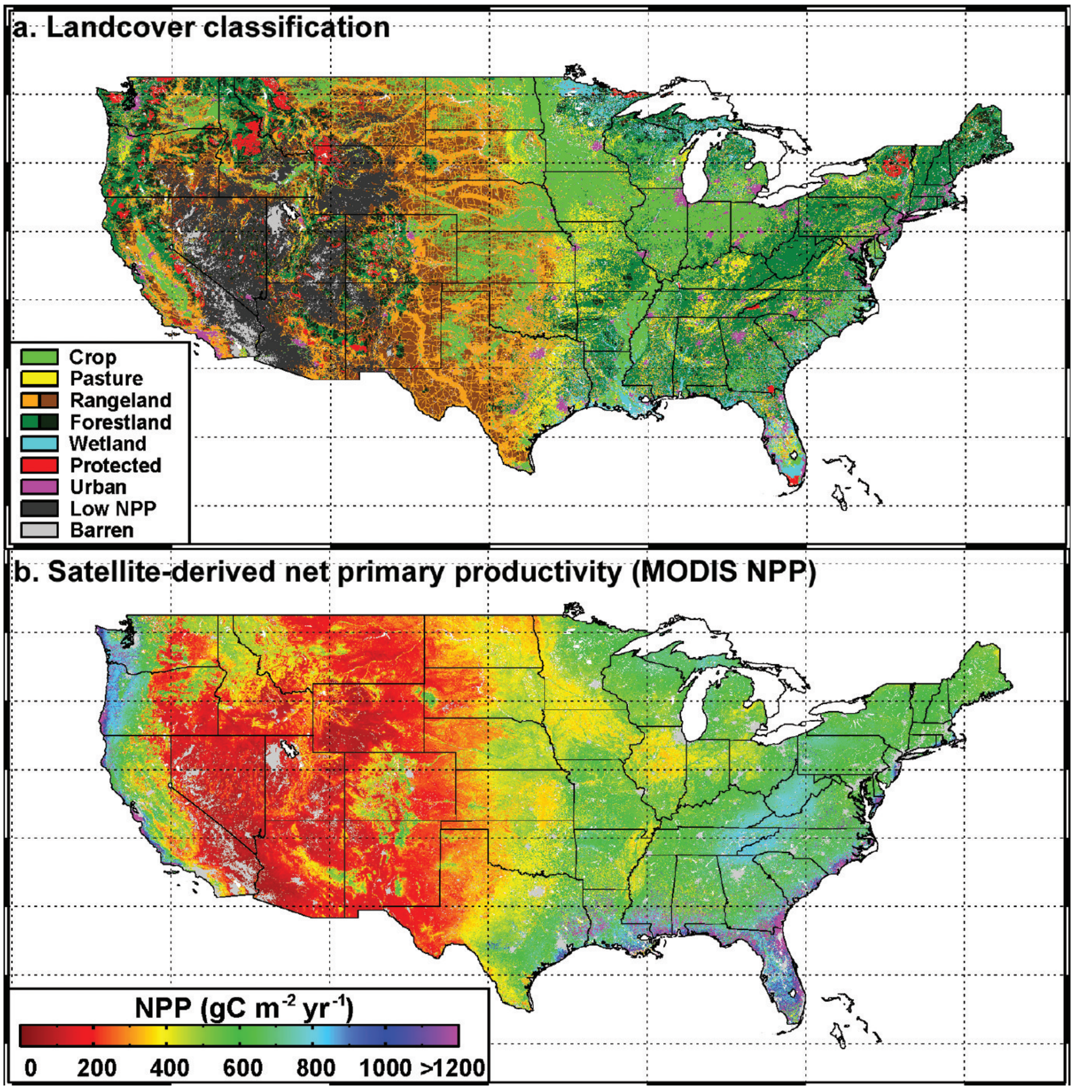

Figure 1. Spatially explicit landcover classification and associated net primary productivity of the conterminous United States. (a) Landcover classification. Classes represent the composite of National Landcover Data,[18] Global Human Footprint,[19] and World Database on Protected Areas[20] data sets. For range and forest land, light colors represent managed land while dark colors represent remote land. Low-productivity (Low NPP) landcover was assigned according to a productivity threshold of 150 g C m^{-2} yr^{-1} utilizing MODIS NPP data.[11−13] (b) Satellite-derived net primary productivity (MODIS NPP). Estimated from the MODIS GPP/NPP algorithm from 2000 to 2006.[11−13]

(primary residuals), and H_{RS} available following harvest processing (secondary residuals), respectively. For agricultural harvest, we utilize an agricultural harvest recovery ratio (r_{rc}) of 0.50 (range: 0.40–0.60)[27] and a secondary residue ratio (r_{rs2}) of 0.10 (range: 0.05–0.15)[27] resulting in a final ratio of yield to aboveground biomass of 0.45 (range: 0.38–0.52), which is consistent with values reported for the three dominant U.S. crop types (SI Table S1).[22,23] For forest harvest, r_{rc} and r_{rs2} were estimated to be 0.85 (range: 0.75–0.95) and 0.40 (range: 0.30–0.50), respectively (SI Table S1).[16,27] These values represent the average for North American coniferous and deciduous species.[16,27] Finally, we utilized an average primary field residual recovery rate (r_{rs1}) of 0.30 (range: 0.25–0.35) for both agricultural and forestry harvest (SI Table S1).[27,28] A summary of the calculated agricultural and forestry harvest pools for the conterminous U.S. are presented by region in SI Table S3. Additionally, a spatial representation of current total harvest (H_{TL}) is shown in SI Figure S3.

Maximum Sustainable Harvest. Maximum sustainable harvest (MSH_{TL}, MSH_{RC}, MSH_{LS}, MSH_{RS}) was calculated utilizing eqs 1–4, by simply replacing the current harvest ratio (r_{hv}) with a literature-derived MSH ratio (r_{msh}) (eq 1). For agricultural systems, r_{msh} equaled r_{hv} which equaled 1.00 (range 1.00–1.00), under the assumption that all aboveground biomass is typically destroyed during harvest and current harvest recovery rates are already maximized in the U.S. (SI Table S1).[16,27] It is important to note that we do not consider the potential to increase productivity on current agricultural land up to that of the natural vegetation replaced.[29,30] For forest systems, a r_{msh} of 0.20 (range: 0.15–0.25) was utilized based on current forestry harvest trends (SI Table S1).[16,27] We utilize a maximum sustainable forest harvest value consistent with the highest current global forestry harvest rates,[16,27] which results in a near doubling of current average U.S. forest harvest (SI Table S3). Values for maximum sustainable forest harvest could increase in the future if natural forests are replaced with high yielding plantations; however, we consider this potential outside the scope of this analysis.

Primary Bioenergy Potential. We calculated PBP based on the assumption that biomass available for energy production could be derived from either intensifying harvest on currently harvested land (intensification) or expanding harvest to currently available nonharvested land (extensification) (Figure 2).

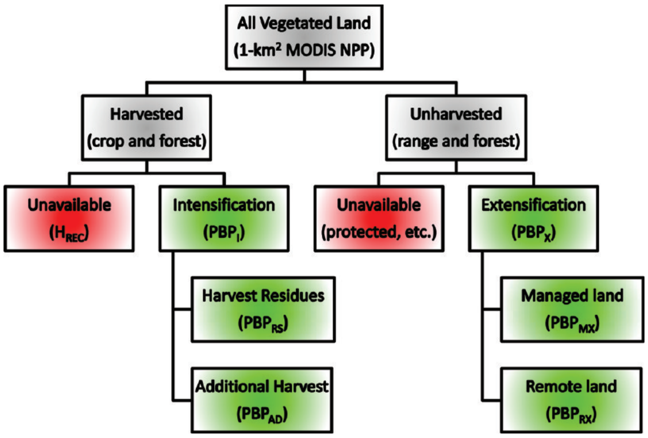

Figure 2. Flow diagram for the quantification of landcover and primary bioenergy potential (PBP) pools. PBP pools include extensification (PBP_X) divided between managed land (PBP_{MX}) and remote land (PBP_{RX}) extensification, and intensification (PBP_I) divided between residual (PBP_{RS}) and additional (PBP_{AD}) harvest. Unavailable resources were defined to include current agricultural and forestry harvest (H_{RC}) as well as protected areas, wetlands, pasturelands, and low productivity regions. Green indicates PBP pools while red indicates unavailable pools.

Intensification (PBP_I) was divided into two pools, PBP of current harvest residuals (PBP_{RS}) and PBP of maximum additional harvest on currently harvested land (PBP_{AD}), and calculated by summing over currently harvested land (n_{hv}). Again, for agricultural intensification we do not consider the potential to increase productivity up to that of the natural vegetation replaced,[29,30] and we therefore only estimate residual potential (PBP_{RS}). We calculate PBP_I according to eqs 5−7.

$$PBP_{RS} = \sum_{i=1}^{n_{hv}} (H_{RS_i}) \tag{5}$$

$$PBP_{AD} = \sum_{i=1}^{n_{hv}} ((MSH_{RC_i} + MSH_{RS_i}) - (H_{RC_i} + H_{RS_i})) \tag{6}$$

$$PBP_I = \sum_{i=1}^{n_{hv}} (GBP_{AD_i} + GBP_{RS_i}) \tag{7}$$

Extensification (PBP_X) was estimated considering all currently nonharvested land excluding land areas defined as unavailable (n_{nhv}). We calculated PBP_X according to eq 8.

$$PBP_X = \sum_{i=1}^{n_{nhv}} (MSH_{RC_i} + MSH_{RS_i}) \tag{8}$$

We further subdivided extensification between managed land (PBP_{MX}) and remote land (PBP_{RX}) according to a human footprint index threshold equivalent to roughly the 10% most inaccessible areas in the U.S.[19] A summary of the calculated PBP pools for the conterminous U.S. is presented by region in SI Tables S4 and S5, respectively. In addition, spatial representations of PBP are shown in SI Figures S4 and S5, respectively.

Bioenergy Conversion. We converted biomass (Pg C yr^{-1}) and ethanol targets (L yr^{-1}) to primary bioenergy potential (PBP; EJ yr^{-1}) according to eqs 9 and 10, respectively,

$$PBP = \text{biomass} \times \frac{CF_{energy}}{CR_{biomass}} \tag{9}$$

$$PBP = \text{ethanol} \times \frac{CF_{energy}}{CF_{ethanol}} \tag{10}$$

where PBP (EJ yr^{-1}) was estimated from biomass (Pg C yr^{-1}) assuming a 0.45 C to dry biomass ratio ($CR_{biomass}$) and an 18.0 MJ kg^{-1} primary energy content ratio for dry biomass (CF_{energy}).[31,32] Additionally, PBP (EJ yr^{-1}) was estimated from ethanol (liters yr^{-1}) assuming an ethanol to dry biomass energy conversion efficiency ($CF_{ethanol}$) of 3.79×10^{-4} and 3.03×10^{-4} liters g^{-1} for starch-derived and cellulosic-derived ethanol, respectively.[6]

RESULTS AND DISCUSSION

NPP and Landcover of the Conterminous United States. We estimated the primary bioenergy potential (PBP) of the conterminous U.S. using satellite-derived NPP as an upper-envelope constraint, since agricultural productivity is typically less than the natural potential.[14−17] We estimated that NPP for the conterminous U.S. is 3.16 Pg C yr^{-1}, which is similar to previous values of 3.13−3.77 and 3.30 Pg C yr^{-1} reported by VEMAP members[33] and Tian et al.,[34] respectively (Table 1). In addition, our estimated total crop NPP and total forestry harvest (H_{TL}) values (0.61 and 0.12 PgC yr^{-1}, respectively), are similar to previous values of 0.62 and 0.12 Pg C yr^{-1} reported by Lobell et al.[22] and Turner et al.,[35] respectively (Table 1; SI Table S3).

Table 1. Total Vegetated Area and Productivity by Landcover Type in the Conterminous United States[a]

landcover type	area (Mkm^2)	total NPP (PgC yr^{-1})	mean NPP range[b] (g C m^{-2} yr^{-1})	mean NPP range[b,c] (MJ m^{-2} yr^{-1})
crop	1.39	0.61	308−570	12.3−22.8
pasture	0.55	0.32	430−728	17.2−29.1
managed range	1.21	0.42	161−533	6.4−21.3
remote range	0.73	0.20	164−384	6.6−15.4
managed forest	1.73	1.09	410−850	16.4−34.0
remote forest	0.34	0.15	262−622	10.5−24.9
wetlands	0.31	0.22	429−991	17.2−39.6
protected	0.25	0.08	109−531	4.4−21.2
low NPP	0.71	0.07	74−122	3.0−4.9
total/average	7.22	3.16	196−680	7.8−27.2

[a] Productivity was estimated from Moderate Resolution Imaging Spectroradiometer (MODIS) net primary productivity (NPP) data over the 2000−2006 period (Figure 1).[11−13] Barren and urban landcover types were assumed to have no vegetation productivity and were not included in the analysis. [b] Mean NPP represents a range of one standard deviation. [c] Mean NPP (MJ m^{-2} yr^{-1}) calculated from mean NPP (g C m^{-2} yr^{-1}) according to eq 9.

We assumed that protected lands, pastures, wetlands, and low-productivity regions were unavailable for bioenergy production. Because our definition of protected lands included national parks and nature reserves only, our estimated protected land extent (0.25 Mkm^2), is significantly less than total U.S. protected area (1.19 Mkm^2)[36] (Table 1). In addition, the extent of pastures—defined as areas managed solely for livestock grazing—was 0.55 Mkm^2, which is significantly less than the estimated extent of total U.S. grazing lands (2.36 Mkm^2)[36] (Table 1). Finally, we estimated that U.S. wetland and low-productivity regions occupy 1.05 Mkm^2, similar to a value of 1.15 Mkm^2 reported by Chum et al.[36] (Table 1). Again, we classified pastures and wetlands as unavailable due to the many negative trade-offs (e.g., GHG emissions, deforestation) associated with displacement of these landcover types.[3−6] It is important to note that in the case of pastures especially, we significantly underestimate the full extent, since nearly all accessible U.S. rangeland is grazed to some extent.[36] By conservatively estimating unavailable land relative to the current literature,[36] we remained consistent with our objective of providing an upper-envelope estimation of the PBP of the conterminous U.S.

Primary Bioenergy Potential of the Conterminous United States. Future increases in bioenergy production can be gained from either expanding harvest to currently nonharvested land (extensification) or increasing harvest on currently harvested land (intensification) (Figure 2). We estimate that the maximum capacity for bioenergy production in the conterminous U.S. is 22.2 (±4.4) EJ yr^{-1}, split between 14.6 (±2.1) EJ yr^{-1} from extensification and 7.6 (±2.3) EJ yr^{-1} from intensification (Table 2; Figures 3 and 4). Extensification (PBP_X) was divided between agricultural and forestry extensification, which were estimated as 13.5 (±1.8) and 1.1 (±0.3) EJ yr^{-1}, respectively (Table 2; Figures 3 and 4). We found that southcentral U.S. managed rangelands, southwest U.S. managed rangelands, and southwest U.S. remote rangelands have the largest associated extensification potential (Figure 5). Intensification (PBP_I) was divided between current harvest residues (PBP_{RS}) and additional harvest (PBP_{AD}), which we estimated to account for 5.9 (±1.4) and 1.7 (±0.8) EJ yr^{-1}, respectively (Table 2; Figures 3 and 4). The northcentral U.S. has the largest intensification potential, due to the region's relatively high agricultural harvest and associated agricultural residue potential (Figure 5). We found the northeast U.S. to be the region with the highest potential for additional forest harvest, due to relatively low current forest harvest rates (Figure 5).

Table 2. Primary Bioenergy Potential (PBP) of the Conterminous United States

primary bioenergy potential	area (Mkm^2)	mean yield range[a] (MJ m^{-2} yr^{-1})	total PBP[b] (EJ yr^{-1})
agricultural extensification (PBP_X)[b]	1.94	3.4−10.6	13.5 (1.8)
managed range (PBP_{MX})	1.21	3.5−11.9	9.2 (1.2)
remote range (PBP_{RX})	0.73	3.3−8.3	4.3 (0.6)
forestry extensification (PBP_X)[b]	0.34	2.3−4.3	1.1 (0.3)
managed forest (PBP_{MX})			
remote forest (PBP_{RX})	0.34	2.3−4.3	1.1 (0.3)
agricultural intensification (PBP_I)[b]	1.39	2.1−3.8	4.1 (1.0)
residual (PBP_{RS})	1.39	2.1−3.8	4.1 (1.0)
forestry intensification (PBP_I)[b]	1.73	1.4−2.8	3.5 (1.3)
additional (PBP_{AD})	1.73	0.5−1.4	1.7 (0.8)
residual (PBP_{RS})	1.73	0.7−1.3	1.8 (0.4)
total/average	5.40	2.3−5.4	22.2 (4.4)

[a] Mean yield range represents a range of one standard deviation. [b] Primary bioenergy potential (PBP) calculated according to eqs 1−9. Values in parentheses represent parameter uncertainty as summarized in SI Table S1.

Average Yield Potential of the Conterminous United States. We estimated an agricultural extensification potential (PBP_X) of 13.5 (±1.8) EJ yr^{-1} for the conterminous U.S., which is significantly less than the estimate of 70.4 EJ yr^{-1} reported by the U.S. Department of Agriculture[8] and the United Nations[9] (Table 2; Figures 3 and 4). The main contributor to this discrepancy is differences in yield potential. We estimated average yield potential on managed rangelands to vary from 9.2 to 18.6 MJ m^{-2} yr^{-1}, while remote rangelands vary from 8.2 to 13.8 MJ m^{-2} yr^{-1} (Table 1). By contrast, the U.S. Department of Agriculture[8] and the United Nations[9] reported an average yield potential of approximately 30 MJ m^{-2} yr^{-1} over 2.35 Mkm^2 of assumed available U.S. grassland. This implies a yield potential almost three times greater than natural average U.S. rangeland productivity (Table 1). Even more striking, Pacca et al.[10] utilized an average yield potential estimate of roughly 69 MJ m^{-2} yr^{-1} over 0.67 Mkm,^{2} and suggested that only 4% of global cropland area would be necessary to power the global automobile fleet. A yield potential estimate of 69 MJ m^{-2} yr^{-1} is more than double average natural productivity rates in the U.S. (Table 1).[3]

How do we reconcile these vastly different estimates? First, it is important to note that the studies cited do not account for the geographic variability of biophysical factors, such as temperature and precipitation. Instead, maximum yield potential estimates were simply extrapolated over areas considered available, a method that has been previously shown to systemically overestimate bioenergy potential per unit area.[7] Because agricultural productivity is almost always less than the natural productivity potential,[14−17] we argue that these yield potentials are unrealistic and thus ineffective in informing sound planning for bioenergy development. We acknowledge that human management factors (e.g., fertilization and especially irrigation) can enhance yield potential, and assumptions regarding these factors could partially explain the large discrepancies in reported yield potential estimates.[14−17] However, due to concerns regarding resource availability in the U.S. (a factor discussed in detail below), sustaining yields that exceed natural rates of productivity over large areas may be unlikely.[29,30]

Current and Future United States Bioenergy Production. In 2009, the U.S. produced roughly 40 billion L of starch-derived ethanol, more than half the 75 billion L global supply, utilizing maize as the main feedstock.[1] According to eq 10, we calculate an equivalent primary bioenergy requirement of 1.9 EJ yr^{-1}, which corresponds to roughly 20% of current recovered agricultural harvest (H_{RC}) (Table 3; Figure 4). Similarly, Graham-Rowe et al.[37] documented that approximately 33% of U.S. maize production is currently reallocated for bioenergy production. The U.S. is responsible for approximately 45% of global maize production and nearly 70% of global maize export, suggesting that increased maize allocation for bioenergy production could displace global export and subsequently drive increased food prices.[37] In 2010, food prices were reported by the food and agricultural organization (FAO) as the highest they have been in their 20-year measurement record.[38] While the role that current U.S. bioenergy expansion has played in driving food prices is still debated,[39,40] there is no question that at some point reallocation of U.S. croplands will directly impact global food prices. Consequences of increased global

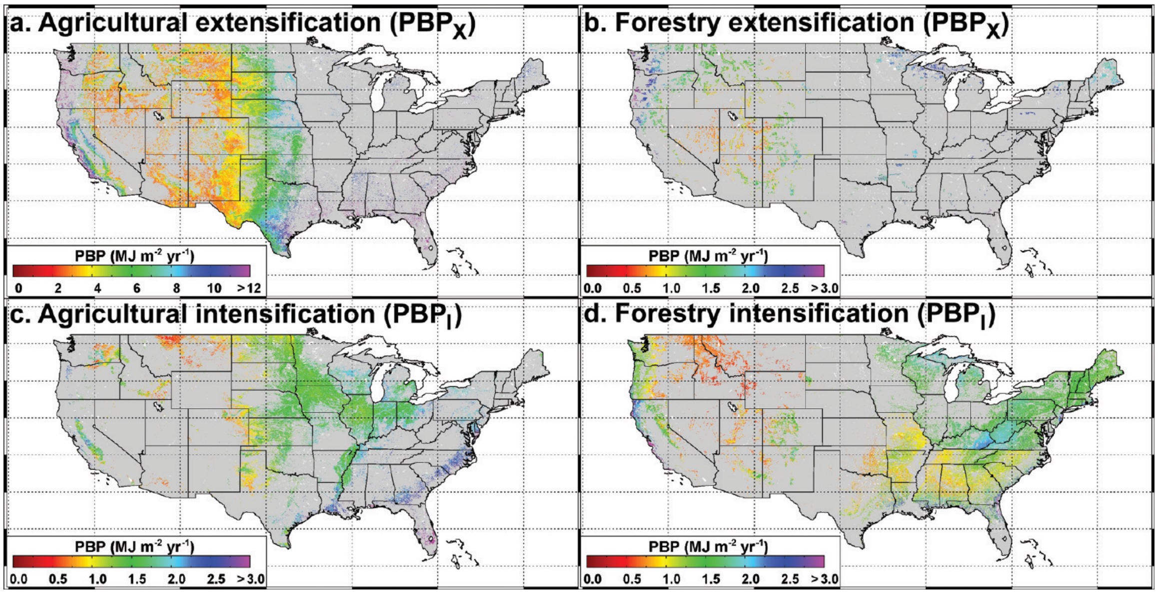

Figure 3. Spatially explicit primary bioenergy potential (PBP) of the conterminous United States. PBP was calculated according to eqs 1−8 utilizing mean parameter values (SI Table S1). (a) Agricultural extensification (PBP_X), including both managed (PBP_{MX}) and remote (PBP_{RX}) extensification. (b) Forestry extensification (PBP_X) defined to include remote extensification (PBP_{RX}) only. (c) Agricultural intensification (PBP_I) defined to include residual harvest (PBP_{RS}) only. (d) Forestry Intensification potential (PBP_I), including both additional harvest (PBP_{AD}) and residual harvest (PBP_{RS}).

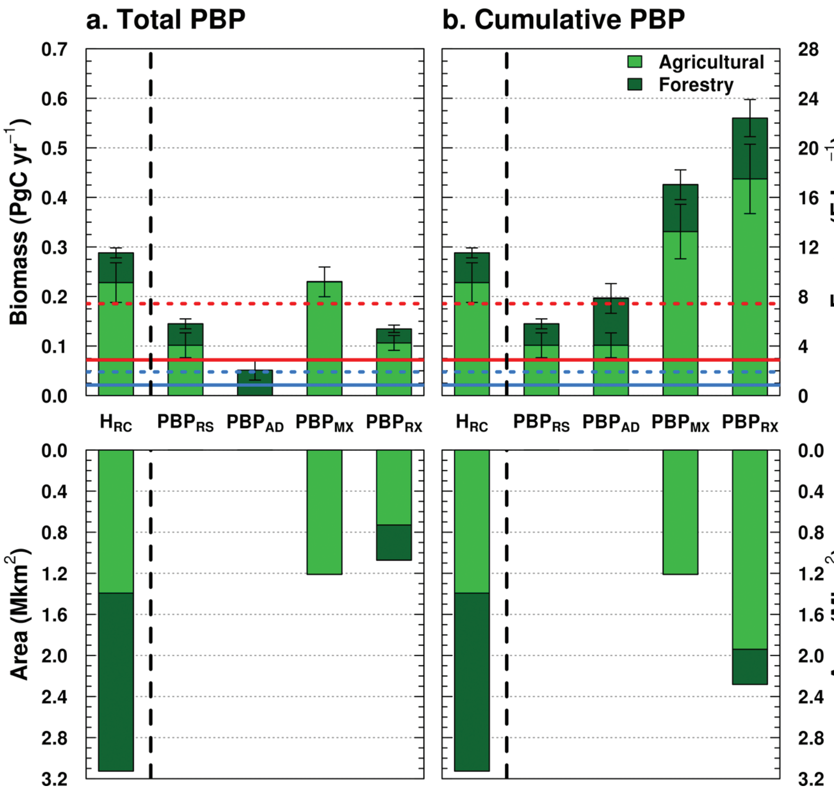

Figure 4. Primary bioenergy potential (PBP) of the conterminous United States. PBP divided into current harvest residue potential (PBP_{RS}), additional harvest potential (PBP_{AD}), extensification of managed lands (PBP_{MX}), and extensification over remote lands (PBP_{RX}). Whiskers depict parameter uncertainties as summarized in SI Table S1. For comparison, current recovered harvest (H_{RC}) is also represented. Biomass (Pg C yr^{-1}) converted to energy (EJ yr^{-1}) according to eq 9. The solid blue line represents U.S. net ethanol production in 2009 (40 billion L).[1] The dotted blue line represents U.S. primary bioenergy production in 2009 (1.91 EJ yr^{-1}; eq 10).[1] The solid red line represents the net energy required by the Energy Independence and Security Act of 2007 by 2022 (EISA; 136 billion L).[2] The dotted red line represents the primary energy required by the EISA by 2022 (7.42 EJ yr^{-1}; eq 10).[2] (a) Total PBP. (b) Cumulative PBP.

food prices include higher rates of poverty and malnutrition as well as increased global deforestation and greenhouse gas (GHG) emissions as forests are cleared to accommodate agricultural expansion.[40] These detrimental impacts, associated

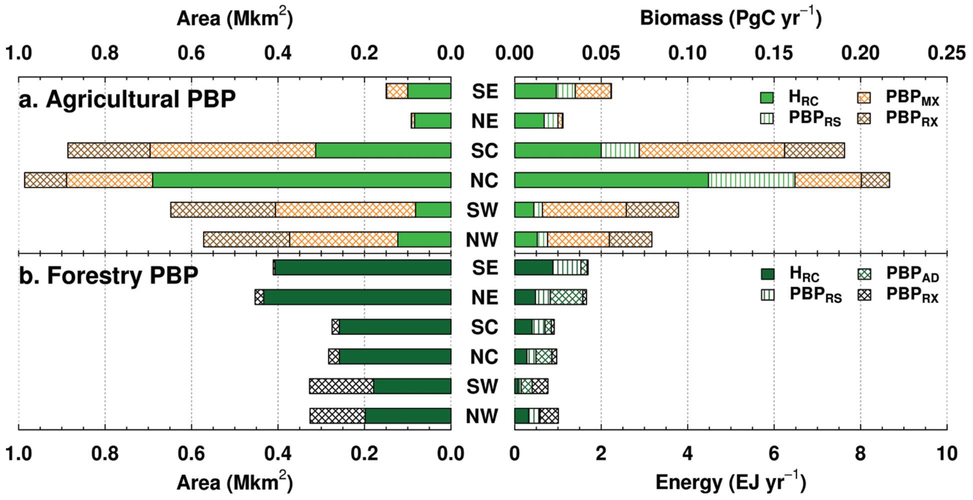

Figure 5. Primary bioenergy potential (PBP) by geographical region of the conterminous United States. PBP divided into current harvest residue potential (PBP_{RS}), additional harvest potential (PBP_{AD}), extensification of managed lands (PBP_{MX}), and extensification over remote lands (PBP_{RX}). PBP pools calculated according to eqs 1−8 utilizing mean parameter values (SI Table S1). Biomass (Pg C yr^{-1}) converted to energy (EJ yr^{-1}) according to eq 9. (a) Agricultural PBP, including current recovered harvest (H_{RC}), PBP of current harvest residues (PBP_{RS}), PBP associated with extensification over currently available managed land (PBP_{MX}), and PBP associated with extensification over currently available remote land (PBP_{RX}). (b) Forestry PBP, including current recovered harvest (H_{RC}), PBP of current harvest residues (PBP_{RS}), PBP associated with additional harvest of currently harvested land (PBP_{AD}), and PBP associated with extensification over currently available remote land (PBP_{RX}).

Table 3. Bioenergy Production of the Conterminous United States

U.S. bioenergy	secondary energy (S^a) (10^9 L yr^{-1})	secondary energy (C^a) (10^9 L yr^{-1})	primary energy^b (S^a) (EJ yr^{-1})	primary energy^c (C^a) (EJ yr^{-1})	total primary energy^b (EJ yr^{-1})
2009 production	40	0	1.9	0.0	1.9
EISA target^c	57	79	2.7	4.7	7.4
EISA target (S)^d	136	0	6.5	0.0	6.5
EISA target (C)^e	0	136	0.0	8.1	8.1

[a] S = starch-based; C = cellulosic-based. [b] Primary energy calculated utilizing eq 10. [c] Energy Independence and Security Act of 2007 (EISA) energy targets. [d] EISA energy targets assuming only starch-based conversion technology. [e] EISA energy targets assuming only cellulosic-based conversion technology.

with global food instability, highlight the importance of minimizing or even reversing current food and feed production displacement due to bioenergy expansion.[40]

The U.S. Energy Independence and Security Act of 2007 (EISA) stipulates a total renewable energy target of 136 billion L by 2022, with 57 billion L of starch-derived ethanol and 79 billion L of cellulosic-derived ethanol (Table 3).[2] Again, utilizing eq 10, the total equivalent primary bioenergy requirement increased to approximately 7.4 EJ yr^{-1}, nearly four times the 2009 total primary bioenergy equivalent (1.9 EJ yr^{-1}; Table 3). If we consider only current U.S. agricultural harvest, we estimate that roughly 80% of current recovered harvest (H_{RC}) would need to be reallocated for the production of bioenergy to meet the target stipulated in the EISA (Figure 4). Conversely, if only expansion of agricultural land is considered, we estimate over 80% of managed rangeland or nearly 60% of total rangeland productivity would need to be allocated to bioenergy production to satisfy EISA targets (Figure 4). Again, since agricultural productivity is almost always significantly less than current natural productivity,[14−17] we likely underestimate the magnitude of rangeland exploitation required to meet policy targets. Not only could converting rangeland to agriculture result in significant detrimental impacts on biological diversity, but the utilization of remote regions would initially require infrastructure establishment resulting in large-scale fossil fuel energy inputs and a significant initial C debt of bioenergy systems.[41] Moreover, even though we excluded permanent pasturelands from our analysis, the majority of rangeland in the U.S. experiences some degree of grazing, indicating that expansion into these areas will likely displace a portion of feed production, which could ultimately drive future deforestation and consequentially, increase GHG emissions.[42,43]

Alternatively, our results suggest that the cellulosic-derived energy target of 79 billion L or 4.7 EJ could potentially be exceeded utilizing only current harvest residues, requiring no additional harvest land (Table 3; Figure 4). As expected, regions with the most forestry and agricultural land were also found to have the largest associated residue potential (Figure 5). However, even under this best case scenario, the EISA still requires starch-derived ethanol production to increase beyond 2009 values by roughly 30%, with an associated increase in primary energy demand from 1.9 to 2.7 EJ yr^{-1} (Table 3).[2] We estimate that such an increase would either require an additional reallocation of roughly 9% of total U.S. agricultural production or the utilization of approximately 9% of accessible natural rangeland (Figure 4). We acknowledge that some of this increase could potentially be satisfied via increasing productivity on current agricultural land, a factor outside the scope of this study.[29,30] However, the potential for increased agricultural productivity in the U.S. is relatively low, since the most advanced seed varieties, human management, and genetics are already widely utilized, while additional resources are limited (a factor discussed in more detail below).[30]

Unfortunately, next generation technology is still unavailable for large-scale bioenergy production due mainly to difficulties in converting lignocellulose to a useable form.[44] Evaluating the EISA energy targets utilizing only starch-derived ethanol technology resulted in an equivalent primary bioenergy requirement of approximately 6.5 EJ yr^{-1}, a value significantly larger than current total U.S. maize production.[22] This suggests that EISA energy targets could not be satisfied under current productivity trends without total displacement of U.S. maize production and significant rangeland expansion (Table 3; Figure 4). Already, delays in up-scaling next generation bioenergy technology have resulted in projections to expand the utilization of the starch-derived ethanol pathway, which will likely result in further displacement of food and feed production land with relatively low net bioenergy output.[45]

Natural Productivity As a Constraint on Yield Potential. While average agricultural yields have the potential to increase,[29,30] achieving yields that exceed natural rates of productivity would likely require either enhanced photosynthetic capabilities or increased resource allocation (e.g., irrigation and fertilization), neither of which currently seems likely in future scenarios. Under optimal growing conditions, yield potential is determined genetically by the efficiency of light capture, the efficiency of the conversion of that captured light to biomass, and the proportion of that biomass partitioned into grain.[46] Long et al.[46] documented that light interception and allocation to grain are near their theoretical maxima for grain crops, leaving light use efficiency as the only genetic control with significant potential to increase yield. However, despite a long history of research, genetic manipulation by plant breeding has yet to significantly increase photosynthetic rate per unit leaf area.[47]

Additionally, evidence suggests current rates of irrigation and fertilization in the U.S. are reaching peak levels, which is resulting in significant detrimental impacts. For instance, the Colorado River, a main irrigation source for the western U.S., is currently at a maximum sustainability limit, with little to none of the peak renewable flow reaching the delta annually.[48] The Rio Grande, Santa Cruz, Gila, Verde, Salt, and other river systems flowing through urban areas of the region are under similar stress, either reaching or exceeding peak ecological limits.[48] Additionally, the Ogallala aquifer in the Great Plains has been documented as exploited, largely for irrigation, beyond its natural recharge rate, resulting in diminishing returns of an essentially nonrenewable resource.[49] As roughly 13% of croplands in the U.S. are irrigated,[50] a more likely scenario for the future may be significant declines in agricultural yields as freshwater limits are exceeded.[51,52]

Similarly, current nutrient fertilization rates are perturbing the natural nitrogen (N) cycle, resulting in extensive eutrophication of freshwater and coastal zones.[53] Incidental fluxes of N into the Mississippi River have contributed to freshwater pollution and an immense "Dead Zone" in the Gulf of Mexico that spans roughly 15 000 km^2.[54] Equally concerning, agricultural intensification has resulted in increased emissions of the highly potent greenhouse gas nitrous oxide (N_2O), a trace gas species with a global warming potential roughly 300 times greater than an equal mass of CO_2.[55,56] Already, research suggests that fertilizer-derived N_2O emissions from some bioenergy cropping systems have exceeded their potential CO_2 offset, resulting in a net increase in atmospheric GHG warming potential.[55,56] Thus, any positive impact of future increases in fertilization on productivity could be offset by amplification of freshwater degradation and acceleration of climate change.[57]

ASSOCIATED CONTENT

Supporting Information

Additional information on unavailable landcover (SI Figure S1), regional divisions (SI Figure S2), current harvest rates (SI Figure S3), global bioenergy potential (SI Figure S4, SI Figure S5), and regional data (SI Tables S1–S5). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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