The Global Potential of Bioenergy on Abandoned Agriculture Lands

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Converting forest lands into bioenergy agriculture could accelerate climate change by emitting carbon stored in forests, while converting food agriculture lands into bioenergy agriculture could threaten food security. Both problems are potentially avoided by using abandoned agriculture lands for bioenergy agriculture. Here we show the global potential for bioenergy on abandoned agriculture lands to be less than 8% of current primary energy demand, based on historical land use data, satellite-derived land cover data, and global ecosystem modeling. The estimated global area of abandoned agriculture is 385−472 million hectares, or 66−110% of the areas reported in previous preliminary assessments. The area-weighted mean production of above-ground biomass is 4.3 tons ha^{-1} y^{-1}, in contrast to estimates of up to 10 tons ha^{-1} y^{-1} in previous assessments. The energy content of potential biomass grown on 100% of abandoned agriculture lands is less than 10% of primary energy demand for most nations in North America, Europe, and Asia, but it represents many times the energy demand in some African nations where grasslands are relatively productive and current energy demand is low.

Introduction

Agricultural land dedicated to bioenergy crops is expanding rapidly (*1*), with multiple consequences for global climate, ecosystems, and food security (*2*). These consequences are closely tied to the land that is used for bioenergy crops. Using food agriculture lands for bioenergy agriculture could increase the cost of the food commodities that are critical to the diets of food-insecure people worldwide (*3–5*). Clearing forest land for new bioenergy crops could result in CO_2 emissions from terrestrial carbon pools that are much greater than any greenhouse gas benefits provided by biofuels (*6–11*). Raising bioenergy crops on agriculturally degraded and abandoned lands is emerging as a sustainable approach to bioenergy that provides environmental benefits and climate change mitigation without creating food−fuel competition for land or releasing the carbon stored in forests (*12, 13*). These lands have been defined as areas that have been abandoned to crop and pasture due to the relocation of agriculture and due to degradation from intensive use (*14, 15*). Growing conventional crops on these lands as a bioenergy feedstock could increase rates of erosion and polluted runoff (*16*), while field studies suggest that growing low-input, perennial grasses as a feedstock would likely reduce such impacts (*13, 17*).

Assessing the global potential of bioenergy production from agriculturally degraded and abandoned lands is challenging because of the high uncertainty associated with the spatial extent of these lands and the potential plant production on these lands. Existing assessments have provided only rough global estimates of the potential bioenergy from these lands, using estimates of the global area that are ultimately based on expert opinion (*18–20*), the assumption of a homogeneous spatial distribution, and spatially invariant or highly aggregated estimates of plant production. Such estimates range from 430 to 580 Mha of abandoned agriculture land, with mean global plant production on these lands of 1−10 tons aboveground biomass (AGB) ha^{-1} yr^{-1}, meeting 2−23% of current global primary energy demand (*13, 21, 22*). In previous work, we developed a new method for estimating the abandoned areas that relies on historical land use data and found that the potential biomass production has an energy content of ~5% of primary energy demand (*23*). Application of our data-driven approach at the national level could help inform policy makers of the potential scale of this bioenergy resource (*24*).

Here we present a new global, spatially explicit estimate of abandoned agriculture and the associated plant production on these lands, using historical land use data, satellite-derived land cover, and global ecosystem modeling. We considered abandoned agriculture as land that was previously used for crop or pasture but has since been abandoned (and has not been converted to forest or urban areas). The spatially resolved biomass production is then combined with national-level energy use data to determine the potential contributions of bioenergy.

Methods

We estimated abandoned agriculture areas using the historical land use data from the History Database of the Global Environment 3.0 (HYDE, 5 min resolution) (*25, 26*). The HYDE gridded maps provide the fractional area of crop and the fractional area of pasture within each grid cell for each decade between 1700 and 2000. Abandoned areas were determined from each map grid cell that had decreasing agriculture areas over time. Shifting agriculture, which also contributes to abandoned agriculture lands (*15*), is not included in these maps. As a check on this HYDE-based analysis, we also considered areas of abandoned crop from the Center for Sustainability and the Global Environment (SAGE) land use database (5 min resolution) (*27, 28*).

While the HYDE database provides the fractional areas of both crop and pasture, it does not provide the underlying land use transitions (*15*). For example, if a grid cell shows a decrease in the fractional area of pasture and an increase in crop then it is not explicit whether these changes were due to a land use transition from pasture to crop or from pasture to some other land cover within the grid cell. Understanding this transition is important because transitions between pasture and crop should not be counted toward the area of abandoned agriculture. We used two alternative approaches to estimate these land use transitions that provide a low and high estimate of total abandoned agriculture for each grid cell. In the more restrictive approach, providing the low

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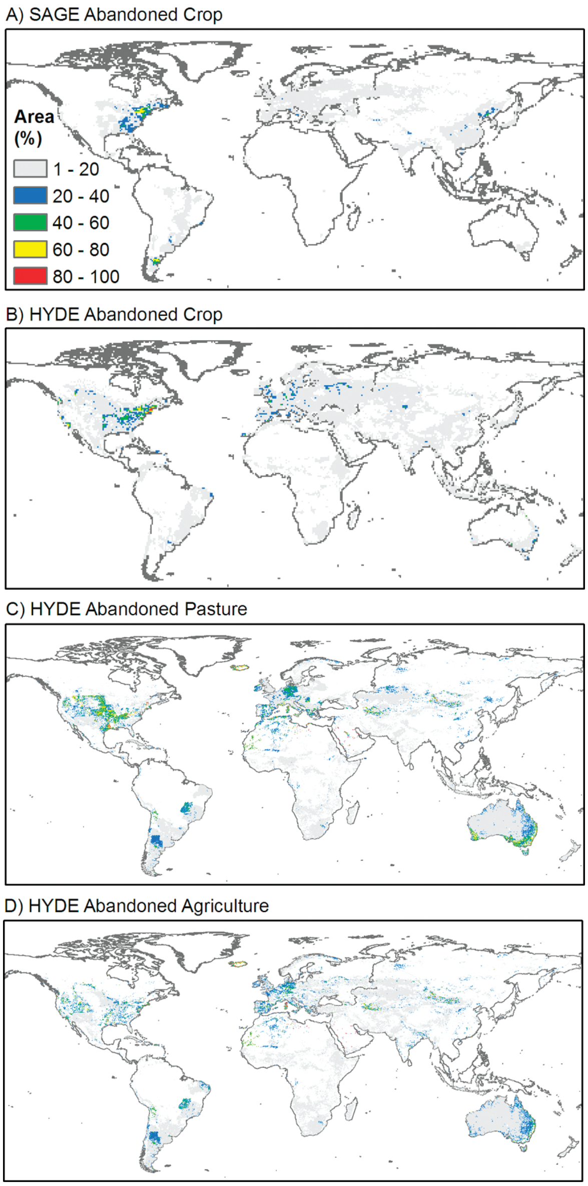

FIGURE 1. Global land areas of crop and pasture abandonment. (A and B) Crop lands that have been permanently converted to land uses other than cropping based on SAGE data andHYDE data. (C) Pasturelands that have been permanently converted to land uses other than pasture based on HYDE data. (D) Total abandoned agriculture based on HYDE data excluding areas resulting from land use transitions of crop to pasture, pasture to crop, agriculture to forest, and agriculture to urban (average of higher and lower estimate).

estimate, we considered any simultaneous increase in crop and decrease in pasture to be a transition from crop to pasture, and vice-versa. In the second approach, providing the high estimate, we calculated abandoned crop area for each grid cell as the difference between the maximum fractional crop area ever attained in a grid cell and the fractional crop area in the year 2000 (when this difference was positive). We followed the same approach for calculating abandoned pasture area. We then estimated the abandoned agriculture for each grid cell to be equal to the sum of the abandoned pasture and abandoned crop areas, but no greater than the difference of the total grid cell land area and the current agriculture area. This is a more self-consistent definition of land use transitions than in our earlier study (*23*), which used MODIS land cover to constrain the land use transitions between pasture and crop.

To exclude areas where abandoned agricultural lands have transitioned to forest or urban areas, we used a MODIS satellite map of the current forest and urban land cover (3 min resolution, MODIS/Terra Land Cover types MOD12C1) (*29*). Combining HYDE and MODIS data within this spatial analysis can introduce errors due to the different assumptions and input data used by the two data sets. Furthermore, the HYDE data provide subgrid cell information (fractional areas) while the MODIS data provide a single classification for the entire grid cell. We discuss the uncertainties in the following section. As a point of comparison, we also estimate the abandoned land area that has transitioned to forest or urban areas based on the International Geosphere Biosphere Programme (IGBP) DIScover data set (*30, 31*).

The biomass production at a specific location will depend on multiple factors including the crop type, management, climate, and soils. Natural production provides an upper estimate of potential agriculture production because agricultural harvest statistics, at a global scale, have been found to be about 65% of natural production (*32*). To provide an upper envelope estimate on the production potential, we used simulated natural plant production from the Carnegie-Ames-Stanford Approach (CASA) ecosystem model (1 degree resolution) (*33*). Estimating biomass yield with the natural production model on a site reflects local constraints from climate and soil types. The simulations (*33*) were driven by climate data (*34*), surface insolation (*35*), soil texture (*36*), land cover (*37*), and the normalized difference vegetation index (NDVI) (*33*). Using simulated natural production allows for the possibility that the total plant production from biomass agriculture may be significantly higher than that for current agriculture, at the global scale. The NDVI input may be sensitive to degradation which may decrease yields (*13*). We do not account for irrigation or very high fertilizer inputs, which could increase yields (*38–40*). Above-ground production rates may also overestimate harvestable biomass as some plant material must be left on the land to prevent further soil degradation (*41*).

Results and Discussion

Based on the HYDE historical land use data we found that between the years 1700 and 2000, 269 Mha of crop lands were permanently converted to land uses other than cropping (Figure 1B), while 479 Mha of pasture lands were converted to land uses other than pasture (Figure 1C), at some point in the last 300 years. This HYDE-based abandoned crop area is somewhat higher than the 210 Mha of abandoned crop area from the SAGE crop data (Figure 1A) (*28*). The abandoned crop areas from HYDE and SAGE data had the highest concentrations over the Eastern United States, as a result of the relocation of cropland from the Eastern to the Midwestern region of North America. The most extensive area of abandoned pasture was over the Midwestern region of North America, where HYDE data indicate that cropland has replaced pasture land. Australia, where pasture areas peaked in the mid-1970s and have since steadily declined, also had high levels of pasture abandonment in the data. We found that 99% of the land abandonment occurred during the past 100 years.

Our low and high approaches to estimating the global area of abandoned agriculture (crop and pasture) yield total areas of 474 and 579 Mha, respectively. These estimates exclude abandoned agriculture areas arising from the conversion of crop to pasture or pasture to crop. These estimates do not exclude abandoned areas arising from agriculture to forest or agriculture to urban transitions. Overlaying the MODIS land cover data, we identified the current land cover classification of each grid cell containing abandoned agriculture areas. Excluding pixels classified as forest or urban areas yielded estimates of 385 and 472 Mha for the low and high approaches, respectively (Figure 1D).

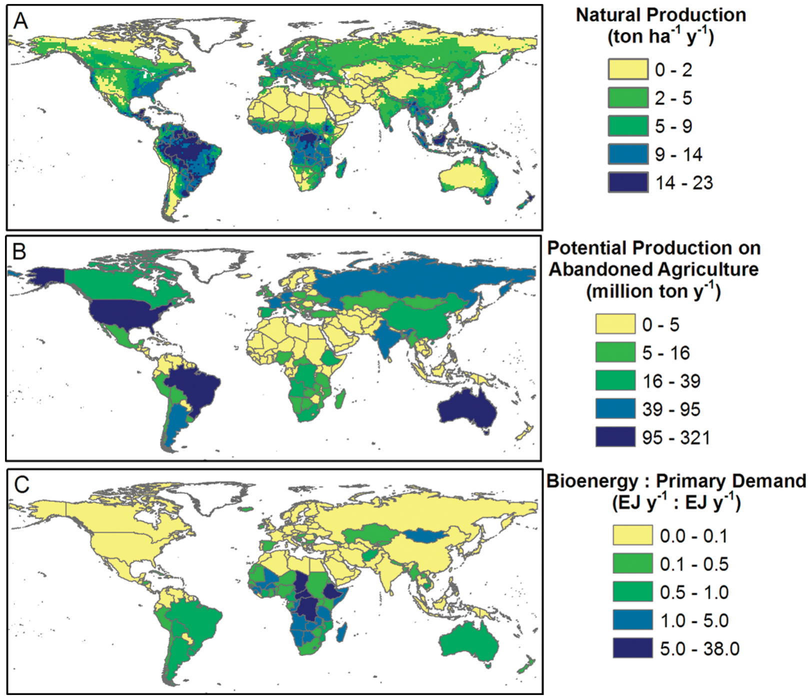

FIGURE 2. Biomass production potential on abandoned agriculture lands. (A) Natural above-ground production of biomass on all lands determined from the CASA model, assuming 50% of the biomass is above-ground and the ratio (by mass) of biomass to carbon is 2.2. (B) Potential above-ground production of biomass on abandoned agriculture lands at the country level. (C) Ratio of the energy content of the biomass on abandoned agriculture lands relative to the current primary energy demand at the country level. The energy content of biomass is assumed to be 20 kJ g^{-1}.

Our area estimates are 66−110% of the areas assumed in previous preliminary assessments (*13, 22, 42*). Excluding additional areas where abandoned agriculture has transitioned to other natural ecosystems types may also be important for maintaining species habitat and preserving natural carbon pools.

Our spatial analysis, relying on both HYDE and MODIS data, introduces additional uncertainty due to the different methods used in the creation of these data. Specifically, historical HYDE maps were, in part, spatially distributed by human population at the subadministrative level (*25, 26*). Since the subadministrative level distribution may be biased toward urban areas, our exclusion of MODIS urban areas may overcorrect our abandoned area estimate. However, the abandoned agriculture areas were reduced by only 3% when using the MODIS data to exclude urban areas. Our application of the MODIS forest map appears to have correctly excluded forest regrowth in the eastern United States (Figure 1D) where abandoned agriculture has transitioned to secondary forests (*43*). Alternatively, using the IBGP land cover data to exclude forest and urban areas resulted in a remaining abandoned agricultural area of 388−480 Mha. The IGBP area estimate is somewhat higher than the MODIS-based estimate of 385−472 Mha.

Using the global distribution of potential plant production (Figure 2A), we found that the abandoned agriculture lands could produce between 1.6 and 2.1 billion tons of AGB per year for the low and high area estimates, respectively. Potential production rates on abandoned lands are highest in regions of tropical grasslands, ranging from 7 to 20 tons AGB ha^{-1} y^{-1}. Globally, the area-weighted average of the production rates on abandoned lands was 4.3 tons AGB ha^{-1} y^{-1}. This is somewhat less than the global average of 4.9 tons AGB ha^{-1} y^{-1} extrapolated from plot experiments (*13*) and in the middle of the range of 1−10 tons AGB ha^{-1} y^{-1} assumed in a preliminary modeling study (*22*).

The energy content of 1.6−2.1 billion tons of dry biomass is 32−41 EJ or 7−8% of primary energy demand. We assumed a high value for energy content of 20 kJ g^{-1}, although this value will depend on multiple factors such as plant type and the timing of harvest (*44*). At the national scale, the bioenergy potential was largest in the United States, Brazil, and Australia, where the available areas were the most extensive (Figure 2B). The national bioenergy potential was less than 10% of primary energy demand for most countries in North America, Europe, and Asia while it represents many times the current energy demand in some African nations where grasslands are relatively productive and current fossil fuel demand is low (Figure 2C). Converting the bioenergy crops to liquid fuels would cut the net energy to half this amount and could result in either a net greenhouse gas source or sink depending on the types of agriculture and biorefineries used (*45–48*).

Overall, the potential bioenergy from abandoned agriculture lands is a small but meaningful fraction of global primary energy consumption. Regionally, it can be more important. The global potential could be increased with additional land areas or through fundamental advances in biomass agriculture. One possible source of additional lands is marginal agricultural lands that have limited potential for food production. Land areas degraded from wood harvesting (*49*), rather than agriculture, are another possible source of land. Forest lands could also produce net greenhouse gas sinks for highly productive sites under sustainable harvest practices (*50*). Consideration of these additional areas will require careful study of the competing uses, including, but not limited to, food production, carbon storage in forests, and habitat conservation. Increasing yields of biomass crops above natural yields is another challenging path toward increasing the potential of bioenergy. Based on abandoned lands and current technologies, however, expanding bioenergy crops to offset more than a small fraction of global primary energy consumption will present major challenges and difficult trade-offs.

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