Biomass energy: the scale of the potential resource

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Increased production of biomass for energy has the potential to offset substantial use of fossil fuels, but it also has the potential to threaten conservation areas, pollute water resources and decrease food security. The net effect of biomass energy agriculture on climate could be either cooling or warming, depending on the crop, the technology for converting biomass into useable energy, and the difference in carbon stocks and reflectance of solar radiation between the biomass crop and the pre-existing vegetation. The area with the greatest potential for yielding biomass energy that reduces net warming and avoids competition with food production is land that was previously used for agriculture or pasture but that has been abandoned and not converted to forest or urban areas. At the global scale, potential above-ground plant growth on these abandoned lands has an energy content representing ~5% of world primary energy consumption in 2006. The global potential for biomass energy production is large in absolute terms, but it is not enough to replace more than a few percent of current fossil fuel usage. Increasing biomass energy production beyond this level would probably reduce food security and exacerbate forcing of climate change.

Biomass energy in context

Biomass energy sources are among the most promising, most hyped and most heavily subsidized renewable energy sources. They have real potential to heighten energy security in regions without abundant fossil fuel reserves, to increase supplies of liquid transportation fuels and to decrease net emissions of carbon into the atmosphere per unit of energy delivered. However, increased exploitation of biomass energy also risks sacrificing natural areas to managed monocultures, contaminating waterways with agricultural pollutants, threatening food supplies or farm lifestyles through competition for land and increasing net emissions of carbon to the atmosphere, as a consequence of increased deforestation or energy-demanding manufacturing technologies. The opportunities are real, but the concerns are also justified. As investments in biomass energy increase, there needs to be an active, continuing discussion on strategies for balancing the pros and cons of biomass energy.

The future of biomass energy in the global energy system is dependent on the complex interplay of four major factors. The first is conversion technology and the prospects for using new plant and microbe varieties as well as novel biomass-to-fuel conversion processes for increasing the yield of usable energy from each unit of available land or water. The second is the intrinsic productive capacity of the land and ocean ecosystems that can be used for biomass energy production. The third is alternative uses for the land and water resources that are candidate sites for biomass energy production. The fourth is offsite implications of biomass energy technologies for invasive species [1] and for levels of air and water pollution. These factors must be effectively integrated to maximize the benefits and minimize the ecosystem and societal costs of biomass energy production. In particular, constraints owing to ecosystem characteristics, competition from alternative land uses and offsite impacts can lead to practical or desirable levels of biomass energy production that are much smaller than theoretical potential levels. A clear picture of these constraints can be an important asset in encouraging rational development of the biomass energy industry.

In this article we briefly review all four of these factors, with an emphasis on their integration. We first discuss the main types of biomass energy production systems, their relative efficiencies, and their environmental impacts. Next, we consider the role of existing vegetation in the distinction between energy and climate security, arguing that biomass energy production on current forest or crop lands is unlikely to result in significant climate benefits relative to fossil fuel use. Finally, we assess the potential total production of biomass on land other than forests or croplands.

Sources of biomass energy

The term biomass energy can refer to any source of heat energy produced from non-fossil biological materials. Biomass energy can come from ocean and freshwater habitats as well as from land. Biomass energy ranges from firewood to ethanol produced from corn or sugarcane to methane captured from landfills. Possible future energy sources such as hydrogen from engineered microorganisms or electricity from photosynthetic cells could also be considered biomass energy, although these will have a different series of technical challenges than those for current biomass energy derived from terrestrial plants. Before the start of the industrial revolution, biomass energy was the world's dominant energy source [2]. It is still important, accounting for ~7% of world primary energy consumption in 2000 [2], or roughly one-third of the energy from sources

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other than fossil fuels [3]. The other two large sources of non-fossil fuel energy (each contributing as much energy as biomass contributes) are nuclear and hydroelectric power [4]. Renewables, such as wind and solar currently sum to <1% of the global energy demand [5].

Energy from biomass is widely used in cooking and heating in the developing world. It is also frequently used as a source of industrial heat, particularly in the forestry and paper industries [6]. Although much of the recent attention on biomass as an energy source focuses on liquid transportation fuels (ethanol and biodiesel), these currently comprise only 2% of world biomass energy [7,8]. However, the contribution of biomass energy to transportation systems varies greatly by country, with ethanol providing 30% of automobile fuel in Brazil [9].

At the global scale, annual total plant growth or net primary production (NPP) fixes a quantity of carbon many times larger than that consumed in the industrial energy system (Figure 1). Total carbon emissions from fossil fuel combustion and natural gas flaring were 7.7 billion tons in 2005 [10], whereas NPP fixed ~57 billion tons of carbon on land and 57 billion in the oceans [11]. The vast majority of this biospheric NPP is returned to the atmosphere through decomposition and wildfire. Human appropriation of terrestrial NPP is estimated to be in the range of 23–40%, where appropriation includes harvest, decreases in NPP resulting from replacement of natural ecosystems by human-modified ecosystems, and shifting of NPP from natural to human-mediated loss pathways, including deforestation and wildfire [12,13]. Total annual NPP in croplands is ~7 billion tons of carbon per year [14], slightly less than the total released through the combustion of fossil fuels. The fact that the fossil fuel energy system already releases more carbon annually than that fixed by all croplands highlights the challenge of replacing a substantial part of the fossil fuel system with a system based on biomass.

Currently, the dominant sources of biomass-based liquid transportation fuels are ethanol from corn or sugarcane and biodiesel from rapeseed, soy, or palm oil [7]. The production systems for these sources of liquid biomass energy are characterized by different yields (in terms of fuel energy per unit of land area) and different net energy balance ratios (the ratio of energy captured in the fuel to the energy inputs for growing, harvesting and manufacturing) (Table 1). The picture for ethanol from corn is particularly depressing. The entire global harvest of corn (700 million tons [15]) converted to ethanol with current technology would yield enough transportation fuels to supply only 6% of the global gasoline and diesel demand [16]. Furthermore, the fossil energy required to produce this amount of ethanol would represent 80–90% of the energy stored in the ethanol [17,18]. Combining these, directing the entire global harvest of corn into ethanol production would offset well under 1% of global carbon emissions from fossil fuel combustion. Even in the best case scenario, making ethanol from corn grain is not an effective route for lowering the carbon intensity of the energy system. From a climate perspective, ethanol from corn is basically a way to make cars run on coal and natural gas [17].

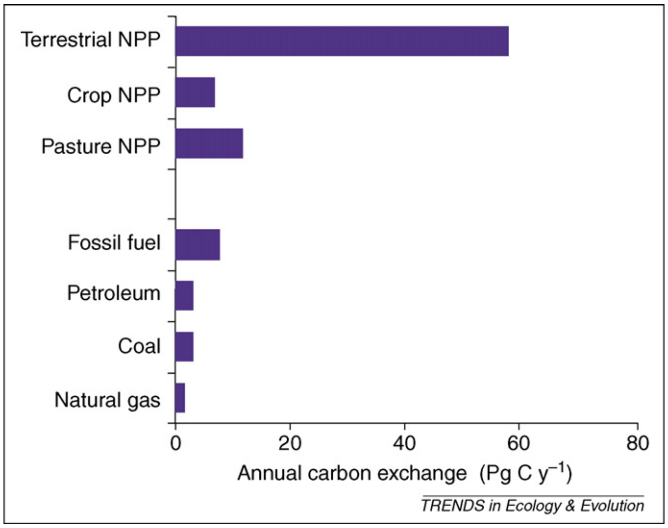

Figure 1. Global scale net primary production (NPP) and fossil fuel emissions. NPP values are for all terrestrial ecosystems, crops and pastures. The global NPP is from [11] and that for areas in crops and pastures is from [46]. Emissions of carbon from major fossil fuel sources for 2005 are from [10]. The energy content of terrestrial plants on a mass carbon basis is 50–100% that of fossil fuels.

The picture is more promising for other technologies. The pathway for sugarcane to ethanol has a net energy balance ratio of 8 to 10, mainly because of the use of the stalks as the heat source for the distillation step [9]. For biodiesel from soy the net energy balance ratio is 1.3 to 1.9 [18]. However, there are not enough of these crops for their corresponding biofuels to comprise a major part of the global energy system. Converting 100% of the global harvest of corn, sugarcane, soy and palm oil into liquid fuels, using the current technology, would provide fuel energy of ~3% of global primary energy from fossil fuel combustion and net energy (after subtracting the energy required to produce the fuels) of ~1.2% of the global primary energy from fossil fuel combustion (Table 1).

Much of the recent enthusiasm for increasing the production of ethanol is based on the prospect of ethanol from cellulose, using a class of enzymes responsible for the ‘jungle rot’ that destroyed many U.S. army tents in the South Pacific during World War 2. With cellulosic processing all parts of the plant can be processed to ethanol and the choice of plant is not limited to those plants that produce large amounts of starch or simple sugars. Although this process has not yet been implemented at industrial scale, results from pilot installations indicate that cellulosic processing might eventually yield 70 gallons of ethanol per ton of dry matter, only slightly less than current yields of ethanol from corn grain [19], with a net energy balance ratio that will possibly eventually be greater than 4 [18]. However, the prospects for ethanol energy from plants such as switchgrass *Panicum virgatum*, Miscanthus *Miscanthus x giganteum* and several tree species depend on the successful industrialization of cellulosic processing, which remains to be demonstrated.

Although much of the recent biomass energy discussion has focused on ethanol, biodiesel and other liquid transportation fuels, the opportunities for biomass as a source for direct combustion fuel can be comparable or even larger. Some heating and electricity-generating facilities are already biomass-based. Even power plants designed to

Table 1. Energy potential from biofuel crops using current technologies and future cellulosic technologies

Feedstock type	Feedstock mass 2002 (Mt y^{-1})	Gross biofuel conversion[a] (GJ/ton)	Gross biofuel energy[b] (EJ y^{-1})	Net energy balance ratio[c] (Output/Input)	Net biofuel energy[d] (EJ y^{-1})	Refs
Corn kernel	696	8	5.8	1.25	1.2	[18]
Sugar cane	1324	2	2.8	8	2.4	[9]
Cellulosic biomass	–	6	–	5.44[e]	–	[17,24]
Soy oil	35	30	1.0	1.93	0.5	[65]
Palm oil	36	30	1.1	9	1.0	[65]
Rape oil	17	30	0.5	2.5	0.3	[9]

[a] Useful biofuel energy per ton of crop for conversion into biofuel (1GJ = 10^9J).

[b] Product of feedstock mass and gross biofuel conversion (1EJ = 10^{18}J).

[c] Ratio of the energy captured in biomass fuel to the fossil energy input.

[d] Energy yield above the fossil energy invested in growing, transporting and manufacturing, calculated as gross biofuel energy × (net energy balance ratio −1)/net energy balance ratio.

[e] Not yet achievable at the industrial scale. Calculated assuming energy for biorefining does not come from fossil fuels.

run on coal can replace up to 10% of the coal with biomass. With appropriate technologies burning compacted biomass energy pellets as a heat source might be the most efficient commercial use of biomass energy [20].

Carbon balance and climate forcing

In an idealized case, biomass energy does not contribute to the forcing of climate change with greenhouse gases. A plant used for biomass energy grows by removing carbon dioxide from the air through photosynthesis. Using that plant as biomass energy returns the carbon dioxide to the atmosphere, with no net change in the amount of carbon in the atmosphere, plants, or soils. Real production systems differ from this ideal in three important ways.

First, as discussed in the previous section, the production of biomass energy almost always entails the use of fossil energy for the farming, transportation and manufacturing stages of the process [18]. Other greenhouse gas emissions from agriculture, particularly nitrous oxide, can greatly increase the net climate forcing from biomass energy production [21]. Because the 100-year global warming potential of nitrous oxide is 296 times that of carbon dioxide, small effects on nitrous oxide emission can have significant effects on overall greenhouse forcing.

Second, the net effect of biomass energy production on climate forcing needs to include changes in the carbon content of the site. Deforestation typically releases a large fraction of the tree and soil carbon to the atmosphere [22], even after accounting for the capture of carbon in wood products [23]. However, managing degraded farmland as perennial grassland harvested for biomass energy can, at least in some settings, increase soil carbon as a consequence of consistent inputs of root and shoot litter [24].

The third effect on climate forcing involves the balance between absorption and reflection of solar energy at the surface of the earth [25]. Darker vegetation produces local warming and lighter vegetation produces local cooling [26]. In general, the overall balance is that at high latitudes, forests (particularly evergreen forests) tend to warm the climate because they are darker than grasslands and crops. In the tropics the pattern is the opposite because forests increase evapotranspiration and cloud cover, which produces a cooling effect [27]. This cooling effect is in addition to the cooling effect of that caused by the trees storing carbon.

Past analyses of biomass energy have placed substantial emphasis on the first set of mechanisms related to the use of fossil fuels and the release of other greenhouse gases from farming and ethanol production. We view the second and third sets of mechanisms as equally crucial in determining the overall consequences of expanding biomass energy production.

The carbon balance consequences of converting a site to biomass energy production largely depend on the pre-existing vegetation and soil. The effects of deforestation can be particularly important when the amount of carbon lost during and after deforestation is large, which includes regions with high standing biomass or soil carbon [22], large amounts of coarse woody debris [23], or thick layers of peat [28]. From the perspective of the atmosphere, the carbon-balance consequence of deforestation for establishing biomass energy agriculture is the sum of losses from the deforestation, plus fossil fuel offsets from the biomass energy. Thus, replacing a forest with a biomass of 200 tons ha^{-1} with biomass energy agriculture producing a harvestable yield of 4 tons ha^{-1} requires ~50 years to reach the break-even point for carbon balance. Losses of soil carbon and energy costs or biomass losses during manufacturing extend this time. However, capturing some of the original forest biomass for energy could shorten the time to the break-even point.

Establishing biomass energy production on land degraded by agriculture, grazing, or erosion can have the opposite effect of deforestation, increasing ecosystem carbon stocks. Tilman *et al.* [24] estimate that low-input high-diversity grassland on degraded agricultural soils in Minnesota can sequester 1.2 tons carbon ha^{-1} y^{-1}, while still yielding more net biomass energy than ethanol from corn on a fertile site. In this study the sequestration of carbon in roots and soil is more than twice that delivered to biomass energy, meaning that the majority of the benefit in decreased climate forcing comes from restoring productive grassland and not from using harvested materials for biomass energy [24]. The climate benefits can be even greater from converting grassland to permanent forest with no harvest for biomass energy. Over a 30 year time period, the creation of permanent forest from cropland has carbon balance consequences that compare favorably with all of the existing technologies for liquid biofuel production [29].

For lands currently in agricultural production and not severely degraded, the carbon consequences of a transition to biomass energy will depend on the cropping system, the management practices and the inputs. Replacing an annual crop with a perennial will tend to increase soil carbon, but harvesting a larger fraction of the aboveground biomass will tend to decrease it [30]. Perhaps most importantly, competition of biomass energy with food production will tend to drive up crop prices, creating more incentive to deforest land for either food or biomass energy production. For example, the recent expansion of corn ethanol production in the United States has reduced the area planted and increased prices for crops such as soybean, which is a major crop on deforested land in Brazil [31]. The climate effects of crop to biomass energy conversion are probably global and indirect, with increased food prices in the global market stimulating deforestation or other land-use changes in areas remote from the sites of increased areas of biomass agriculture [32].

Land available for biomass energy production

The overall potential yield of biomass energy depends on the land area allocated to producing it. Many of the concerns about expanding the biomass energy industry involve the possibility that new production will occupy land needed for growing food and for conservation. The justification for this concern depends on the quantity and quality of alternative lands.

Economic models indicate that agriculture for biomass and agriculture for food will directly compete for land area. Even modest greenhouse gas regulations (e.g. US $20/ton carbon tax), combined with the successful industrialization of cellulosic ethanol manufacturing, could lead agriculture for cellulosic biomass to expand by 2050 to occupy a total area comparable to all current agricultural areas [1500 million hectares (Mha)] [33–37]. In this scenario, agriculture for biomass energy displaces significant areas of crop and grazing lands, and could more than double the price of food commodities on the global market [35,38]. This price increase, in turn, would probably lead to deforestation for agriculture in other parts of the world. The price increase could also constrain the growth of the biofuels industry [38]. In countries with developed economies, the increased food commodity prices should not alter food consumption [39]. However, on a global scale higher food prices could greatly increase malnutrition [38].

In addition to expanding into areas traditionally used for food production, agriculture for biomass energy could potentially move into other areas, including abandoned agricultural land, degraded land and other marginal land that does not have competing uses [24,40–42]. Although economic models show that biomass energy agriculture would displace food agriculture in a free-market economy, the expansion of biomass energy agriculture could be limited through regulations to surplus and abandoned areas. Based on the area of tropical lands formerly forested but not currently used for agriculture, settlement, or other purposes, Houghton *et al.* [43,44] roughly estimated degraded land available to be 500 Mha globally, with 100 Mha in Asia, 100 Mha in Latin America and 300 Mha in Africa. Using this area as a starting point Hoogwijk *et al.* [42] and Tilman *et al.* [24] estimate that the total NPP on this land, converted to ethanol with an efficient industrial process, could meet 2%–35% of global energy demand. The large range accounts for uncertainty in yields in each area but does not address additional uncertainty in the rough area estimates.

To provide a spatially explicit, independent estimate of the available area, we started with the HYDE 3 database [45], which includes gridded (5′ spatial resolution) estimates of crop and pasture area for each decade between 1700 and 2000. We calculated abandoned crop area (Figure 2b) in each grid cell as the difference between the maximum crop area (from 1700 to 2000) and the crop area in 2000 if the difference was positive. The same approach was also used to estimate abandoned pasture area (Figure 2d). The resulting abandoned area is 746 Mha. However, overlaying these data with current land cover maps derived from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data for 2004 [46] revealed that much of the abandoned agricultural area is currently in urban areas (3%) or that lands abandoned from pasture were actually converted to crops (33%). A fraction of abandoned cropland is probably currently used as pasture, although satellite land cover maps do not distinguish pasture from other grasslands. An additional fraction of the abandoned area (13%) is currently forested. We omit forested land from the available category because, as discussed above, conversion of forests to biomass energy production is unlikely to be an attractive option for reducing climate forcing. Excluding areas converted into crops, forests and urban areas, we estimate abandoned agricultural land at 386 Mha globally (Table 2). The regional distribution of agriculture and pastures is relatively certain, but the uncertainty for this abandoned area estimate is substantial (probably ± 50% or more).

Estimates of the amount of marginal land that has never been used for agriculture but that is potentially available for biomass energy production are even more uncertain. For example, Chinese officials project that the country, which has 130 Mha of arable land, has an additional 23 Mha of marginal land suitable for biofuel feedstock production. However, the economic feasibility of developing these remote, marginal lands is questionable [38].

Some biomass energy modeling studies project that additional areas beyond degraded, abandoned and marginal lands will become available as agricultural land is abandoned in response to surplus food supplies [41,42,47]. The estimated amount is as high as 2000 Mha in one study [41], which is more than the current global cropland area. By contrast, nearly all of the major international assessments of future food supply project a global expansion of crop area for food production, with particularly high rates in Africa and South America [48,49]. For example, the Food and Agriculture Organization of the United Nations (FAO) projects that the cultivated area for food in 2030 will be 120 Mha higher in developing countries than it was in 1999, with increases of 60 Mha in Sub-Saharan Africa and 31 Mha in Latin America and the Caribbean [48].

Potential yields of biomass energy crops

To estimate the potential for new biomass energy production that does not reduce food security, remove forests, or endanger conservation lands, we combine the estimate of available land, based on the HYDE 3 database

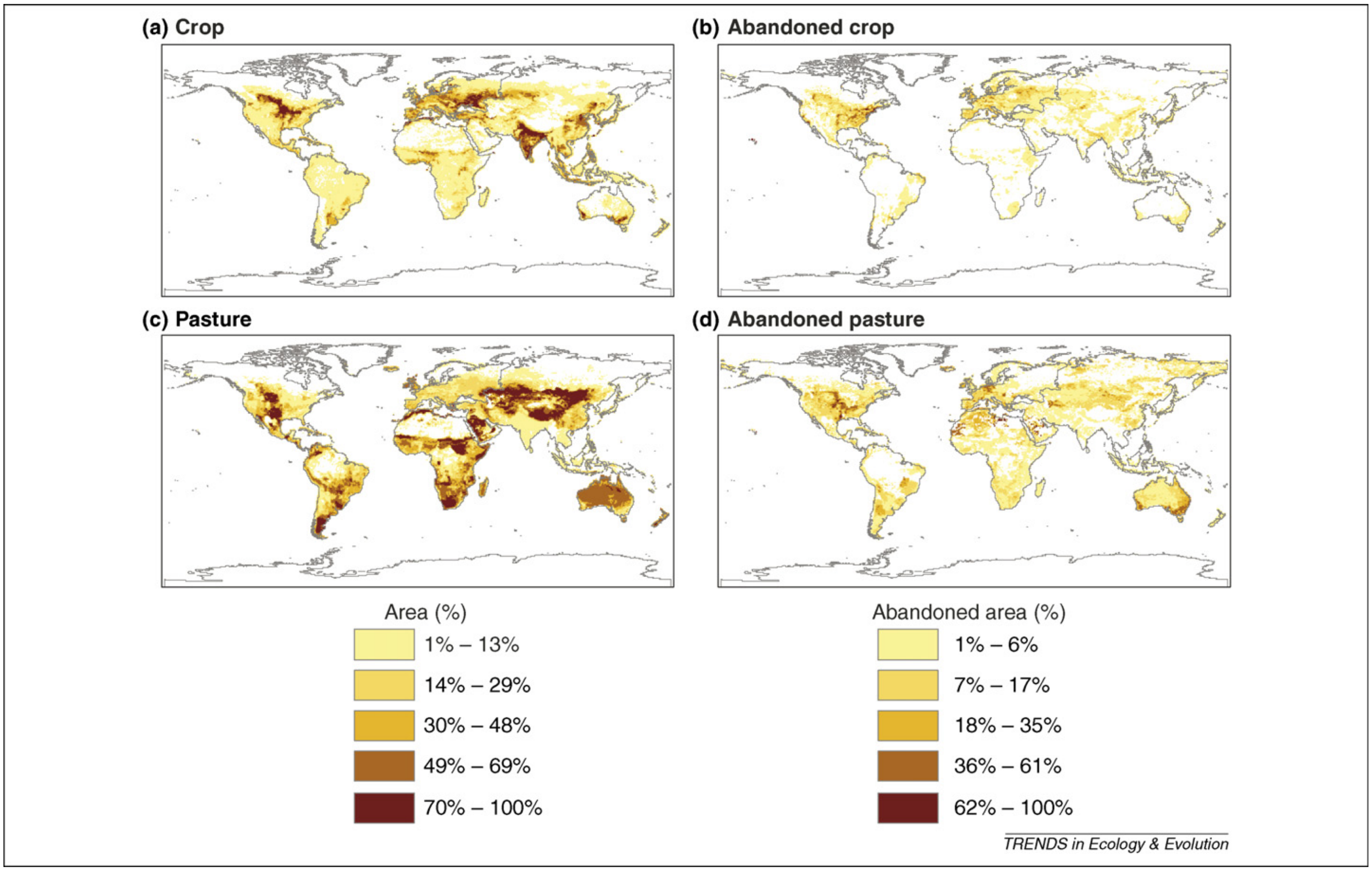

Figure 2. Global land areas in **(a)** crops, **(b)** abandoned crops, **(c)** pasture and **(d)** abandoned pastures as estimated from the HYDE 3 land-use change database, with a spatial resolution of 5′ [45]. Crop and pasture areas are for the year 2000. Abandoned areas are the positive differences between the pre-2000 maximum areas and the 2000 areas. This estimate misses areas where crops or pastures were shifted from one place to another, without a change in area, but the relatively high spatial resolution of the HYDE 3 dataset means that it should capture shifts of more than 10–20 km.

(Figure 3a) with climatological NPP (Figure 3b) [50] for each grid cell. Globally, the potential NPP on the available lands averages 3.2 tons carbon $\mathrm{Ha}^{-1}\ \mathrm{y}^{-1}$ (Table 2). Based on this approach, potential NPP on the land available for biomass energy production is 1.2 billion tons of carbon per year for the globe (Table 2). If we assume that half of this total is aboveground [51] (and therefore harvestable), that biomass is 45% carbon [52] and that dry biomass has an energy content of 20 kJ g^{-1} [52], this NPP of 1.2 billion tons represents a potentially harvestable energy source of ~27 EJ (1EJ = 10^{18}J), a little more than 5% of the 483 EJ of global primary energy consumption in 2005 [4].

These estimates of potential biomass from available lands are large enough to make a meaningful contribution to meeting future energy demand. They certainly do not suggest the possibility of a future energy system based largely on biomass. Is this really the limit of the potential? Here we argue that increasing the area beyond the 386 Mha used for the calculation runs the risk of threatening food security, damaging conservation areas, or increasing deforestation. Is increasing yield per hectare another option?

Literature estimates of biomass energy yields circa 2050 span a wide range, 2–25 tons carbon $\mathrm{ha}^{-1}\ \mathrm{y}^{-1}$ [24,53,54]. The lower end of this range is roughly half the average value for current croplands (Table 2). The upper end of this range is based largely on field trials of the tropical grass *Miscanthus x giganteus*, a candidate feedstock for cellulosic ethanol production [55]. Average yields over large areas are likely to be much lower than in these field trials because the available lands are likely to be at the lower end of the quality spectrum for fertility and climate. For example, although NPP on fields with contest-winning yields in Iowa are roughly 20 tons carbon $\mathrm{ha}^{-1}\ \mathrm{y}^{-1}$ [56],

Table 2. The global area and net primary production (NPP) in croplands, pasture lands and lands abandoned from cropping or pasture estimated from the HYDE 3 land-use change database and spatially explicit NPP estimates from [50]

Land type	Area (Mha)	Mean NPP (t C $\mathrm{ha}^{-1}\ \mathrm{y}^{-1}$)	Total NPP (Pg C y^{-1})[a]
Crop	1 450	4.7	6.8
Pasture	3 320	3.5	11.6
Abandoned	746	4.4	3.3
In forest	94	6.3	0.6
In crop	246	5.4	1.3
In urban	20	4.9	0.1
In other	386	3.2	1.2

[a] 1Pg = 10^{15}g.

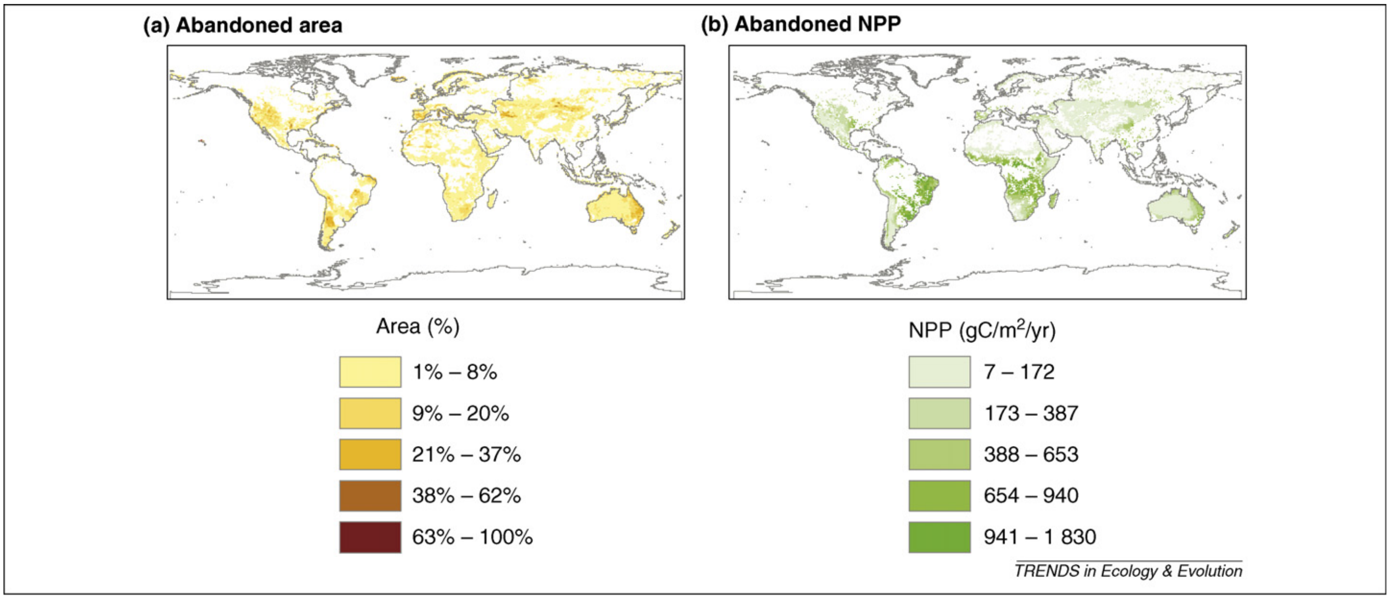

Figure 3. **(a)** Total abandoned land area, as in Figure 2, but summing over abandoned crop and pasture and excluding areas currently covered by forests, urban area and areas converted from pasture to crops and **(b)** net primary production (NPP) on this land, from [50].

average cropland NPP across a single county rarely exceeds 7 tons carbon $\text{ha}^{-1}\,\text{y}^{-1}$ [57].

In general, we expect that average NPP in biomass energy plantations over the next 50 years is unlikely to exceed the NPP of the ecosystems they replace. Rates of photosynthesis have not been increased through plant breeding [58] and native plants are typically more drought-resistant than agricultural species. Worldwide, NPP of croplands is roughly 35% below the NPP of 6.1 tons C $\text{ha}^{-1}\,\text{y}^{-1}$ for native vegetation on the same lands [12]. The main exception has been irrigated agriculture in arid regions [59], which is not a likely management system for biomass energy crops.

Technological progress will continue but improvements over the next 50 years are unlikely to push agricultural NPP above the NPP of native ecosystems. Economic models project that grain yields for major cereal crops, including maize, will increase by ~1% per year, or ~35% over the next 30 years [48,49]. These projections include assumptions of substantial improvements in crop varieties – albeit at slower rates than have occurred historically – as well as an intensification of inputs, with a 20% increase in irrigated area and >35% increase in fertilizer use [48]. These yield projections are probably optimistic relative to the biophysical potential of many intensive crop systems [60]. Moreover, some of the yield increase will be associated with greater harvest indices (the ratio of grain to total biomass), so that NPP will rise more slowly than grain yields. Thus, even with substantial external inputs, NPP for major food crops – whether destined for food or biomass energy uses – will probably remain below native NPP over several decades at least.

Modeled yield projections at the higher end of the range tend to be based as much on optimistic extrapolation as on analysis. For example, Hoogwijk *et al.* [41] set the parameters in their model to project that yields in 2050 will be 50% above levels currently considered the theoretical maximum for rainfed agriculture. Other studies using the same model set the parameters so that yields in 2050 are still below this theoretical maximum [61].

Climate change could also influence future yields of biomass energy crops. Maize and sorghum yields will probably decrease in response to warming, with an average ~8% yield loss for each degree Celsius [62]. The response of non-food crops to climate change is less well known, although one simulation study indicated that switchgrass yields in the Great Plains will increase by as much as 50% for 3.0–8.0 °C warming, because switchgrass experiences substantial cold temperature stress under current conditions [63]. In the US, switchgrass might gain an advantage relative to most other crops as the climate warms. This represents a potential adaptation option for farmers who currently grow maize or sorghum. Carbon dioxide fertilization effects on biomass energy crops such as maize and switchgrass will probably be small because they have C4 photosynthesis and are relatively insensitive to rising atmospheric carbon dioxide [64].

Conclusions

Global terrestrial annual plant growth is more than five times the ~8 billion tons of carbon released to the atmosphere in fossil fuel combustion. In principle, diverting a small fraction of total plant growth into biomass energy could satisfy the majority of global energy needs. However, the potential for producing biomass energy without negative climate or food security impacts lies mainly in the use of abandoned agricultural lands. The total aboveground NPP on these lands represents just 5% of global energy demand.

Previous studies have suggested that the area of abandoned and surplus agricultural land might expand greatly in the future, or that the use of tropical grasses might provide yields many times above native NPP. In our opinion, the balance of evidence indicates that both of these assumptions are too optimistic. Demands for land use in agriculture and grazing are unlikely to decrease.

Although agricultural yields will probably continue to increase, so will demands for food and grazing land, driven by a combination of increasing human population and increasing demands for a meat-based diet.

With surging interest and investment in biomass energy, it is crucial to recognize the risks as well as the opportunities in this area. At a scale consistent with the available resources, biomass energy presents a range of exciting opportunities for increasing energy independence, sustaining farm economies and decreasing the forcing of climate change. But deployed at a larger scale, it could threaten food security and exacerbate climate change.

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