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PERSPECTIVE

Bioenergy: how much can we expect for 2050?

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Abstract

Estimates of global primary bioenergy potentials in the literature span almost three orders of magnitude. We narrow that range by discussing biophysical constraints on bioenergy potentials resulting from plant growth (NPP) and its current human use. In the last 30 years, terrestrial NPP was almost constant near 54 PgC yr^{-1}, despite massive efforts to increase yields in agriculture and forestry. The global human appropriation of terrestrial plant production has doubled in the last century. We estimate the maximum physical potential of the world's total land area outside croplands, infrastructure, wilderness and denser forests to deliver bioenergy at approximately 190 EJ yr^{-1}. These pasture lands, sparser woodlands, savannas and tundras are already used heavily for grazing and store abundant carbon; they would have to be entirely converted to bioenergy and intensive forage production to provide that amount of energy. Such a high level of bioenergy supply would roughly double the global human biomass harvest, with far-reaching effects on biodiversity, ecosystems and food supply. Identifying sustainable levels of bioenergy and finding ways to integrate bioenergy with food supply and ecological conservation goals remains a huge and pressing scientific challenge.

Record-high prices for fossil fuels, concerns over imminent peaks of conventional oil and natural gas production and the necessity to reduce global GHG emissions to a level consistent with limiting global warming to 2 °C motivate an intensified search for renewable low-carbon energy. Biomass is an attractive option, due to its relatively low costs, its storability, and also because it can be rather easily substituted for fossil fuels in many important applications such as heat, power and mobility [1].

But how much bioenergy can we—or should we—expect the terrestrial ecosystems of the earth to deliver in the next decades? At present, some 55 EJ yr^{-1} (1 EJ = 10^{18} J) of bioenergy are produced globally which is 12% of fossil fuel use and almost 80% of all renewable sources [1]. However, diametrically opposed views on bioenergy's future prospects to deliver sustainable, low GHG energy abound in the scientific community. Some analysts expect biomass to provide large amounts of clean energy at acceptable environmental costs with little negative and large positive socioeconomic effects in the next decades. But others project low potentials and large adverse effects such as increased hunger, biodiversity loss and substantial GHG emissions. Estimates of global primary bioenergy potentials available around 2050 published in the last five years span a range of almost three orders of magnitude, ranging from ≈30 to ≈1.300 EJ yr^{-1} [2]. Recently, the IPCC Special Report on Renewable Energy [1] reported a huge range, as did the Global Energy Assessment [3].

One crucial piece of information that can help to tackle that conundrum has played a remarkably small role in that discussion: the current global annual biomass growth of green plants on the earth's lands (net primary production, abbreviated as NPP) and its use by humanity [4]. According to a recent metaanalysis, global terrestrial NPP is estimated to be approximately 56 GtC yr^{-1} with an uncertainty of ±15% (gigaton carbon per year is abbreviated as GtC yr^{-1}; 1 Gt = 10^9 tons) [5]. The best available consistent time-series data on global terrestrial NPP are being derived from remote sensing as part of the MODIS data product. According to that source, global terrestrial NPP stayed near to 53.6 GtC yr^{-1} without showing any discernible trend over the last 30 years. Year-to-year variation was stunningly low at <2% [6]. In other words, considerable global efforts to increase annual yields in agriculture and forestry through irrigation, fertilization or forest management have not increased total plant growth. According to standard conversion factors from the literature [7] the aboveground part of NPP is approximately 30 GtC yr^{-1} of biomass growth with a gross energy value of ≈1.100 EJ yr^{-1}, which thus represents the biospheric maximum capacity.

At present, humans harvest ≈230 EJ yr^{-1} worth of biomass for food, livestock feed (including grazing), fibre and bioenergy (a substantial fraction of which is derived from residues and waste flows). In order to produce that biomass, humans affect or even destroy roughly another 70 EJ yr^{-1} of biomass in the form of plant parts not harvested and left on the field and biomass burned in anthropogenic vegetation fires [8, 9]. Hence, some 800 EJ yr^{-1} worth of biomass currently remain in the aboveground compartment of global terrestrial ecosystems. Of this 800 EJ yr^{-1}, 48% grows in forest ecosystems, and much of the remainder in ecosystems which either cannot easily be exploited, such as tundra and drylands (28%), in national parks, conservation areas and wilderness or in cultivated ecosystems which are already heavily harvested (grazing lands, cropland). In order to meet their biomass demand, humans affect approximately three quarters of the earth's ice-free land surface [10] with huge implications for ecosystems and biodiversity.

Growth of human population to perhaps 9 billion around 2050, continuing economic growth and transitions towards richer diets with a higher share of animal products in emerging economies will probably result in a growth of global food production by 60–100% [11, 12]. These trajectories are not likely to result in the same growth rates in global demand for primary biomass and farmland area as the efficiency of human use of biomass as well as commercial agricultural yields have grown substantially in the last century [13] and are generally expected to continue to rise in the next decades [11, 12]. In the past 40 years, the cropland area required to meet humanity's rising food demand grew by approximately 30%, despite substantial agricultural intensification [14]. A continuation of current yield trends until 2050 will not suffice to meet the rising global food demand without further growth of cropland areas [15]. Hence, it seems unrealistic to expect that yield growth of food crops would free up large areas currently used as croplands for planting energy crops.

In the last century, yield growth and efficiency gains in biomass conversion and use kept growth rates of the human appropriation of NPP lower than those of population and economic development. If current trends of agricultural intensification and livestock feeding efficiency growth are projected into the future, meeting global food demand might be achieved without reducing the amount of annual plant production remaining in ecosystems, but only in the absence of large-scale additional bioenergy production [13].

The big contested issue is how much humans might derive from purpose-grown energy plants in the future. Large estimates of bioenergy potentials are contingent on assuming large amounts of purpose-grown bioenergy because residue potentials are limited. Large energy crop potentials can only be justified by assuming (1) the use of a large fraction of the earth's surface, (2) yields far exceeding current NPP, or both.

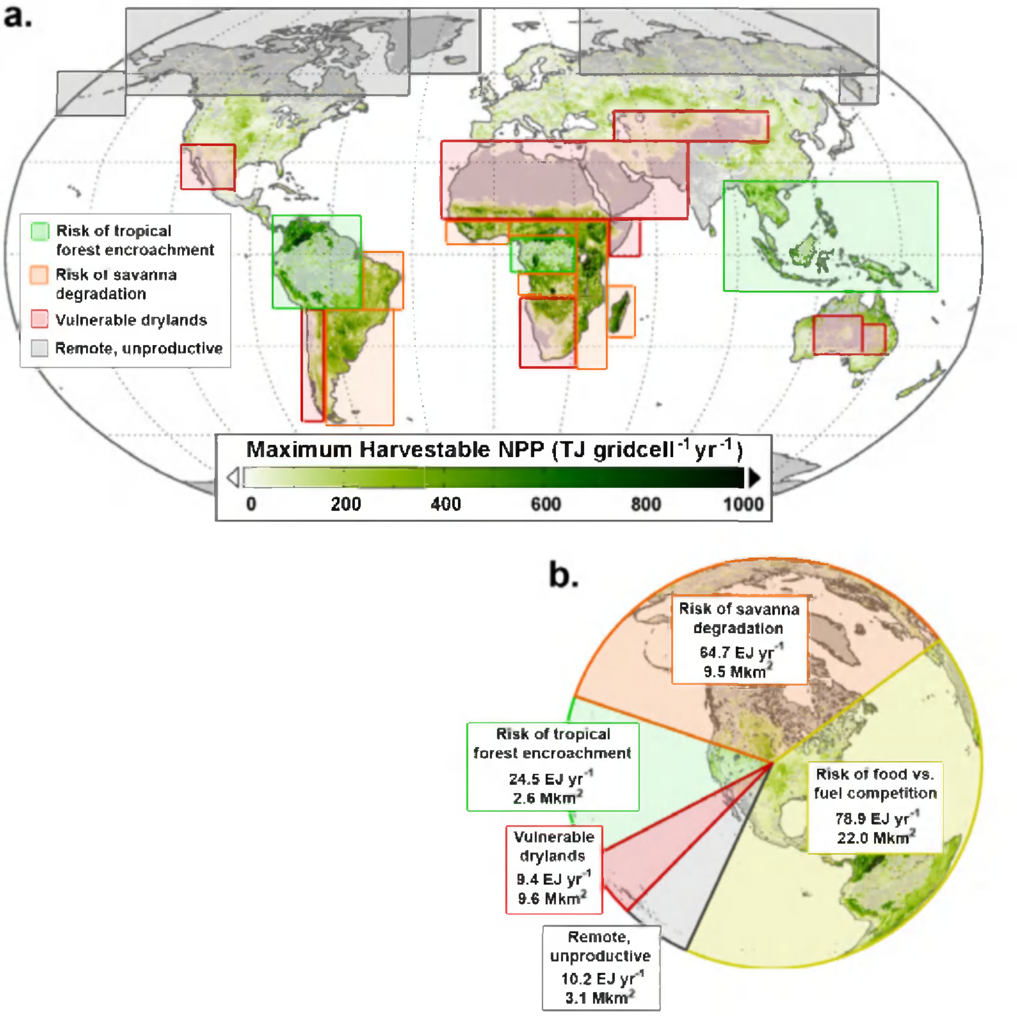

Figure 1. Map of the biophysical maximum biomass production ($\approx$190 EJ yr^{-1}) that might be generated from the 4.7 billion hectares of the world's vegetated land outside denser forests, croplands, urban areas and wilderness, outlining selected potential trade-offs and risks. Aboveground NPP of these areas was taken from [8, 10] from which biomass grazed by livestock [8, 9] was deducted. Numbers were adjusted to reflect the fact that on average less than three quarters of the annual productivity is accessible for harvest due to constraints resulting, among others, from seasonality, limits to harvesting efficiency or pre-harvest losses to wild-living heterotrophs.

The first option is both impractical and unsustainable due to the economic challenges associated with low energy returns per unit area, as well as the considerable additional pressures on biodiversity and substantial releases of CO_2 to the atmosphere from conversion of natural lands, above all forests [16].

The second option is questionable, given that current management inputs (e.g., fertilization and irrigation) have had a limited—if any—impact on global terrestrial NPP [4, 6], yet are quickly approaching sustainability limits [17]. High energy crop yields are often extrapolated from small-scale measurements to large areas, but this method is not suitable to estimate energy crop yields that can be achieved under field conditions in large regions [2, 4, 18]. Most notably, increases in irrigation have resulted in a doubling of global groundwater depletion rates from 1960 to 2000. Water extractions now far exceed natural recharge rates for numerous aquifers around the world [19]. Freshwater availability will likely become more limiting in the future due to climate change, perhaps even resulting in yield declines [20].

Figure 1 shows that optimistic assumptions regarding the fraction of the NPP currently remaining in land ecosystems that could be used for bioenergy suggests an upper biophysical limit for primary bioenergy of ≈190 EJ yr^{-1}. Forests are excluded (except for residues, see below) due to the high GHG costs of strongly increasing wood harvest [16, 21]. This would entail cultivating all vegetated lands outside denser forests, urban areas, cropland and the world's remaining wilderness areas at the highest conceivable exploitation rate, considering current livestock grazing. This hypothetical calculation implicitly assumes that these lands will be intensified to meet expected increases in feed demand for livestock. It also assumes that all other biomass production of the world's sparse woodlands, savannas and pastures can be diverted to bioenergy use, even as these lands simultaneously meet growing needs for grazing forage [10]. This is not an estimate of the upper limit of the sustainable bioenergy potential because the trade-offs in terms of social, economic and ecological (carbon, biodiversity, etc) impacts of such a massive intervention would be large although the full dimensions are at present unknown. Due to the risk of increased land competition, large-scale expansion of bioenergy crop production may result in substantial trade-offs with food production as well as with other important ecosystem functions and services such as carbon storage or nature conservation if not managed well [1, 3, 22–24]. Some of these trade-offs are depicted in figure 1.

Assessments of available residues, with only some exceptions [8, 9], do not account for the large volume of residues already harvested. In most of the world, residues are badly needed to maintain soil fertility [25], and even in the US maize belt, there is reason to doubt whether residues can be removed without productivity impacts or soil carbon loss [26]. Forestry residues might come to 20–40 EJ yr^{-1} in 2050, but only if all the world's forest slash were harvested and used [1–3]. Municipal wastes and biogas from animal manures could each provide some 10 EJ yr^{-1} [2, 3]. The upper biophysical limit for the bioenergy potential of residues is hence ≈60 EJ yr^{-1}, but would involve substantial trade-offs as well.

The challenges associated with bioenergy ultimately result from the fact that plant growth is an inefficient way of converting sunlight into useable energy. The energy efficiency of photosynthesis is usually $<1\%$ under field conditions [27]—far below the efficiency of commercial solar photovoltaic cells of 12–20% [1]. For food, and many fibre and wood products, people have no alternative to using plants, but for energy the detour via photosynthesis may in many cases result in exceedingly high land demand. Developing more efficient methods of storing solar energy than relying on plants (e.g., hydrogen produced from photovoltaic electricity) may hence be a more promising route.

Given the biospheric constraints outlined above, it seems impossible that bioenergy could physically provide more than ≈250 EJ yr^{-1} in 2050 [2, 4, 13], substantially below many published bioenergy projections. We consider that figure to be the upper biophysical limit and there are good reasons why even partially realizing this potential would entail substantial trade-offs and risks (figure 1). 250 EJ yr^{-1} equals 20–30% of global primary energy demand, assuming the range of energy demand scenarios in the Global Energy Assessment [3]. Reaching such a level of supply would require roughly a doubling of global biomass harvest in less than four decades and would result in massive increases in humanity's pressures on land ecosystems [13]. Large-scale promotion of bioenergy could result in economic incentives to divert land from food production to bioenergy which puts the world's poor at risk, driving up hunger and inequality. What international policies can prevent such adverse effects and instead foster sustainable production and consumption of bioenergy at sustainable levels?

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