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A reassessment of global bioenergy potential in 2050

STEPHANIE SEARLE and CHRIS MALINS
The International Council on Clean Transportation, I St NW, Washington DC 20008, USA

Abstract

Many climate change mitigation strategies rely on strong projected growth in biomass energy, supported by literature estimating high future bioenergy potential. However, expectations to 2050 are highly divergent. Examining the most widely cited studies finds that some assumptions in these models are inconsistent with the best available evidence. By identifying literature-supported, up-to-date assumptions for parameters including crop yields, land availability, and costs, we revise upper-end estimates of potential biomass availability from dedicated energy crops. Even allowing for the conversion of virtually all 'unused' grassland and savannah, we find that the maximum plausible limit to sustainable energy crop production in 2050 would be 40–110 EJ yr^{-1}. Combined with forestry, crop residues, and wastes, the maximum limit to long-term total biomass availability is 60–120 EJ yr^{-1} in primary energy. After accounting for current trends in bioenergy allocation and conversion losses, we estimate maximum potentials of 10–20 EJ yr^{-1} of biofuel, 20–40 EJ yr^{-1} of electricity, and 10–30 EJ yr^{-1} of heating in 2050. These findings suggest that many technical projections and aspirational goals for future bioenergy use could be difficult or impossible to achieve sustainably.

Keywords: bioenergy, biofuel, biomass, energy crops, potential, renewable energy

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Introduction

In the past decade public interest in bioenergy has grown, as has use of bioenergy for transport, heat and power. In 2010, bioenergy overall provided approximately 50 exajoule (EJ) or about 9% of all global energy (IEA, 2011). Transport biofuels constituted about 3 EJ of this; much of the remainder is used in a traditional form (e.g., cook stoves) and in some cases drives deforestation (Webersik, 2005). An increasing use of biofuels for transport and biomass for heat and power has largely been driven by government policies and regulations. It is likely that many countries will continue to support bioenergy in the future – the EU is considering setting a target for 50% of total energy consumption to be from renewable sources in 2050, which would amount to 39% from biomass following the current trajectory (European Commission, 2011, 2013). Such high targets for bioenergy appear achievable to policymakers when they are compared against projections like the IPCC's (IPCC, 2011) or the IEA's Biofuel Technology Roadmap (IEA, 2011), which, (based on many of the same sources) both estimate that 500 EJ yr^{-1} of biomass primary energy could potentially be available in 2050. Recently, however, the use of biofuels for transport has been questioned as the increasing diversion of grains and oils to fuels has increased food prices (Timilsina & Shrestha, 2010). Additionally, due to indirect land-use change some biofuels may not deliver the greenhouse gas reductions anticipated (Timilsina & Shrestha, 2010; Malins, 2012). Given these concerns, it is necessary to consider how much bioenergy could be produced sustainably in an increasingly constrained world, and how this may limit the contribution of bioenergy to renewable energy targets.

The IEA's bioenergy projection is informed by modeling studies that predict high technical global bioenergy production potential, but these studies have highly divergent results ranging from 27 to 1546 EJ yr^{-1} (Fischer & Schrattenholzer, 2001; Yamamoto *et al.*, 2001; Wolf *et al.*, 2003; Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007; Field *et al.*, 2008; Van Vuuren *et al.*, 2009; WBGU, 2009; Beringer *et al.*, 2011). For comparison, the world's total energy usage in 2008 was about 550 EJ and is forecasted to increase to about 650 EJ by 2050 (IEA, 2011). High bioenergy targets sound reasonable in the context of a potential bioenergy supply three times total current energy usage, but many of the scenarios in these studies contain assumptions that are unsupported by the scientific literature, as will be described below. Nevertheless, these studies are referenced in politically influential reports (IEA, 2011; IPCC, 2011) which, in turn, are utilized as justification for an expanding bioenergy industry. If targets driving bioenergy expansion run ahead of the world's ability to produce biomass sustainably, there are likely to be deleterious consequences to both food markets and climate goals.

Correspondence: Stephanie Searle, tel. +1 202 534 1612, fax +1 202 523 1601, e-mail: stephanie@theicct.org

In this study, we review ten key modeling studies projecting global biomass potential for all energy uses to 2050. We identify fundamental assumptions, assess values for these based on primary data sources, and apply adjustment factors to each study to ensure a consistent application of state-of-the-art scientific knowledge and generate revised biomass potential estimates. In the following sections, we discuss these assumptions and present the results of our reassessment.

Materials and methods

All studies reviewed here analyze the potential of dedicated energy crops, and some also included other feedstocks such as wastes, residues, and forestry (Fig. 1). Below, we list the key assumptions we have identified as drivers of the results and explain the basis of our revisions to make these plausible and consistent; first for energy crops, then for forestry, residues, and wastes. For each of the assumptions identified, additional literature review and discussion is included in the supporting online material. We apply adjustments to final biomass availability in each modeling study based on our revisions to each assumption. All adjustments are made assuming linearity (e.g., that halving the average yield would halve the potential).

Available land area

All the studies reviewed here state that bioenergy production should not come at the expense of food production or forests. They therefore model the land area for bioenergy crops by predicting the area of land needed for future food crops, keeping forest area constant, and subtracting these areas from total available land. Several studies assume that food crop yields will increase at high rates, such that even with a growing global population less rather than more cropland will be needed in the future to feed everyone (Wolf *et al.*, 2003; Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007; Field *et al.*, 2008), leaving up to one half of the Earth's land area (Wolf *et al.*, 2003) available. However, there is little basis for such an assumption. In reality, yield growth of cereals (the bulk of most people's diet) in $t\ ha^{-1}\ yr^{-1}$ has been slowing as we have already picked the low-hanging fruit of yield increase (Kucharik & Ramankutty, 2005; Brisson *et al.*, 2010; Finger, 2010; Lin & Huybers, 2012) – we have exhausted conventional breeding techniques and have saturated soils with fertilizer in the developed world (Evans, 1997). While there is in principle more potential to improve cereal yields in developing countries that have yet to implement technological innovations or cultivate the highest yielding varieties, the factors that have prevented this in the past (e.g., lack of infrastructure, access to capital, and materials) are likely to persist in the future.

In addition, one study reviewed here includes scenarios assuming global vegetarianism in 2050 (Wolf *et al.*, 2003), further reducing global cropland area as meat production requires more land and other resources than grains and vegetables (Bouwman *et al.*, 2005). Given more moderate expectations for meat consumption and for yield growth in food crops, it is clear that cropland must continue expanding to meet the needs of the world's population (FAO, 2003; Balmford *et al.*, 2005; Bruinsma, 2009; Wirsenius *et al.*, 2010). We calculate expected land use in 2050 as follows. We assume that all land that is not forest, wetlands, tundra, desert, cropland, or pastureland is potentially available for bioenergy production. As the conversion of all unused grassland and savannah would cause

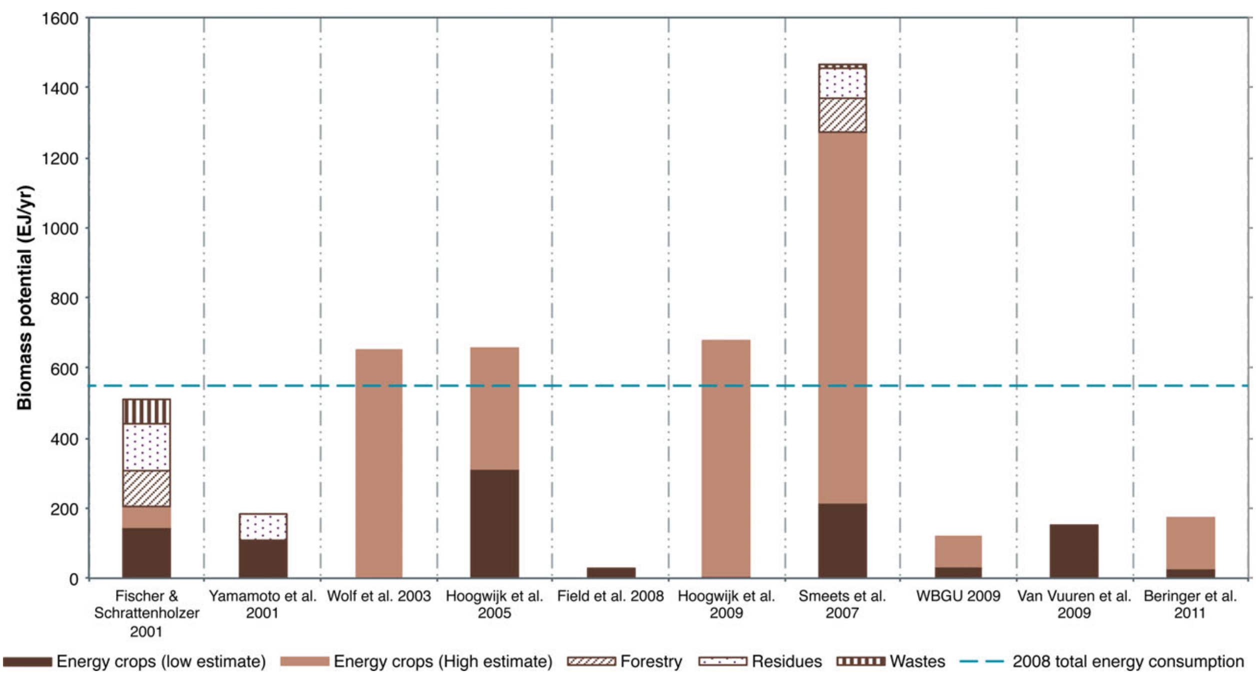

Fig. 1 Total biomass potential broken down by feedstock in original studies compared to world energy consumption.

extensive ecological damage, this can be considered to be an absolute upper limit on land availability. We use FAOSTAT for current areas of cropland, pasture, grassland/savannah, and forest. With yield growth of cereals starting to stagnate (Evans, 1997), all of the projections on future cropland area we found (not including biomass projection studies) predict an increase in the global cropland (FAO, 2003; Balmford *et al.*, 2005; Bruinsma, 2009; Wirsenius *et al.*, 2010) and pasture area (Wirsenius *et al.*, 2010) necessary to feed the world's population in the coming decades, with a median projection of about 10% total expansion of agricultural area. We apply this expansion to both cropland and pasture. We combine the FAOSTAT estimates of land area with the WWF Ecoregions database (Olson *et al.*, 2001) to estimate which ecosystem types are affected. We assume that cropland and pasture expansion occur proportionally on forestland and grassland/savannah. We assume that pasture occurs equally on all types of nonforest land. The remaining land is 499 Mha tundra, 1.4 Gha desert, 40 Mha wetlands, 128 Mha Mediterranean woodland, 218 Mha montane grasslands/shrublands, 356 Mha temperate grassland/shrubland, and 667 Mha tropical grassland/shrubland. We exclude tundra, desert, wetlands, and Mediterranean woodland due to biodiversity, high C stocks and/or difficulty to cultivate. The sum of remaining grassland/shrubland area is 1.24 Gha. Following Van Vuuren *et al.* (2009), we apply an accessibility factor of 0.75 to this estimate, for a final land availability of 930 Mha (accessibility factors of 0.75 and 0.5 are applied to abandoned agricultural land and natural grassland, respectively, in Van Vuuren *et al.*, 2009 to account for the protection of some areas for biodiversity and lack of roads or other infrastructure).

Energy crop yields

Just as food crop yields determine how much land may be available for bioenergy, future energy crop yields will determine how much biomass can be cultivated on the available area. Potential dedicated energy crops including perennial grasses like *Miscanthus* and switchgrass, and short-rotation forestry or coppice (SRC) using trees like poplar, willow, and Eucalyptus can be high-yielding, but have much lower yields on poor quality 'marginal land' than they do on the fertile land used in most trials. If the best land is to be reserved for food production as the studies suggest, then marginal areas are the ones likely to be available for biomass cultivation. Commercial scale yields are also generally lower than those measured in small plots due to biomass losses with drying, harvesting inefficiency under real world conditions, and edge effects in small plots. In addition, in the commercial production of biomass, plants are not cared for as meticulously as in experimental trials, with regards to weeding, pest and disease control, and thinning. In another study, (S. Searle & C. Malins, unpublished data) we show that typical current yields of dry matter on non-arable land for the highest-yielding biomass crops with complementary ranges are: 3–15 t ha^{-1} yr^{-1} for Miscanthus after drying; 3–10 t ha^{-1} $yr^{-1}$for poplar and willow SRC; and 5–15 t ha^{-1} yr^{-1} for Eucalyptus SRC.

Some studies (Hoogwijk *et al.*, 2005, 2009; Smeets *et al.*, 2007) predict that yields of these crops will increase substantially by 2050, much as yields of cereals like maize have increased over the past 50 years. However, there are reasons why energy crop yields are unlikely to grow as quickly as cereal yields have in the past – for example, major yield gains in cereals have come from increasing the ratio of grain to stalk, which would not increase the total biomass of a plant. Energy crops are more difficult to breed, have longer reproductive cycles, and have limited yield response to fertilizer. We expect overall slow yield growth of energy crops, especially for *Miscanthus* which is extremely difficult to breed (Lewandowski *et al.*, 2000). We project the average yield of these three crops in 2050 to be 7.5 dry t ha^{-1} yr^{-1}. This estimate is substantially lower than the 18 t ha^{-1} yr^{-1} assumed in Smeets *et al.* (2007), but for example is higher than the 3.2 t ha^{-1} yr^{-1} based on native vegetation that is used in Field *et al.* (2008) (Table 1). For studies that did not report average yield (Yamamoto *et al.*, 2001; Hoogwijk *et al.*, 2005, 2009; Van Vuuren *et al.*, 2009), we inferred it from the total biomass potential and land area.

Production costs

Biomass could, in theory, be cultivated on virtually all available land, but the economic reality is that even with policy support in some places yields will not be high enough to cover the cost

Table 1 Assumptions and energy crop potential in original studies. Cost viability in Van Vuuren *et al.* (2009) was determined but not applied to the reported energy crop potential

Study	Land area (Gha)	Energy crop yields (t ha^{-1} yr^{-1})	Fraction cost viable	Heating value ($MJ\ kg^{-1}$)	Energy crop potential ($EJ\ yr^{-1}$)
Fischer & Schrattenholzer, 2001;	3.3	4.4–5.7	1	Unclear	147–207
Yamamoto *et al.*, 2001;	0.4	13.1	1	Unclear	110
Wolf *et al.*, 2003;	0–7	4–7.3	1	18	0–648
Hoogwijk *et al.*, 2005;	3.5–3.7	4.3–9.0	1	15	311–1115
Field *et al.*, 2008;	0.4	3.2	1	20	27
Hoogwijk *et al.*, 2009;	3.5–3.7	4.3–9.0	0.48	15	130–270
Smeets *et al.*, 2007;	0.7–3.6	18	1	19	215–1272
WBGU, 2009;	0.2–0.5	7.5–10.8	1	19	34–120
Van Vuuren *et al.*, 2009;	0.7	10.1	(0.62)	Unclear	150
Beringer *et al.*, 2011	0.1–0.5	9.6–21.1	1	19	26–174

of production. Most of the studies reviewed here do not account for any cost limitation at all. While this may be appropriate for estimating the 'technical potential' for biomass, cost does need to be considered if policymaking is to be based on realistic expectations.

To project production cost, we follow the spatially explicit cost analysis reported in Van Vuuren *et al.* (2009), which is similar to that used in Hoogwijk *et al.* (2009). This study determined the response of biomass availability to price. Biomass, at least for power production, should be cost competitive with coal (\$41 t^{-1} or \$1.44 GJ^{-1} – US average price in 2011) (U.S. Energy Information Administration, 2011). We assume a carbon price of \$30 $t\ CO_2^{-1}$ (Stern, 2006) (this is also approximately the carbon price implicit in the US cellulosic biofuel tax credit of \$1.01 ga^{-1} assuming 80% GHG savings compared to fossil fuels). Also assuming 80% GHG savings of cellulosic biomass compared to fossil fuels, the price of biomass that would be cost viable is \$3.62 GJ^{-1}. Thus, we divide the global biomass availability at \$3.62 GJ^{-1} in the cost curve in Van Vuuren *et al.* (2009) by the total availability at any price. On this basis, 78% of the physical potential of biomass production would be economically viable in 2050. At the same time, we note that a stronger commitment to decarbonization could increase the global potential of cost-viable biomass to some extent. For example, a higher carbon price of \$100 $t\ CO_2^{-1}$ would increase the cost-viable fraction of biomass to 98% in this analysis.

Clearly, future carbon and energy prices are both highly uncertain, and costs of harvesting etc. similarly cannot be predicted with absolute precision. Any estimated future cut-off cost for economically viable biomass is therefore at least somewhat arbitrary. Today, cellulosic feedstocks are expensive to produce (\$5.04–6.18 GJ^{-1}, \$4.59 GJ^{-1}, and \$6.07–8.24 GJ^{-1} for perennial grasses, forestry residues and agricultural residues, respectively, calculated from the National Research Council of the National Academies (2011) assuming 15% moisture and the heating values described below). Still, we believe it is reasonable to expect production costs in this nascent industry to decrease over time as farmers gain experience. It is also likely that the price of energy alternative (here, coal) and/or the price of carbon will increase by 2050 to the point that a substantial fraction of biomass is cost competitive to produce. Various factors could push both willingness to pay and production costs either up or down as compared to what we have presented, and it is unlikely that either our proposed cut-off of \$3.62 or the Van Vuuren cost curve will be exactly matched in reality. Nevertheless, the cost of biomass production will place an important limit on potential future deployment, and therefore we prefer to make our best estimate based on existing literature rather than ignore this factor.

Governance quality

Many countries today are unstable and suffer from varying degrees of corrupt governance. While some countries will no doubt achieve improvements in governance in the period to 2050, the underlying problems in others are likely to persist or even worsen, and it is likely that some countries that are currently stable will become less stable over time. Corruption and lack of regulatory control have been linked to poor infrastructure development and low effectiveness of environmental regulation, both of which would limit the feasibility of large-scale sustainable biomass cultivation (Fredriksson & Svensson, 2003; Cubbin & Stern, 2006). For example, in Somalia it has been found that a weak government allows an illegal charcoal trade to deforest the country (Webersik, 2005). It is difficult to imagine that full exploitation of potential agricultural resources could be achieved sustainably in countries with limited capacity for and/or interest in environmental governance. Strong and effective governance will also be required to stop the traditional but unsustainable harvesting of firewood for cooking and heating (which will also require that more sustainable alternatives should be made available), and to ensure all sustainably harvested biomass is directed to the efficient forms of energy production assumed here (e.g., combined heat and power). WBGU (2009) recommends governance issues be considered in global biomass potential, but none of the studies reviewed here accounts for it in their final estimates.

We use the World Bank (2012) to quantify strength of governance in each country. We sum the ranks of the six factors in the WGI: Voice & Accountability, Political Stability/No Violence, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption, with a scale 0–600. From the combined rankings, we make weighted averages by area of countries in geographic regions defined in each modeling study. For regions with a rank >500, we assume all biomass potential could be achieved. A rank of 0 is associated with 50% biomass production potential (which is likely somewhat optimistic), and values 0–500 were accordingly assigned potentials linearly between 50% and 100%. The global adjustment factor is calculated as the average of these scores weighted by biomass potential in each geographic region. For studies that do not provide biomass potential by geographic region (e.g., Wolf *et al.*, 2003; Field *et al.*, 2008), we use the average adjustment factor from the other studies, which are all within a narrow range of 0.68–0.82. The governance adjustment is applied to all feedstocks. This adjustment factor is, necessarily, somewhat arbitrary, as the connection between governance and sustainable bioenergy production potential cannot be precisely quantified, and there is limited literature available in this area. Nevertheless, this issue must be addressed in a discussion of what level of aspiration for sustainable biomass production is reasonable, and is an important area for further work.

We apply adjustment factors to the results of each of the scenarios in these studies to bring their assumptions in line with best estimates from the scientific literature (Fig. 2).

Additional biomass potential can be found in forestry, forestry residues, crop residues, and wastes. Three studies (Fischer & Schrattenholzer, 2001; Yamamoto *et al.*, 2001; and Smeets *et al.*, 2007) include the potential of some of these feedstocks (Fig. 1), but due to methodological inconsistencies between them we do not perform a reassessment of these feedstocks as we did for energy crops. We derive independent estimates of the potential of forestry, wastes, and residues based on additional literature and our own analysis.

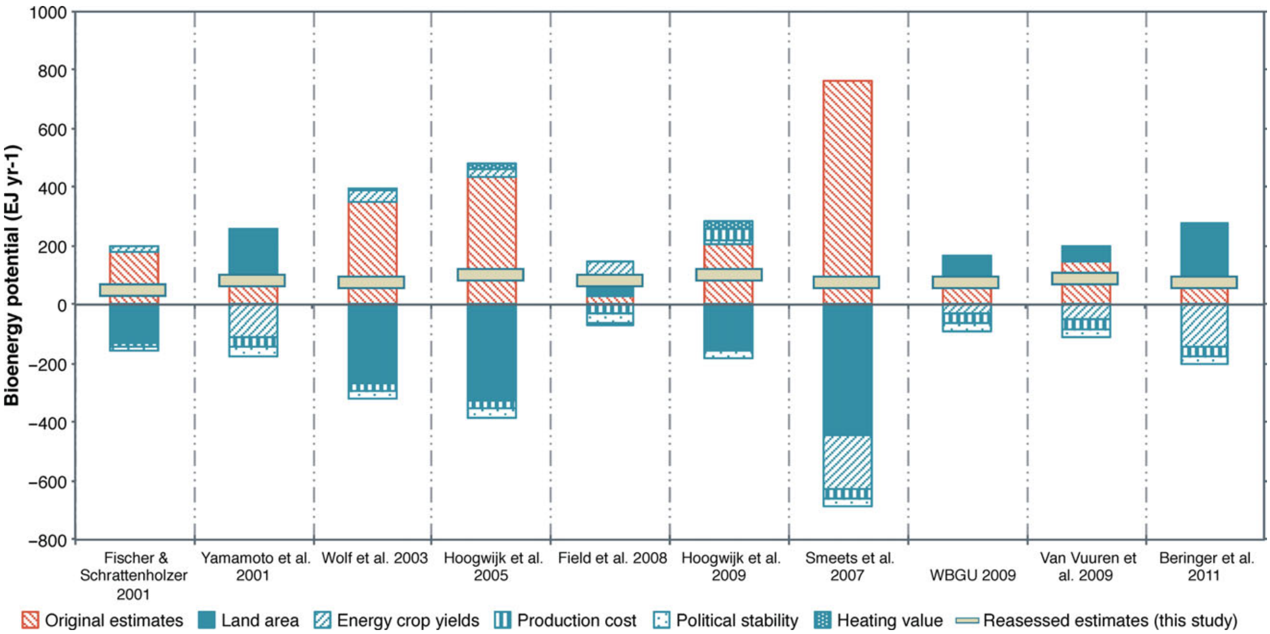

Fig. 2 Decomposition of reassessment for the 2050 potential from dedicated energy crops. Bars show original estimate (in cases with multiple scenarios, the average is shown), changes made by the reassessment, and final revised estimates in EJ yr^{-1}.

Forestry residues

Forestry biomass could potentially include wood and residues from natural forests and from plantations. Much of the world's wood harvests are from natural or unmanaged forests, especially in the tropics (Von Amsberg, 1994). We exclude the potential from natural forests because bioenergy from existing forest is likely to have a net negative impact on greenhouse gas emissions (Manomet Center for Conservation Sciences, 2010), and would severely impact total forest area, carbon stocks, and biodiversity (even if selective logging is used) (Gillman *et al*., 1985; Thiollay, 1992). Residues from natural forest logging (operations that exist for wood products, not energy) should not be used for energy because their removal would cause nutrient losses and reduced forest growth in the next cycle (Smith *et al*., 1994; Proe *et al*., 1996) and would thus be unsustainable. We also excluded increasing the harvest rate from plantations because existing and potential future plantations are not likely to meet or exceed the demand for wood products, according to our analysis (see Data S1), but some residues could sustainably be removed from wood plantations, where nutrients can be returned through fertilizer (Smith *et al*., 1994).

Using FAOSTAT data, we calculate the world total plantation area in 1990, 2000, 2005, and 2010 and consumption of roundwood and wood fuel in 1990, 2000, and 2005. We extrapolate linear trends (R^2>0.99) in plantation area and wood fuel to 2050; there is no time trend in roundwood and so we assume this to be constant. We estimated the quantity of wood and residues harvested yearly from plantations (assuming average plantation age of 30 years, average wood density of 0.5 g cc^{-1}, and typical plantation standing stock of ca. 93 *t* ha^{-1}; see Data S1). Wood consumption is and will continue to exceed supply from plantations (excess wood consumption is sourced through deforestation); thus we assume no availability of plantation wood for bioenergy. Assuming a residue generation factor of 0.3, about 280 Mm^3 or 4 EJ yr^{-1} of forestry residues would be produced in 2050 and potentially available for bioenergy. Adjusting for governance yields 3 EJ yr^{-1}.

Crop residues and wastes

Crop residues consist of the parts of the aboveground plant that are not eaten or have other primary uses (e.g., corn stover, wheat straw). The residue ratio, or ratio of residues to main crop, is typically around 1–1.5 for grains (Koopmans & Koppejan, 1997; Scarlat *et al*., 2010) and can be highly variable for other crops such as potatoes (0.5, Milbrandt, 2005) or soybeans (3.5; Koopmans & Koppejan, 1997). We made adjustments for the moisture content of residues and report availability in dry weight. We do not account for processing residues here. Some fraction of crop residues will not be harvestable for logistical reasons; e.g., straw and stover are cut a few inches above the soil surface and the resulting stubble cannot be harvested. To account for this, we assume only 90% of residue produced can be physically harvested. A fraction of crop residues should be left on the ground to prevent soil erosion and carbon and nutrient loss – it has been determined that 70% should remain in the field for this purpose (Andrews, 2006). We therefore assume that on average 20% may be sustainably harvested. A smaller fraction is used for animal bedding and horticulture; here we assume this to be 10% based on Scarlat *et al*., 2010. We calculate crop residue availability as:

Availability = ([crop production] × [residue ratio]) – [unharvestable fraction] – [fraction for SOC] – [fraction for other uses]

Using FAOSTAT data for crop production and literature sources for residue ratios, we calculate total residue production for the world's 12 crops with the highest annual production in

2011 (see Data S1). The available fraction, after accounting for harvesting losses, soil quality and other uses, amounts to 460 million tons or 8 EJ yr^{-1}. After applying the adjustments for cost and governance as described above, we arrive at 5 EJ yr^{-1} for total crop residue availability for bioenergy. As discussed above, we project global cropland area to increase to 2050, but since the harvest index of plants (the ratio of grain to residues) has increased over time for major grains (Calderini *et al*., 1995) and will likely continue to do so, we expect overall residue generation to be similar at the present.

Dung, in areas where it is collected (e.g., East Africa, Southeast Asia), is often used for fertilizer and is likely to be needed to support food crop yields (Lupwayi *et al*., 2000; FAO, 2003). While it is possible to produce biogas from dung and return the digestate to fields, it is not clear this would necessarily occur. In addition, dung serves functional purposes beyond its nutrient content, including adding to soil stability, moisture retention, and erosion prevention. Municipal solid waste, in areas with collection infrastructure, should be considered available for energy use – this has been estimated to amount to 5 EJ yr^{-1} (Shi *et al*., 2009), which, after applying the governance correction, is to 3.4 EJ yr^{-1} in 2050.

Heating values

The studies reviewed here evaluate the global biomass potential in units of mass and apply an assumed heating value to convert to primary energy. These values range from 15 MJ t^{-1} in Hoogwijk *et al.* to 20 MJ t^{-1} in Field *et al.* The average heating values (HHV for dry mass) we identified (Sannigrahi *et al*., 2010; see Data S1) are 19 MJ t^{-1} for our energy crop mix, 20 MJ t^{-1} for forestry and forest residues, 17.5 MJ t^{-1} for crop residues, and 17 MJ t^{-1} for MSW– we adjust biomass potentials accordingly. While it is possible that some of these studies, e.g., Hoogwijk *et al.* (2005, 2009), calculated yields on a fresh and not dry mass basis, our reassessment of their estimated potentials is based on dry mass (see section on Energy crop yields above), and so we utilize typical HHVs rather than LHVs.

Conversion efficiency

Some energy is always lost in the conversion to biofuel or electricity. We assume conversion efficiencies for both these processes will improve over the coming decades, from 80 to 87% efficiency in combined heat and power, producing about 60% electricity and 40% heating (Hedegaard *et al*., 2008; IEA, 2008) and from 30 to 60% efficiency in conversion to biofuel (including electricity generation from coproducts) (Hamelinck *et al*., 2005; IEA, 2008; National Renewable Energy Laboratory, 2011) and that the split in usage will follow current policy-driven trends in the U.S. and EU (see Data S1) (European Union Member States, 2010; U.S. Energy Information Administration, 2011). We assume that current inefficient usage of biomass in cook stoves and heating will be phased out, and that all biomass for energy outside of transport will go to CHP.

Results

In this study, we reassess previous attempts to model the global potential for biomass production in the year 2050. While the basic modeling approaches in these studies are valid, some input assumptions diverge from those indicated in the literature – these are shown in Table 1. Here, we make linear adjustments to global biomass potential with changes in input assumptions, for each of the reassessed studies. This coarse approach necessarily assumes linearity of final results with each input. As bioenergy potential in one of the major models used in these studies (IMAGE; Hoogwijk *et al*., 2009, 2005; Van Vuuren *et al*., 2009) is explicitly identified as linear with respect to energy crop yields, food crop yields (inversely) and land availability (Van Vuuren *et al*., 2009), and so we consider this approximation to be reasonable. All our adjustments based on revised input assumptions are shown by study in Table 2.

We reassess the modeled amount of biomass that can be produced on marginal land and report a revised

Table 2 Adjustment factors applied to the energy crop potential in each study. Factors without units are multipliers

Study	Original potential (EJ yr^{-1})	Land availability adjustment	Energy crop yield adjustment	Cost adjustment	Governance adjustment	Heating value adjustment	Revised potential (EJ yr^{-1})
Fischer & Schrattenholzer (2001)	147–207	0.28	1.32–1.70	0.78	0.82	N/A	45–49
Yamamoto et al. 2001	110	2.33	0.57	0.78	0.71	N/A	81
Wolf et al. (2003)	0–648	0.13–2.51	1.03–1.88	0.78	0.73	1.06	75–111
Hoogwijk et al.(2005)	311–1115	0.25–0.27	0.83–1.74	0.78	0.71–0.77	1.27	97–104
Smeets et al. (2007)	215–1272	0.26–1.27	0.42	0.78	0.73	1	65–87
Field et al. (2008)	27	2.33	2.34	0.78	0.73	0.95	79
Hoogwijk et al. (2009)	6–875	0.25–0.27	0.83–1.74	1.27–1.95	0.72–0.78	1.27	99–105
WBGU (2009)	34–120	1.88–3.91	0.69–1.01	0.78	0.73	1	76
Van Vuuren et al. (2009)	150	1.33	0.74	0.78	0.78	N/A	89
Beringer et al. (2011)	26–65	2.05–6.64	0.36–0.78	0.78	0.74	1	76–78

maximum potential of 40–110 EJ yr^{-1} in primary energy from dedicated energy crops, with a median estimate of 80 EJ yr^{-1}. The reassessed results for each study are shown in Fig. 2, along with a breakdown of the adjustments made for each assumption. When residues and wastes are combined with energy crops, a total of 60–120 EJ yr^{-1} is projected, with a median estimate of 90 EJ yr^{-1}. This estimate is for primary energy, or the inherent energy in the feedstocks before they are utilized.

Our reassessment significantly reduces the estimated potential from some studies (Fischer & Schrattenholzer, 2001; Wolf *et al*., 2003; Hoogwijk *et al*., 2005, 2009) but increases it in others based on more conservative assumptions (Field *et al*., 2008; WBGU, 2009; Beringer *et al*., 2011). Overall, our reassessed estimates are much more consistent than the original studies' estimates (Table 2, Fig. 2).

Some energy is lost upon conversion, and this fraction depends upon conversion method. We extrapolate current trends in policies supporting biofuels and biomass heat and power, and apply conversion efficiencies substantially higher than those achieved with typical current practice. This results in 20 EJ yr^{-1} (range 10–20) of biofuel for transport, 30 EJ yr^{-1} (range 20–40) of electricity, and 20 EJ yr^{-1} (range 10–30) of heating as final end-use energy consumption. For context, this amount of transport biofuel consumption is equivalent to about 3 billion barrels of oil per year (9 million barrels per day), or about six times current biofuel consumption. In power and heat, we have 10 million GWhrs of electricity and 20 EJ yr^{-1} of heating.

Discussion

The assumptions used in this reassessment are optimistic but reasonable – rapid technological progress, improved governance, continued yield growth – and so our revised estimate represents the maximum sustainable bioenergy potential that could realistically be achieved in 2050. Actually mobilizing this amount of energy sustainably would require strong political commitment both to support measures and to accompanying sustainability controls, and what will actually be achieved is almost certainly lower.

Previous studies (Hoogwijk *et al*., 2005, 2009; Smeets *et al*., 2007; Field *et al*., 2008; Van Vuuren *et al*., 2009; WBGU, 2009; Beringer *et al*., 2011), adopt two primary sustainability limitations (protection of forests and the food supply). Here, we adopt these as our only sustainability principles for bioenergy crop production, but we note that internationally recognized sustainability frameworks for bioenergy crops [such as the principles and criteria of the Roundtable on Sustainable Biomaterials (2013) and the sustainability indicators of the Global Bioenergy Partnership (2013)] suggest much broader sustainability assessment. Indeed, biomass projection studies that include more strict criteria protecting biodiversity (Field *et al*., 2008; WBGU, 2009; Beringer *et al*., 2011) tend to estimate lower biomass availability than others. It should be understood that allowing most grasslands and savannahs to be converted to managed bioenergy production is a strong assumption that would result in extensive biodiversity loss and significant land-use change emissions, not to mention creating enormous potential for land conflict. We have not assessed impacts on water availability of this level of bioenergy crop cultivation, or considered impacts on soils. We note that it will be very challenging to enforce a regulatory regime with global scope to ensure that any given set of sustainability criteria is enforced, even the limited principles we have used here, and hence in reality it is hard to imagine such a massive expansion of bioenergy taking place without at least some encroachment onto forest ecosystems and competition with food markets.

Applying the adjustments to bioenergy potential outlined in this study significantly reduces the estimate of potential in some studies (Fischer & Schrattenholzer, 2001; Wolf *et al*., 2003; Hoogwijk *et al*., 2005, 2009). Conversely, other studies apply conservative assumptions about yields or strict environmental standards with large conservation areas (Field *et al*., 2008; WBGU, 2009; Beringer *et al*., 2011) – thus our revisions increase rather than decrease the bioenergy potential from these scenarios. Our revised estimations of other studies' bioenergy potential fit within a narrower range than the original studies' estimates (Table 2; Fig. 2), confirming that differing inputs have been a significant driver of variability between model results in this field.

Importantly, our results of a maximum availability of 20 EJ yr^{-1} in biofuel, 30 EJ yr^{-1} of electricity and 20 EJ yr^{-1} in heating from biomass in 2050 are similar to IEA's predicted global demand for 32 EJ yr^{-1} of biofuel and 60 EJ yr^{-1} of electricity/heating in 2050 (IEA, 2011, 2012). Given that our estimated potential is a maximum value, it is clear that achieving bioenergy utilization at the level envisioned by IEA would require strong government commitment, and even then likely that demand could not be sustainably met. Furthermore, as policymakers continue to consider expanded use of end-use bioenergy policies, and as researchers consider the place for biomass as a feedstock for the road vehicle, aviation, chemicals and/or power sectors, it is important that adequate recognition should be given to likely resource constraints and the inevitability of intersectoral competition for the resources.

Policymakers around the world would greatly benefit from an improved understanding of the supply limits for sustainably produced biomass. Policies that promote bioenergy use could result in unmet targets, unsustainable practices, undermined climate mitigation goals, inadvertent deforestation, encroachment on the world's food supply, or some combination of these outcomes. Future bioenergy targets and scenarios ought to be consistent with global capacity, not only for biomass production but also for sustainability governance. Decentralized national or regional regulatory policies (e.g., for vehicles, aircraft, and power) that require or assume bioenergy use should explicitly acknowledge these constraints, whereby they are drawing from the same finite pool of biomass resources.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. A reassessment of global bioenergy potential in 2050.