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Bioenergy production potential of global biomass plantations under environmental and agricultural constraints

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Abstract

We estimate the global bioenergy potential from dedicated biomass plantations in the 21st century under a range of sustainability requirements to safeguard food production, biodiversity and terrestrial carbon storage. We use a process-based model of the land biosphere to simulate rainfed and irrigated biomass yields driven by data from different climate models and combine these simulations with a scenario-based assessment of future land availability for energy crops. The resulting spatial patterns of large-scale lignocellulosic energy crop cultivation are then investigated with regard to their impacts on land and water resources. Calculated bioenergy potentials are in the lower range of previous assessments but the combination of all biomass sources may still provide between 130 and 270 EJ yr^{-1} in 2050, equivalent to 15–25% of the World's future energy demand. Energy crops account for 20–60% of the total potential depending on land availability and share of irrigated area. However, a full exploitation of these potentials will further increase the pressure on natural ecosystems with a doubling of current land use change and irrigation water demand. Despite the consideration of sustainability constraints on future agricultural expansion the large-scale cultivation of energy crops is a threat to many areas that have already been fragmented and degraded, are rich in biodiversity and provide habitat for many endangered and endemic species.

Keywords: biodiversity, bioenergy, climate change, global biosphere model, mitigation

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Introduction

Recent analyses of the transformations required in the global energy system to mitigate dangerous climate change arrive at the conclusion that bioenergy will play an important part in the global energy mix of the next decades (van Vuuren *et al*., 2010a, b). Scenarios that assume, not unrealistically, that CO_2 emissions will continue to rise as they currently do for several more years and peak not before 2020 show a large bioenergy sector that would have to additionally be coupled with carbon capture and storage (Edenhofer *et al*., 2010; Leimbach *et al*., 2010) in order to still achieve a 2° target of maximal global warming with sufficient likelihood. Transitioning to a low-carbon energy economy while meeting increasing future energy demands would therefore require the rapid development of a large global bioenergy sector, producing between 150 and 400 EJ yr^{-1} (van Vuuren *et al*., 2010a, b). At this level, all available sources of biomass, dedicated energy crops, harvest and process residues as well as organic waste materials, need to be exploited at a large scale.

Additional arguments have been made for an expansion of bioenergy production: globally traded biomass could add to energy security by reducing dependence of nations on oil, coal and gas imports from limited regions (Ragauskas *et al*., 2006; IEA Bioenergy, 2009) bioenergy could, some proponents have argued, also create employment in struggling rural economies in the developed world, and provide new income opportunities for farmers in the developing countries and thus

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help alleviate poverty (Faaij & Domac, 2006; Mathews, 2007). Private businesses have entered this developing market, anticipating large commercial potentials, scaling up their investments in biofuels and other processing technologies (WBGU, 2009).

At the same time, there are major concerns about the introduction of another large land use sector that could further accelerate deforestation and biodiversity loss (Ehrlich & Pringle, 2008; Melillo *et al.*, 2009). If not managed correctly, the large-scale cultivation of energy crops and a substantial utilization of residues from agriculture and forestry, may actually increase greenhouse gas (GHG) emissions, environmental degradation, introduce new risks for food security and/or marginalize local communities (WBGU, 2009). Clearing carbon-rich ecosystems for biomass plantations leads to substantial losses of CO_2 from vegetation and soils into the atmosphere. If tropical forests or peatlands are converted, it may take >100 years until the associated carbon debt is compensated by the replacement of fossil fuels (Gibbs *et al.*, 2008; Searchinger *et al.*, 2008). The destruction or fragmentation of pristine ecosystems for new cultivated areas also contributes to the ongoing degradation of the World's biodiversity (Fitzherbert *et al.*, 2008; Eggers *et al.*, 2009). Most plants converted into biofuels today are modern food crops that are responsible for massive N_2O emissions and nitrogen leaching due to their overdependence upon agrochemicals (Crutzen *et al.*, 2008; Donner & Kucharik, 2008). In addition, biomass production is very water intensive and may thus contribute to regional water shortages, salinization and water logging (Tilman *et al.*, 2001; Gerbens-Leenes *et al.*, 2009). Some, however argue that biomass plantations, if managed well, may actually increase biodiversity (Semere & Slater, 2007; Baum *et al.*, 2009b) and soil qualities (Tilman *et al.*, 2006; Baum *et al.*, 2009a), at least on previously degraded land.

While the environmental sustainability of large-scale bioenergy production raises serious questions, the technology is still regarded as a key bridging technology during the transformation toward a low carbon society because it has the potential to deliver negative carbon emissions at comparatively low costs required for substantial emission reductions (WBGU, 2009). In this context, attempts have been made to estimate 'sustainable bioenergy potentials' on the basis of land use restrictions to avoid additional GHG emissions and biodiversity loss (Fang *et al.*, 2005; van Vuuren *et al.*, 2009; WBGU, 2009). Here we study the global potential of dedicated biomass plantations for bioenergy under environmental and agricultural constraints using an advanced biogeochemical model of plant carbon and water balances and study some of the broad implications that follow.

Biomass for bioenergy – The role of dedicated energy crops as a source of biomass

Different sources of biomass are available for energy production. These fall into three main categories: residues from agriculture and forestry, organic wastes, surplus forestry and energy crops. Dedicated energy crops are generally assumed to make up most of the total potential (Berndes *et al.*, 2003; IEA Bioenergy, 2009), although their large-scale cultivation is also one of the most controversial aspects of bioenergy. By contrast, residues and waste materials are considered to be more sustainable because they entail fewer direct impacts on land use (WBGU, 2009); their indirect impacts, however, are also discussed controversially. Agricultural residues, for example, are also required to maintain soil organic matter and prevent erosion and their excessive removal can damage soil quality and reduce agronomic productivity (Blanco-Canqui & Lal, 2009; Lal, 2010); in forests, detritus supports important elements of the ecosystem (Chapin *et al.*, 2002) and it's removal may lead to the depletion of nutrient pools essential for long-term soil fertility and plant growth (Akselsson *et al.*, 2007).

Recent analyses of energy crops have shown that current practices to convert food-product carbohydrates or plant oils into ethanol and biodiesel have only limited, if any capabilities to curb emissions (Crutzen *et al.*, 2008; Fargione *et al.*, 2008). They also compete directly with food production for the most fertile lands (Searchinger *et al.*, 2008; Melillo *et al.*, 2009; Lapola *et al.*, 2010). High hopes rest therefore on the development of second-generation bioenergy technologies based on the conversion of lignocellulosic plant materials from fast growing tree and grass species. These energy crops, such as poplar, willow, Miscanthus and Panicum (switchgrass) are less dependent on favorable climatic and soil conditions and require fewer inputs of agrochemicals, thus reducing their direct competition with food production. Because most of the harvested aboveground biomass is fed into a conversion process, per area energy yields and the potential to reduce GHG emissions are inherently higher (Farrell *et al.*, 2006; Adler *et al.*, 2007; Schmer *et al.*, 2008). Although technologies required to process cellulosic feedstocks into electricity, heat, biofuels or biomaterials are not yet commercially competitive, they are expected to mature within the next 10–20 years (Faaij & Domac, 2006; Ragauskas *et al.*, 2006).

But how large is the potential of global bioenergy plantations when environmental and agricultural constraints are taken into account? The literature on this question is quickly growing but currently shows a wide variety of estimates, ranging from some 30 to 700 EJ for the World's total bioenergy potential, not taking into account some extreme scenarios (WBGU, 2003; Tilman *et al*., 2006; de Vries *et al*., 2007; IFEU, 2007; Campbell *et al*., 2008; Dornburg *et al*., 2008; Field *et al*., 2008; van Vuuren *et al*., 2009; WBGU, 2009; Wise *et al*., 2009). For comparison, the World's current total primary energy supply is about 510 EJ a^{-1} (IEA, 2010) and expected to reach 600–1000 EJ a^{-1} by 2050 (IEA Bioenergy, 2009).

This is partially due to differences in assumptions and effects included, and partly due to tradeoffs with other interests on land determining the potential. Such tradeoffs cannot be resolved by science, only investigated. The requirements of environmental conservation, such as limiting future deforestation, and the emerging need to provide an additional 2–3 billion people with food and fiber by midcentury are the main factors competing with bioenergy production for land. Some published estimates indicate that a large bioenergy potential can be realized through the use of marginal or abandoned lands and utilizing the agricultural intensification potentials offering themselves on land, at least theoretically.

There are, however, major social risks involved in the use of abandoned or marginal land for biomass cultivation. These areas are often not privately owned and used by small-scale farmers and the rural poor for food crops, livestock grazing or fuelwood collection (WBGU, 2009). Large-scale land privatization may therefore lead to the displacement of rural communities (Cotula *et al*., 2009; Friends of the Earth Europe, 2010).

However, many of these studies have not been based on rigorous biogeochemical and bioclimatic analysis of plant growth potentials around the world, but have extrapolated findings from plantation field studies to the larger scale and have assumed rapid progress in corresponding bioenergy plant breeding (Smeets *et al*., 2007). For example, the strong limitations imposed upon global biomass potential due to limitations in the water available for plant transpiration (Rost *et al*., 2009) has been frequently underestimated or downplayed, if not ignored (Berndes, 2002). The magnitude of global bioenergy potential including such effects therefore remains uncertain.

The scope of this paper

It is the purpose of this paper to investigate the potential of lignocellulosic biomass plantations to contribute to a future global bioenergy mix, and to investigate some of the implied consequences. Assessments of global bioenergy potentials suffer inherently from a lack of data and limited field experience from extensive biomass cultivation. Large-scale plantations of lignocellulosic crops do not exist yet and it is debatable whether yield levels observed at controlled test sites are transferable to huge areas with less favorable climate, soil and management conditions.

Therefore, we use here a well-established and well-tested global biogeochemical model of plant growth, carbon exchange and water limitations, LPJmL (Bondeau *et al*., 2007), expanded to include biomass plantations, to compute state-of-the-art biogeochemical potentials under spatially varying present and future climatic conditions. Available observations from test plantations are used to validate the model and climate scenarios from the latest IPCC assessment report (Meehl *et al*., 2007) to simulate global future yield potentials. These estimates are combined with a set of four scenarios of land availability for biomass plantations that consider the spatial requirements for future food production and nature conservation. We then analyze the environmental consequences of these scenarios in terms of ecosystem change, freshwater consumption and fertilizer demand to highlight the order-of-magnitude of some inevitable consequences of currently so-called 'sustainable' bioenergy potentials.

Our study follows strictly a food first paradigm, assuming that a strongly increasing world calorie demand in the next 50 years will already require an increase in global food production by about 70% (FAO, 2009) that will in itself be a challenge and therefore land currently used for food and fiber production will not be available for dedicated biomass plantations, at least not by midcentury. In accordance with projections of the FAO (2003), we therefore exclude current agricultural lands from bioenergy production, recognizing that there may indeed be additional potential on these lands at least in some regions, and in some in the interim.

We note that our computations are made in the face of a number of fundamental uncertainties that remain: the extent of future yield improvements in species suitable for biomass plantations, most of which have not undergone extensive cultivation and breeding for this purpose (Karp & Shield, 2008); the magnitude of carbon dioxide fertilization effects on plant growth and the associated plant physiological effects of increased plant water use efficiency (Long *et al*., 2006; Oliver *et al*., 2009). Our study does not investigate the economic, political or institutional realism of these potentials, as we aim at determining the magnitude of the potential that could be achieved as the maximum under environmental and agricultural constraints. Real-world potentials will be lower and follow complex deployment pathways in time (Knopf *et al*., 2010).

Materials and methods

LPJmL DGVM

LPJmL is a model of the terrestrial land surface that represents both natural and managed ecosystems at the global scale (Sitch *et al.*, 2003; Bondeau *et al.*, 2007). Major ecosystem processes controlling plant geography, physiology, biogeochemistry and vegetation dynamics are represented in the model to simulate the exchange of carbon and water between the atmosphere and the land biota. Photosynthesis is calculated using a modified Farquhar scheme (Farquhar *et al.*, 1980; Collatz *et al.*, 1992) coupled to a soil water scheme (Neilson, 1995) to compute gross primary production and plant respiration (Haxeltine & Prentice, 1996). Soil respiration is estimated as a function of temperature and soil moisture based on a modified Arrhenius formulation (Lloyd & Taylor, 1994) in combination with an empirical soil moisture relationship (Foley, 1995). The diversity of the world's flora is described in the form of nine plant functional types, representing natural vegetation, and 12 crop functional types (CFTs), representing the most important economic crops (Gerten *et al.*, 2004; Bondeau *et al.*, 2007). LPJmL is driven by monthly fields of temperature, precipitation, cloud cover, atmospheric CO_2 concentration and soil texture (Sitch *et al.*, 2003). The model has been successfully evaluated against various observational data, such as net primary production (Cramer *et al.*, 1999), vegetation activity measured by leaf area index (Lucht *et al.*, 2002), biosphere–atmosphere carbon exchange over both natural and agricultural lands (Peylin *et al.*, 2005; Erbrecht & Lucht, 2006; Bondeau *et al.*, 2007), and runoff (Gerten *et al.*, 2004). The plant water balance as a limitation to agricultural production has also been studied (Rost *et al.*, 2009).

Recently, we developed LPJmL further to simulate the cultivation of cellulosic energy crops on dedicated biomass plantations. Three additional highly productive bioenergy functional CFTs were introduced into the model (Table 1), two tree species for temperate and tropical regions, and one fast growing grass. Note that due to the inherent uncertainty in the future performance of lignocellulosic energy crops, differentiating more types, though possible, does not yield increased accuracy, and that environmental variations alter potentials depending on location and year. Tree CFTs were parametrized as temperate deciduous, to match the field performance of poplars and willows, and tropical evergreens, respectively, to reproduce growth and biomass production of appropriate Eucalyptus species. Energy trees are managed as short rotation crops and coppiced every 8 years (Lemus & Lal, 2005). The implementation of energy grasses reflects growth and productivity characteristics of *Miscanthus* and switchgrass cultivars. To be noted is the fact that in contrast to other important agronomic species that use the C_4 photosynthetic pathway, such as Maize or sugarcane, *Miscanthus* can maintain high rates of photosynthesis at low ambient temperatures around 5 °C (Naidu *et al.*, 2003). Simulated grasses are harvested annually at the end of the growing season.

Freshwater availability for irrigation is calculated on the watershed level (Arnell, 2004), including only renewable water resources (Rost *et al.*, 2008). Irrigation of biomass plantations is possible where excess surface runoff is available after sufficient water has been allocated to food production and natural ecosystems (Smakhtin *et al.*, 2004).

Figure 1 shows simulated rainfed yield potentials of grasses and trees under current climate. In the lower panels, the reduction of yield levels relative to irrigated biomass cultivation highlights the spatial pattern of the impact of water stress on biomass cultivation (here measured as the ratio of not water-stressed to actual net primary production, i.e. annual growth).

This modified version of LPJmL was validated against observations both from existing biomass plantations as well as predictions of biomass yield levels in 2050 (Baral & Guhab, 2004; Clifton-Brown *et al.*, 2004; NRDC, 2004; Pellis *et al.*, 2004; Aylott *et al.*, 2008; Dowell *et al.*, 2009; Stape *et al.*, 2010).

Compared with the reference data, we find that LPJmL simulations of biomass yields are in the right order of magnitude and show a realistic spatial variability (Fig. 2). Among the different ecophysiological processes affected by climate change, the positive impact of elevated CO_2 on vegetation productivity, known as CO_2 fertilization, is the most important driver of rising biomass yields in the simulations. The magnitude of this effect is debated (Körner *et al.*, 2005; Norby *et al.*,

Table 1 CFT parameter values: minimum canopy conductance (g_{min}), leaf longevity (a_{leaf}), leaf (f_{leaf}), sapwood ($f_{sapwood}$) and fine root (f_{root}) turnover times, minimum coldest-month temperature for survival ($T_{c,min}$), maximum coldest-month temperature for establishment ($T_{c,max}$), rotation length (R) and maximum time before replanting of plantation (R_{max})

CFT	g_{min} (mms^{-1})	a_{leaf} (year)	f_{leaf} (year^{-1})	$f_{sapwood}$ (year^{-1})	f_{root} (year^{-1})	$T_{c,min}$ (°C)	$T_{c,max}$ (°C)	R (year)	R_{max} (year)
Tropical tree	0.2	2.0	2	10	2	7	–	8	40
Temperate tree	0.3	0.5	1	10	1	−30	8	8	40
C_4 grass	0.5	0.5	1	–	2	−40	–	–	–

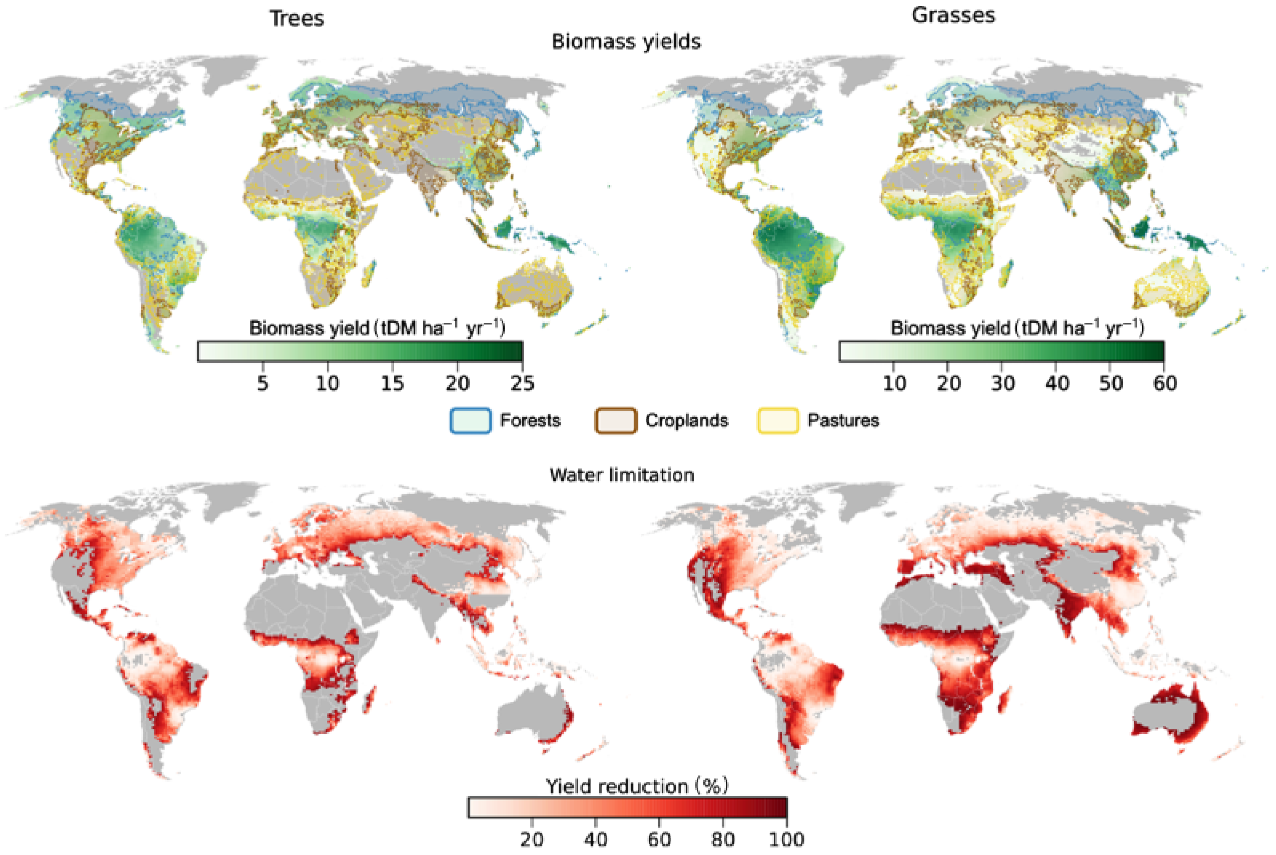


Fig. 1 LPJmL simulations of rainfed biomass yields and water limitation under current climate. The upper images show simulated biomass yields for woody and herbaceous energy crops averaged over the 1966–2005 period. Current distributions of croplands, pastures and forests are taken from the HYDE database (Klein Goldewijk, Beusen, De Vos, & Van Drecht, 2010). The lower part of this figure illustrates the reduction of potential rainfed biomass yields due to water limitations relative to irrigated biomass yields assuming unlimited water supply.

2005). Modeled net primary production of woody energy crops in 2050 is 20–30% higher compared with present climate and atmospheric CO_2 concentrations. CO_2-induced stomatal closure is responsible for higher water use efficiency through reduced transpiration and thus increasing soil water water availability. Largest gains in NPP occur in warm and dry regions where potential evapotranspiration is highest. These gains are well within the range of observed CO_2 fertilization in FACE experiments with poplar and other species grown as SRWC (Calfapietra *et al.*, 2003; Norby *et al.*, 2005; Liberloo *et al.*, 2006; Hickler *et al.*, 2008).

For this study, we ran LPJmL with 21st century climate projections from five general circulation models based on SRES emission trajectories A1B, A2 and B1 (IPCC, 2000) that were produced for the IPCC's fourth assessment report. The climate models selected due to their ability to reproduce current temperatures and precipitation correctly were ECHAM5 (Roeckner *et al.*, 2003), HadCM3 (Pope *et al.*, 2000), CM2.1 (Delworth *et al.*, 2006), ECHO-G (Legutke & Voss, 1999) and CCSM3.0 (Collins *et al.*, 2006).

Scenarios of land availability for biomass plantations

General land use constraints. In order to estimate future land availability for energy crop cultivation we used four scenarios (developed jointly with the WBGU for it's latest flagship report (WBGU, 2009)). These scenarios prioritize food security and climate change mitigation as central elements of sustainable land management (Steffen, 2009) and define a set of spatial constraints to reduce adverse effects of large-scale biomass cultivation on food production, biodiversity and GHG emissions (Balmford *et al.*, 2002; Millennium Ecosystem Assessment, 2005).

Some areas are completely excluded from any human use in all scenarios, such as conservation areas (WDPA, 2008) and wetlands (Lehner & Döll, 2004), that are home to a diverse range of species and store large

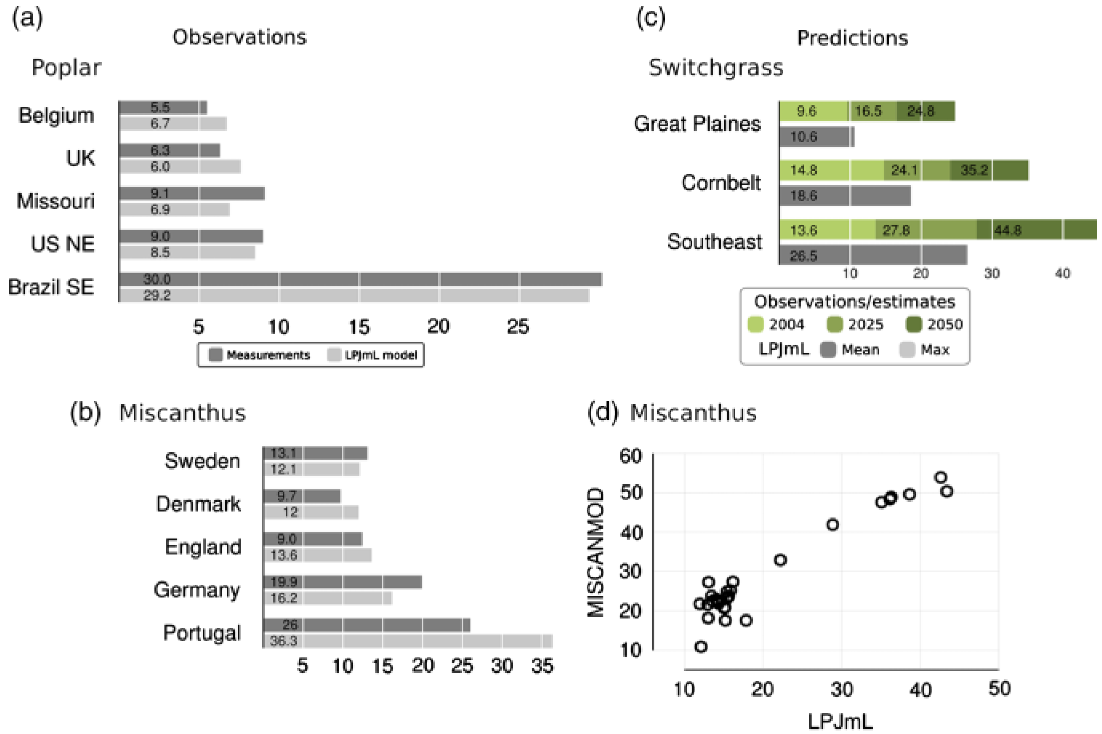


Fig. 2 Comparison of simulated biomass yields with observed (a) Poplar (Baral & Guhab, 2004; Pellis, Laureysens, & Ceulemans, 2004; Aylott *et al*., 2008; Dowell, Gibbins, Rhoads, & Pallardy, 2009; Stape *et al*., 2010) and Eucalyptus yields, (b) observed Miscanthus yields (Clifton-Brown *et al*., 2004), current and predicted yields of (c) Switchgrass in different regions of North America (NRDC, 2004), and with simulation results for Miscanthus cultivation in Europe from the specialized energy crop model MISCANMOD (Clifton-Brown *et al*., 2004). Annual biomass yields are given in metric tons dry-matter per hectare and year.

amounts of carbon. Forests and other important carbon reservoirs where simulated carbon losses after land use change are not compensated for by subsequent biomass yields within 10 years are also not used to calculate global bioenergy potentials. Likewise, the conversion of current croplands and pastures (Fader *et al*., 2010) was not allowed. Soil degradation may now affect nearly a quarter of the land surface (Bai *et al*., 2008), so that some areas potentially available for biomass plantations are likely to suffer from accelerated erosion, nutrient depletion or salinization and thus reduced yield potentials (Lal, 2009). It is assumed biomass cultivation is impossible on the most severely degraded soils (Oldeman *et al*., 1991) and achievable yield levels are reduced by 50% where degradation is high.

Land for food production. The first scenario (F1) follows a prediction by the United Nations Food and Agriculture Organization (FAO) in which cropland for food production expands by 120 M ha until 2030 (FAO, 2003). Based on LPJmL simulations of food crops, additional areas were allocated to the most productive lands. The second scenario (F2) assumes no further expansion of agriculture over the present extent. This implies that any increases in food demand are covered exclusively through intensified production. It also implies that the current agricultural land expansion (FAOSTAT, 2010) is brought to a halt. At the same, recent trends of declining yield increases have to be reversed and stabilized at about 1.2% per year, slightly below historical rates of yield increases that averaged 1.4% between 1970 and 1995 (Lotze-Campen *et al*., 2010). In view of progressive soil degradation (Millennium Ecosystem Assessment, 2005) and the increasing effects of climate change (Lobell *et al*., 2008) this is nevertheless an optimistic scenario.

Biodiversity and nature conservation. Likewise, two scenarios account for future needs in nature protection (Brooks *et al*., 2002; Rodrigues *et al*., 2004; Naidoo *et al*., 2008). Seven data sets featuring pristine wilderness areas [High-Biodiversity Wilderness Areas (Mittermeier *et al*., 2003), Frontier Forests (Bryant *et al*., 1997), Last of the Wild (Sanderson *et al*., 2002)] and areas with exceptional concentrations of biodiversity [Biodiversity Hotspots (Myers *et al*., 2000), Endemic Bird Areas (Stattersfield *et al*., 1998), Centres of Plant Diversity (WWF & IUCN, 1994) and Global 200 (Olson & Dinerstein, 2002)] were

Table 2 Share of natural areas within a grid cell excluded from biomass cultivation to conserve hotspots of biodiversity and valuable wilderness areas

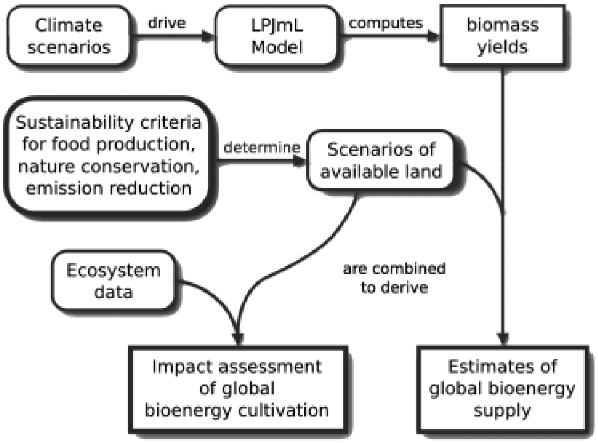
	Number of corresponding data sets							
Scenario	Wilderness indicators		Biodiversity indicators					
C1	0	1–3		0	1	2	3	4
C2	0–1	2–3	0-2				3	4
	0%	100%	0%	10%	20%	30%	50%	80%
	Share of exclusion areas in grid cell							

The spatial agreement between seven indicator data sets (Brooks *et al*., 2006) is used to assess the need for future protection: High-Biodiversity Wilderness Areas (Mittermeier *et al*., 2003), Frontier Forests (Bryant *et al*., 1997), Last of the Wild (Sanderson *et al*., 2002), Biodiversity Hotspots (Myers *et al*., 2000), Endemic Bird Areas (Stattersfield *et al*., 1998), Centres of Plant Diversity (WWF & IUCN, 1994) and Global 200 (Olson & Dinerstein, 2002).

used to derive conservation priorities. Following the approach of Brooks *et al*. (2006), the more of these data sets occur in an area, the higher the share of this area taken to be unavailable for energy crops (see Table 2 for an overview). Criteria for wilderness areas and biodiversity indicators are applied separately, with the more stringent rule applied. In the more restrictive conservation scenario C1, all wilderness areas included in at least one of the data sets are fully protected, while in scenario C2 areas are excluded if two or more wilderness indicators concur. For the biodiversity indicators, following the Convention on Biological Diversity's recommendations to establish a comprehensive and representative system of protected areas including all ecoregions (Secretariat of the Convention on Biological Diversity, 2006), 10% of all natural areas are always protected in C1. The proportion of land under protection rises to 20% where one biodiversity indicator is present, and to 30%, 50% and 80%, respectively, where two, three and four data sets concur. Scenario C2 is less stringent and excludes wilderness areas only if they appear in two or more data sets. In addition, 50% and 80% of the areas with high biological diversity are protected where three or four, respectively, indicators agree spatially.

Four scenarios of land availability are derived from the combination of all spatial constraints and scenarios for food production and nature conservation (Table 3). Figure 3 shows the spatial distribution of the different exclusion criteria in scenario III and the resulting land availability for biomass plantations.

Table 3 Brief overview of the four scenarios that define land availability for energy crop plantations



Scenario	*Description*
F1C1	Cropland expansion Higher nature conservation
F1C2	Cropland expansion Lower nature conservation
F2C1	No cropland expansion Higher nature conservation
F2C2	No cropland expansion Lower nature conservation

The flow diagram shows the methodology used here to estimate global bioenergy potentials.

Results

We find that global rainfed bioenergy potentials range between 26 and 116 EJ yr^{-1} by 2050 (Fig. 4). Of these, around a quarter originate from woody plantations assuming that short rotation and herbaceous crops are cultivated in equal shares where climatic conditions allow. Using renewable surface runoff for irrigation could increase bioenergy production from dedicated plantations to 52–174 EJ yr^{-1}. These potentials imply 142–454 M ha of new biomass plantations replacing natural vegetation, expanding the world's cropland area by another 10–30% over the current extent.

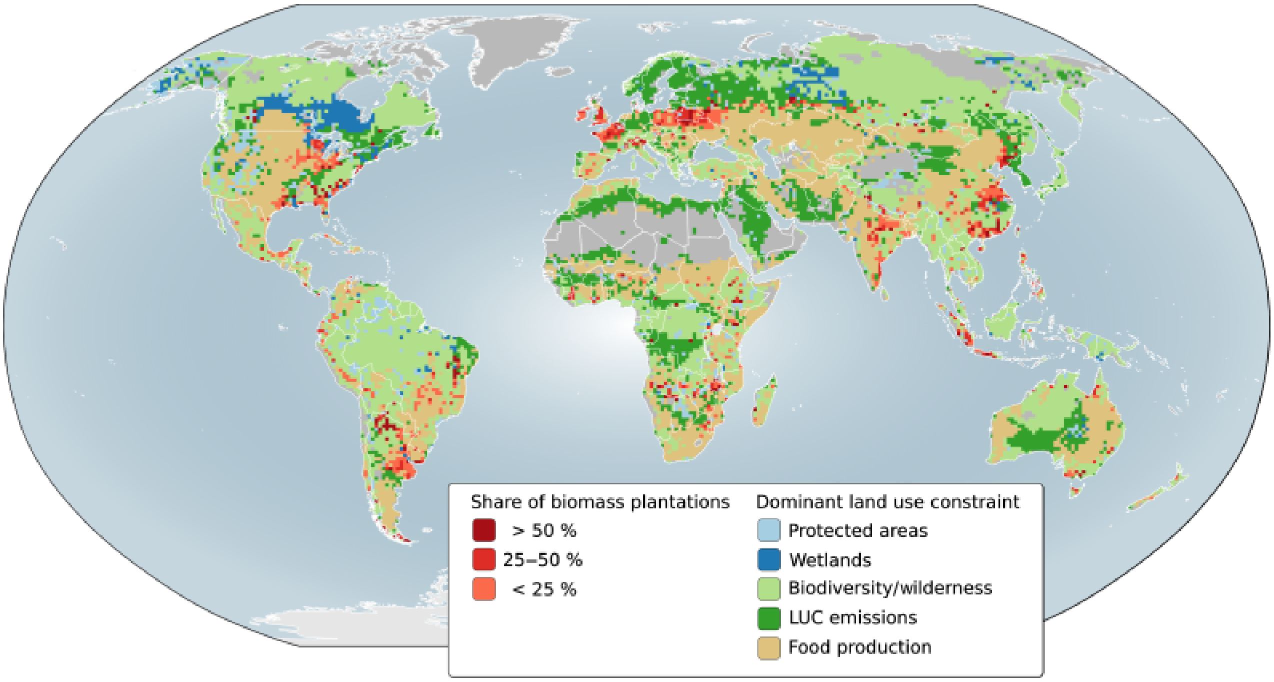


Fig. 3 Spatial distribution of potential bioenergy plantations and their relative share within grid cells in scenario F2C1. Dominant land use constraints are shown where the cultivation of energy crops is not allowed in this scenario. These areas are excluded because they are already protected (*protected areas*), belong to the World's remaining wetlands (*wetlands*), contain large contiguous areas of undisturbed ecosystems with high nature conservation value due to the provision of important ecosystem services or high concentrations of biodiversity (*wilderness/biodiversity*), carbon losses would result from land conversion that can not be compensated by subsequent carbon uptake within a compensation period of 10 years (*LUC emissions*), or because they are already agricultural areas required for food production (*food production*). Note that in most cases several constraints apply at the same time.

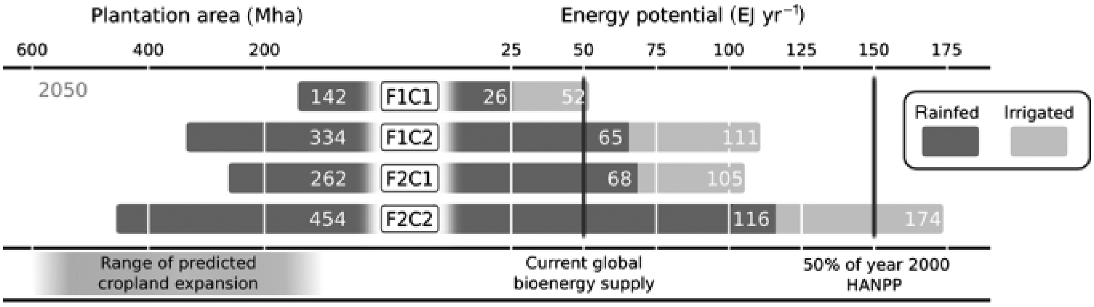


Fig. 4 Global bioenergy potentials and corresponding land requirements for dedicated biomass plantations in 2050 for all scenarios. The respective values appear inside the bars. For comparison, the current global bioenergy production is around 50 EJ yr^{-1}. The gross calorific value of all harvested biomass in the year 2000 amounted to about 300 EJ (Haberl *et al.*, 2007), Increasing the World's energy crop production to 150 EJ would thus raise the human appropriation of net primary production by 50%. Recent estimates of future agricultural expansion for food production range between 100 and 600 M ha (Rockström *et al.*, 2007; OECD, 2008; Erb *et al.*, 2009; IAASTD, 2009).

In our simulations water consumption for irrigation of biomass plantations amounts to 1481–3880 km^3 yr^{-1}. In other words, while using all renewable water resources for biomass cultivation increases bioenergy production by 70% on average, agricultural irrigation water use would approximately double compared with current values of about 2500 km^3 yr^{-1} (Rost *et al.*, 2008). Realistic and achievable shares of irrigated energy crop cultivation are probably much smaller, because major parts of the land that might be used for energy crops are located in developing countries where water requirements for food production are expected to increase significantly during this century (CAWMA, 2007) and economic conditions may constrain the implementation

Table 4 Relative contribution of different world regions to global bioenergy potentials from biomass plantations averaged over all scenarios

	Share of global bioenergy potential in world regions (%)				
	SAM	ESA	AFR	EUR	NAM
2050	26	18	17	14	11

AFR, Sub-Saharan Africa; ESA, Eastern and Southern Asia; EUR, Europe; NAM, North America; SAM, South America.,

of large-scale irrigation systems and advanced water management strategies (Rost *et al*., 2009).

Some regions with favorable climatic conditions and abundant land resources appear particularly suitable for the large-scale cultivation of energy crops. South America alone is responsible for about a quarter of the total bioenergy potentials in the four scenarios. Together with Sub-Saharan and Southern Africa, North America, China and Europe, they provide about 75% of global biomass yields (Table 4).

Establishing and maintaining large supplies of bioenergy from dedicated energy crops as described by our scenarios will increase the pressure on the World's land resources substantially and thus poses large challenges for infrastructural and institutional capacities, especially if, for example, modern irrigation technologies need to be installed or biomass certification systems have to be implemented. Converting 142–454 M ha of natural ecosystems into modern biomass plantations until 2025 means that on average between 10 and 30 M ha of new plantations are taken into operation each year. Compared with the 1961–2005 period when about 14 M ha of new permanent crops and pastures were developed annually (FAOSTAT, 2010), land use change activities would have to double on average for bioenergy alone.

Nutrients extracted from the soil when biomass is harvested need to be replaced in order to sustain high yields in the long term (Karp & Shield, 2008). Following Crutzen *et al*., (2008), we estimate the global demand for fixed nitrogen from the nitrogen content of the biomass removed from the fields. Assuming that cellulosic biomass contains about 0.5% N in the dry matter (Kauter *et al*., 2001; Karp & Shield, 2008), we estimate the global demand for fixed nitrogen from dedicated biomass plantations to range between 7 and 31 Mt N. This corresponds to average application rates of 50–70 kg N ha yr^{-1}, which is in line with recent studies of well-managed energy crop cultivation at different sites (Fike *et al*., 2006; Lewandowski & Schmidt, 2006; Karp & Shield, 2008; Schmer *et al*., 2008). At this scale, the cultivation of biomass will increase the projected demand for nitrogen fertilizer in 2030 by 4–23% (Tenkorang & Lowenberg-DeBoer, 2008) beyond expected short-term production surpluses of 15 Mt in 2011/2012 (FAO, 2008).

Discussion

We find that biomass plantations have the potential to become a significant source of renewable energy even if sustainability guidelines for climate mitigation and nature protection constrain the availability of land resources. Given that residues from agriculture and forestry, municipal solid waste and animal manures may provide around 100 EJ yr^{-1} (IFEU, 2007; IEA Bioenergy, 2009; WBGU, 2009; Haberl *et al*., 2010), the total bioenergy potential for the year 2050 ranges between 126 and 216 EJ, equivalent to about 13–22% of the World's primary energy demand in 2050 (IEA, 2009). Depending on the share of irrigated biomass plantations, the contribution of bioenergy may rise to 15–27%.

Our results are in the lower range of recent bioenergy modeling studies. These tend not to consider water constraints on rainfed and irrigated biomass cultivation, as well as the impacts of future climate change on plant productivity (Hoogwijk *et al*., 2005; Smeets *et al*., 2007). In addition, these assessments assumed massive increases in crop yields above historic levels so that large amounts of agricultural land are abandoned in the future and become available for bioenergy crops. Assuming extensive land abandonment also contradicts recent findings from international assessments of future changes in land use that project further expansion of croplands (Field *et al*., 2008). A worldwide decrease in meat consumption could reduce agricultural land demand for food and feed production significantly (Stehfest *et al*., 2009) and improve the opportunities for biomass cultivation (Erb *et al*., 2009). But recent trends in dietary habits toward larger shares of animal products as a main driver of deforestation and expansion of agricultural areas do not show any signs of a decline in global meat demand (Nepstad *et al*., 2008; McAlpine *et al*., 2009).

Exploiting these potentials will, however, incur significant additional human interventions in the environment as newly established energy crop plantations are responsible for the largest share of global biomass production. Human land use is already the most important driver behind environmental degradation (Foley *et al*., 2005), biodiversity loss (Butchart *et al*., 2010) and fresh water consumption (Rodell *et al*., 2009), and if energy crops are not restricted to abandoned and surplus agricultural land, the spatial expansion of agricultural activities could affect a large number of natural ecosystems, many of which already under significant pressure from habitat loss and fragmentation. Limiting extensive biomass plantations to marginal lands could reduce some of the environmental risks, but may threaten rural livelihoods. Owing to it's large requirements for space and the need for a rapid development of new plantations in the face of climate change and the peak oil debate, bioenergy may become one of the most important drivers of global environmental and social change in the coming decades.

In our scenarios, about 40% of the prospective biomass plantations replace natural grasslands and shrublands, 10% seminatural vegetation in the vicinity of existing agricultural areas and about 30% would be developed on now forested areas (ESA, 2009). Even though the use of sustainability constraints preserves the most important hotspots of biodiversity and carbon reservoirs in the scenarios, the ecological, economic and social value of natural areas that remain potentially available for energy crop cultivation can still be very high. A spatial analyses with the 'Terrestrial Ecoregions of the World' data set (Olson *et al*., 2001) reveals that many of the affected regions feature a large diversity of wildlife.

Examples include European and North American temperate forests and grasslands, which have a long history of human land use and where the remaining patches provide habitat for endangered and endemic species. Even though favorable climatic and soil conditions allow for high potential yield levels and GHG emission reductions, converting these iconic landscapes into large-scale biomass plantations may not be regarded as socially acceptable. Available lands in South America are mainly located in the semiarid scrub forests of the Caatinga, the biologically rich Cerrado savanna, the savannas and thorn forests of the Chaco and the grasslands of the Humid Pampas. All of these regions are rich in biodiversity with a large share of endemic species and have been greatly reduced by human activities. A similar picture emerges for Africa, India, and China, where population growth, land fragmentation and overexploitation of water resources drive widespread habitat destruction and degradation. Despite the consideration of land use constraints for climate mitigation and nature conservation, the environmental sustainability of dedicated biomass plantations outside areas of abandoned or degraded croplands seems questionable.

A possible twofold increase in irrigation water requirements, global cropland increasing by up to 30% for energy crops alone, and additional nitrogen demand that may exceed future fertilizer production illustrate the great challenges of integrating large-scale bioenergy into global sustainable land use. Bioenergy will only contribute to greater energy security, reduced emissions of greenhouse gases, and rural development if coordinated transformations in agriculture, energy systems, environmental protection, international trade and global cooperation are achieved. Global land policy, including but extending climate policy, needs to develop a range of new cross-sectoral instruments, including biomass certification schemes (WBGU, 2009) and precise carbon accounting (Searchinger *et al*., 2009), to optimize environmental and social benefits of bioenergy.

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