GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012), doi: 10.1111/j.1757-1707.2012.01169.x

INVITED EDITORIAL

Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral

ERNST-DETLEF SCHULZE*, CHRISTIAN KÖRNER†, BEVERLY E. LAW‡, HELMUT HABERL§ and SEBASTIAAN LUYSSAERT¶

*Max-Planck Institute for Biogeochemistry, Box 100164, 07701, Jena, Germany, †Institute of Botany, University of Basel, 4056, Basel, Switzerland, ‡Department of Forest Ecosystems and Society, Oregon State University, 321 Richardson Hall, Corvallis, OR, USA, §Institute of Social Ecology Vienna, Alpen-Adria University Klagenfurt, Wien, Graz Schottenfeldgasse 29, 1070, Vienna, Austria, ¶Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA CNRS UVSQ, Centre d'Etudes Ormes des Merisiers, 91191, Gif-sur-Yvette, France

Abstract

Owing to the peculiarities of forest net primary production humans would appropriate ca. 60% of the global increment of woody biomass if forest biomass were to produce 20% of current global primary energy supply. We argue that such an increase in biomass harvest would result in younger forests, lower biomass pools, depleted soil nutrient stocks and a loss of other ecosystem functions. The proposed strategy is likely to miss its main objective, i.e. to reduce greenhouse gas (GHG) emissions, because it would result in a reduction of biomass pools that may take decades to centuries to be paid back by fossil fuel substitution, if paid back at all. Eventually, depleted soil fertility will make the production unsustainable and require fertilization, which in turn increases GHG emissions due to N_2O emissions. Hence, large-scale production of bioenergy from forest biomass is neither sustainable nor GHG neutral.

Keywords: bioenergy, biomass, ecosystem function, forestry, greenhouse gas emission, human appropriation of net primary production

Received 28 December 2011 and accepted 31 January 2012

Climate change impacts resulting from fossil fuel combustion challenge humanity to find energy alternatives that would reduce greenhouse gas (GHG) emissions. One important option in this context is bioenergy. There is a wealth of literature on actual yields of different energy crops and production systems (WBGU, 2009; NRC, 2011). Beringer *et al.* (2011) estimate that 15–25% of global primary energy could come from bioenergy in the year 2050. A prominent recent assessment suggested that bioenergy provision could even be up to 500 EJ yr^{-1}, more than current global fossil energy use (Chum *et al.*, 2012) and that GHG mitigation could be sustained under future climate conditions (Liberloo *et al.*, 2010).

Western and developing countries are on a course to increase bioenergy production substantially. For example, the United States enacted the Renewable Fuels Standard as part of the 2005 Energy Policy Act and amended it in 2007, mandating the use of renewable fuels for transportation from 2008 to 2022 and beyond. In addition, 20% of all EU energy consumption is to come from renewable sources by 2020 with bioenergy as a focal point in this effort (COM, 2006a). In 2005, the European Commission adopted the Biomass Action Plan (COM, 2005) and in 2006 the Strategy for Biofuels (COM, 2006b), both of which aim to increase the supply and demand for biomass. Strategies that could substantially diminish our dependence on fossil fuels without competing with food production include substitution with bioenergy from forests (Tilman *et al.*, 2009), either by direct combustion near the source or by conversion to cellulosic ethanol. There are important questions about GHG reduction, economic viability, sustainability and environmental consequences of these actions.

Correspondence: Ernst-Detlef Schulze, tel. + 49 3641 576 100, fax + 49 3641 577 102, e-mail: dschulze@bgc-jena.mpg.de

Greenhouse gas reduction

The general assumption that bioenergy combustion is carbon-neutral is not valid because it ignores emissions due to decreasing standing biomass and contribution to the land-based carbon sink. The notion of carbon-neutrality is based on the assumption that CO_2 emissions from bioenergy use are balanced by plant growth, but this reasoning makes a 'baseline error' by neglecting the plant growth and consequent C-sequestration that would occur in the absence of bioenergy production (Searchinger, 2010; Hudiburg *et al.*, 2011), and it ignores the fact that fossil fuels are needed for land management, harvest and bioenergy processing.

Recent life cycle assessments cast doubt on the existence of emission savings of bioenergy substitution from forests. In the Pacific Northwest United States, policies are being developed for broad-scale thinning of forests for bioenergy production, with the assumed added benefit of minimizing risk of crown fires. This includes forests of all ages and thus timeframes of biomass accumulation. However, a recent study suggests that more carbon would be harvested and emitted in fire risk reduction than would be emitted from fires (Hudiburg *et al.*, 2011). Furthermore, policies allow thinning of mesic forests with long fire return intervals, and removal of larger merchantable trees to make it economically feasible for industry to remove the smaller trees for bioenergy. These actions would lead to even larger GHG emissions beyond those of contemporary forest practices (Hudiburg *et al.*, 2011).

Increased GHG emissions from bioenergy use are mainly due to consumption of the current carbon pool and from a permanent reduction of the forest carbon stock resulting from increased biomass harvest (Holtsmark, 2011). When consumption exceeds growth, today's harvest is carbon that took decades to centuries to accumulate and results in a reduction of biomass compared to the current biomass pool (Holtsmark, 2011; Hudiburg *et al.*, 2011). Hence, it is another example of 'slow in and fast out' (Körner, 2003). Consequently, reduction in forest carbon stocks has been shown to at least cancel any GHG reductions from less use of fossil fuel over decadal time spans (Haberl *et al.*, 2003; Mc-kechnie *et al.*, 2011). Boreal forests with relatively low carbon sequestration potential may take centuries before permanent reduction of the carbon stocks resulting from increased bioenergy harvest is repaid by reduced emissions from fossil fuels (Holtsmark, 2011). For more productive temperate regions, an infinite payback time was found implying that lower GHG emissions are achieved through C-sequestration in forests rather than through bioenergy production (Hudiburg *et al.*, 2011).

Recent studies of the differences in timing of CO_2 emissions from bioenergy production and forest carbon uptake (Cherubini *et al.*, 2011a,b) suggest that the 'upfront' CO_2 emitted during biomass harvest and combustion stays in the atmosphere for decades before the CO_2 is removed by the growing forest. It results in a 'pulse' of warming in the first decades of bioenergy implementation. This contrasts calls for a rapid reduction of the growth rate of climate forcing (Friedlingstein *et al.*, 2011) required to achieve the policy of limiting warming to 2 °C.

The initially reported emission savings from forest bioenergy are based on erroneous assumptions in the accounting schemes. Studies that corrected these errors suggest that forest management that reduces the current biomass pool is unlikely to result in the envisioned emissions savings at all, and certainly not over the next decades.

Economic viability

Emerging technologies such as biofuel refineries and combined heat and power plants have to compete against established technologies applied in coal, gas and nuclear power plants. In the United States, a recent National Research Council report concluded that only in an economic environment characterized by high oil prices (e.g. >$191 per barrel), technological breakthroughs (cellulosic ethanol) and at a high implicit or actual carbon price would biofuels be cost-competitive with petroleum-based fuel (NRC, 2011). Hence, incentives favouring bioenergy (i.e. production quota, subsidies, tax cuts) will be needed to complement or even replace fossil fuel-based technologies (Schneider & Kaltschmitt, 2000; Ryan *et al.*, 2006; Ahtikoski *et al.*, 2008; NRC, 2011).

Schemes favouring the economics of one practice or technology over another often lead to unanticipated side-effects. For example, side-effects have been documented for the Common Agricultural Policy of the European Union (Macdonald *et al.*, 2000; Stoate *et al.*, 2001), and forest-based bioenergy production would seem to be similar. In Germany, where bioenergy is subsidized, the market price for woody biomass increased from 8 to 10 € m^{-3} in 2005 to 46 € m^{-3} for hardwood and 30–60 € m^{-3} for coniferous wood in 2010. Prices for woody biomass for bioenergy now reach 60–70% of saw log prices (Waldbesitzerverband, 2010; wood sales by one of the authors). Such prices discourage the production of quality timber and make root extraction and total tree use attractive options despite the documented unfavourable effects on soil carbon, soil water and nutrient management (Johnson & Todd, 1998; Johnson & Curtis, 2001; Burschel & Huss, 2009; Peckham & Gower, 2011).

For the German example, the price increase is driven by the installation of distributed bioenergy plants and the competitive market of other uses for biomass, such as wood for production of cellulose. Although the details will differ among regions and countries, increasing imports by developed nations is the most likely response to an increasing wood demand (Seintsch, 2010), because total wood harvest has not substantially changed in the developed world (i.e. ~1.4×10^9 m^3

between 1990 and 2010 in Europe and North America, FAO, 2010). Increased imports are likely to be met through land-use (intensity) change in other regions (lateral transfer of emissions). In the case of increased imports, these are most likely met by harvesting previously unmanaged forests or forest plantations. Thus, similar to crop-based production systems, forest-based bioenergy requires additional land, contrary to previous expectations (Tilman *et al.*, 2009). Increased wood imports, thus, represent a global footprint of local energy policies and should be accounted for in life cycle assessment of wood-based bioenergy.

Reduced manufacturing residue losses and other technological advances such as glued wood-based elements initiated a trend towards shorter rotations and thus younger forests. However, the economics of bioenergy production supported by existing subsidy schemes is expected to reduce rotation length to its lowest limit and promote questionable management practices and increased dependency on wood imports. Further, high prices for biomass will discourage forest owners from investments in long rotations, resulting in a shortage of quality timber. Given the time required to produce high-quality timber, such shortage cannot be remedied by short-term (economic) incentives.

Environmental consequences

Homogeneous young stands with a low biomass resulting from bioenergy harvest are less likely to serve as habitat for species that depend on structural complexity. It is possible that succession following disturbance can lead to young stands that have functional complexity analogous to that of old forests; however, this successional pathway would likely occur only under natural succession (Donato *et al.*, 2011). A lower structural complexity, and removal of understory species, is expected to result in a loss of forest biodiversity and function. It would reverse the trend towards higher biomass of dead wood (i.e. the Northwest Forest Plan in the United States) to maintain the diversity of xylobiontic species.

Cumulative impacts of bioenergy-related management activities that modify vegetation, soil and hydrologic conditions are likely to influence erosion rates and flooding and lead to increased annual runoff and fish habitat degradation of streams (Elliot *et al.*, 2010). Young uniform stands with low compared to high standing biomass have less aesthetic value for recreation (Tahvanainen *et al.*, 2001) and are less efficient in avalanche control and slope stabilization in mountains owing to larger and more frequent cutting (Brang, 2001). A potential advantage is that younger forests with shorter rotations offer opportunities for assisted migration, although there is great uncertainty in winners and losers (species, provenances, genotypes) in a future climate (Larsen, 1995; Millar *et al.*, 2007; Pedlar *et al.*, 2011). Plantations, however, largely contribute to pathogen spread, such as rust disease (Royle & Hubbes, 1992).

Forests offer several important ecosystem services in addition to biomass and some would be jeopardized by the bioenergy-associated transition from high to low standing biomass. Agriculture provides a visible example for abandoning most ecosystem services except biomass production (Foley *et al.*, 2005); communities in intensive agricultural regions often rely on (nearby) forested water sheds for drinking water, recreation and offsetting GHG emissions from intensive agriculture (Schulze *et al.*, 2009).

Sustainability

From a historical perspective, a transition from forest biomass burning to fossil fuels literally fuelled the industrial revolution, and consequently, caused rapid climate change. However, the collapse of biomass use enabled the recovery of largely degraded forest ecosystems (Gingrich *et al.*, 2007). Partly due to recovery from previous (mis)use, C-sequestration is especially strong over Europe (Ciais *et al.*, 2008; Luyssaert *et al.*, 2010) and the United States (Williams *et al.*, 2011). As such, C-sequestration can be considered a side-effect of the transition of energy sources from wood to fossil fuels (Erb *et al.*, 2008). Industrial-scale use of forest biomass for energy production would likely reverse this trend or at least reduce the carbon sink strength of forests (Haberl *et al.*, 2003; Holtsmark, 2011; Hudiburg *et al.*, 2011). The historical forest resource use in Europe and the United States is the present day situation in Africa. For example, southern African *miombo* forests have been degraded into shrubland as a result of charcoal production, where charcoal is the main energy source for rural communities even at a very low level of total energy consumption (Kutsch *et al.*, 2011).

A widespread misconception is that the most productive forests are necessarily the strongest carbon sinks. Actually, net primary productivity of forests is typically negatively correlated with the cumulative amount of carbon stored in biomass (Fig. 1). In reality, old forests show lower NPP but store the largest amount of carbon (Luyssaert *et al.*, 2008; Hudiburg *et al.*, 2009; Bugmann & Bigler, 2011) because slow growing forest live longer than fast growing forest (Schulman, 1954; Bigler & Veblen, 2009). Hence, on areas currently forested, any fast rotation management and use for fossil fuel substitution is reducing forest carbon sequestration. At regional scales, a permanent increase in annual wood harvest results in a permanent reduction in the amount of

  doi: 10.1111/j.1757-1707.2012.01169.x

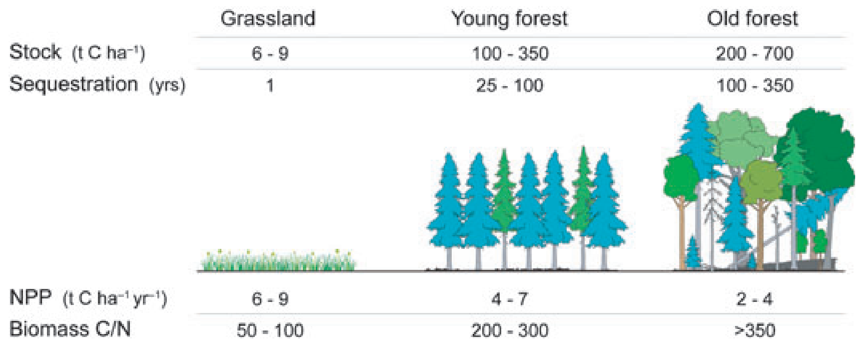

Fig. 1 Land management trade-off: maximizing productivity vs. carbon stocks. Given fixed resource availability, land managers can maintain highly productive ecosystems with a low standing biomass such as grasslands. The dominant tissues are leaves and roots with a low C/N ratio (~50). The same resources could be used to grow forest. With time forest accumulate considerable amounts of carbon in their biomass but forest that grow old have a lower net primary production than young forest and grasslands. Woody biomass has high C/N ratios (~400) and with an increasing share of woody biomass in the total biomass, the C/N ratio of the ecosystem decreases. Consequently, the time integral of productivity will be lower for an old forest compared with grassland, but at the same time, the time integral of nitrogen export will be lower for an old forest (closed nitrogen cycle) compared with a grassland (open nitrogen cycle). Hence, increasing the biomass pool size is the sustainable way of capitalizing from forests in the C-sequestration vs. C substitution debate. Ranges in the figure are for temperate ecosystems based on (Van Tuyl *et al.*, 2005; Luyssaert *et al.*, 2007, 2008; Schulze *et al.*, 2009; Keith *et al.*, 2009).

carbon stored in forests at the regional scale due to a lower average stand age (Körner, 2009; Holtsmark, 2011).

Globally, ~7% of global forest net primary production (NPP) outside wilderness areas is used by humans annually (Haberl *et al.*, 2007a). In Europe, human appropriation of forest NPP reaches ~15% (Luyssaert *et al.*, 2010). Thus, even in the absence of industrial production of wood-based bioenergy, humans already seize a remarkable share of forest production. To produce 20% of current primary energy consumption from wood-based bioenergy, as suggested by policy targets, it would require more than doubling the global human appropriation of NPP (HANPP) to 18–21% (Table 1; ratio of row 1 and 6). Such an increase in human appropriation would have serious consequences for global forests. Due to its nature, much of forest NPP cannot be harvested, e.g. fine root NPP, NPP for mycorrhizal associations and NPP in volatile organic emissions. Further, forests are harvested after decades of growth; hence, much of the NPP is already consumed by herbivores, added to the litter pool or decomposed in the detritus food chains long before harvest, e.g. leaves, fruits, fine

Table 1 Global HANPP in forests in the year 2000 and future HANPP that would result from providing 20% of world primary energy from forest harvest. NPP denotes net primary production and HANPP the human appropriation of net primary production. Using a gross caloric value of 19 kJ g^{-1} forest biomass or 38 kJ g^{-1} biomass carbon and a net caloric value of 41.9 GJ for 1 ton of oil equivalent. Conversion from net to gross calorific value was based on the following multipliers (gross/net): coal 1.1, oil 1.06, natural gas 1.11 and biomass 1.1 (Haberl *et al.*, 2006)

	Global C-flux (PgC yr^{-1})	Energy equivalent (EJ yr^{-1})	Source
(1) Current NPP of forest ecosystems	27–29	1030–1100	Haberl *et al.* (2007a) and Pan *et al.* (2011)
(1a) Belowground NPP (40%)	10–11	–	Luyssaert *et al.* (2007)
(1b) Leaf + twigs NPP (30%)	8.4–8.7	–	Luyssaert *et al.* (2007)
(1c) Aboveground woody NPP (30%)	8.4–8.7	330	Luyssaert *et al.* (2007)
(2) Primary energy use in 2006–2008	–	550	IEA (2008) and BP (2009)
(3) Global fossil energy use in 2006–2008	6–7	450	IEA (2008) and BP (2009)
(4) Additional fuel wood to produce 20% of primary energy	2.3	87	From 3 and 5
(5) NPP lost in harvest (10–30%)	0.5–1.4	19–53	From 2 and 6
(6) New HANPP level in forests	4.4–5.3	170–200	From 2, 6 and 7

roots, mycorrhiza and plants in early succession stages. Last, part of the NPP could be harvested but typically has no economic value, e.g. perennials, mosses and lichens. Consequently, the maximum HANPP is about 30% of the total NPP; hence, the proposed HANPP of 18–21% already represents ca. 60% of the global increment of woody biomass (Table 1; ratio of rows 1c and 6). Note that our maximum level of harvestable increment of woody biomass is most likely overestimated because the estimate did not account for economic (e.g. distance to population centre), logistic (e.g. steep mountain slopes) and legal (e.g. conservation areas) constraints on harvest. In addition to the increased GHG emissions that would result from such a programme due to reduced biomass stocks (see above), this increase in human appropriation of forest production would likely contribute to forest biodiversity loss, according to recent evidence on the correlation between HANPP and species richness (Haberl *et al*., 2005, 2007b).

Typically, the most fertile lands are in urban and agricultural use (Scott *et al*., 2001), leaving the poorer soils for forest use. The industrial-scale of envisioned forest bioenergy production would export substantial amounts of nutrients, further depleting the soil nutrient stock, particularly if wood removal includes relatively nutrient-rich biomass residues (slash) and root stocks (Peckham & Gower, 2011) as for total tree use. Nutrient and cation losses would have to be compensated for by fertilization, which in turn increases GHG emissions and increases N and P levels in nearby rivers leading to eutrophication of aquatic ecosystems (for a crop related example see Secchi *et al*., 2011).

A persistent 60–70% appropriation of woody biomass increment for bioenergy production from forest harvest over decades will erode current biomass pools, lower average stand age, deplete soil fertility and could thus only be sustained by amendments to nitrogen and phosphorous-depleted soils, activities that also produce GHG (N_2O) emissions.

Conclusion

Although bioenergy from forest harvest could supply ~20% of current energy consumption, this would increase human appropriation of NPP in forests to ~20% which is equivalent to 60–70% of the global increment in woody biomass. We argue that the scale of such a strategy will result in shorter rotations, younger forests, lower biomass pools and depleted soil nutrient capital. This strategy is likely to miss its main objective to reduce GHG emissions because depleted soil fertility requires fertilization that would increase GHG emissions, and because deterioration of current biomass pools requires decades to centuries to be paid back by fossil fuel substitution, if paid back at all. Further, shorter rotations would simplify canopy structure and composition, impacting ecosystem diversity, function and habitat. In our opinion, reasonable alternatives are afforestation of lands that once carried forests and allowing existing forests to provide a range of ecosystem services. Yet, on arable or pasture land, such a strategy would compete with food and fodder production. Society should fully quantify direct and indirect GHG emissions associated with energy alternatives and associated consequences prior to making policy commitments that have long-term effects on global forests. Reasonable alternatives for reducing GHG emissions on the order of the proposed bioenergy substitution include increased energy efficiency and reduced waste of energy via technological improvements and behaviour modification. There is a substantial risk of sacrifying forest integrity and sustainability for maintaining or even increasing energy production with no guarantee to mitigate climate change.

Acknowledgements

E. D. S. thanks the Max-Planck Society for support. B. E. L.'s research was supported by the Office of Science (BER), US Department of Energy. H. H. acknowledges funding by the Austrian Science Funds FWF (project P20812-G11), by the Austrian Academy of Sciences (Global Change Programme) and by the Austrian Ministry of Research and Science (BMWF, proVision programme). S. L. is funded by ERC Starting Grant 242564. C. K. was supported by ERC advanced grant 233399.

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