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EDITORIAL

Biomass with capture: negative emissions within social and environmental constraints: an editorial comment

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1 Introduction

Biomass has long been investigated both as a (nearly) CO_2 neutral substitute for fossil fuels and as a means for sequestering carbon in terrestrial ecosystems (Kheshgi et al. 2000). More recently, the potential to integrate carbon capture and storage technologies (“CCS”)—conceived to enable fossil fuel use without atmospheric CO_2 emissions—with bio-energy systems has emerged as a means to capture atmospheric carbon, fixed through photosynthesis, and sequester it from the atmosphere for geologic timescales (Obersteiner et al. 2001; Yamashita and Barreto 2004; Mollersten et al. 2003; Rhodes and Keith 2005). The ability of such integrated systems to produce energy products with negative net atmospheric carbon emissions could have important implications for mitigating anthropogenic climate change.

The scale and timing of biomass-based mitigation is limited by the availability and cost of conversion technologies, many of which are currently inefficient or technologically immature. More fundamentally, it is limited by feasible scales of biomass production, estimates of which are highly uncertain and indicate that the capacities envisioned within aggressive proposals, including those by Read (2008), may not be achievable (Hoogwijk et al. 2003; Berndes et al. 2003). Concern for environmental, social, and economic impacts of biomass development may further constrain production below technically feasible levels.

The current biofuels boom may be illustrative in this context. On the one hand, it demonstrates the feasibility of rapid, large-scale bio-energy deployments; while on the other hand, it provides examples of undesirable environmental and social consequences from large-scale biomass production (Ziegler 2007; Rosenthal 2007a, b).

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2 Technology

Biomass is uniquely positioned at the intersection of industrial energy systems and the natural carbon cycle. This enables four basic routes for carbon mitigation:

- Carbon storage in terrestrial ecosystems by reforestation and conservation (Metz et al. 2001);
- Substitution of bio-energy in forms such as bio-ethanol for fossil fuels (Metz et al. 2001);
- Carbon storage by harvest and remote burial of terrestrial biomass in locations such as deep ocean sediments where carbon cycling is slow (Metzger et al. 2002); and,
- Substitution of bio-energy with remote carbon storage (“biomass-CCS”) (Obersteiner et al. 2001; Yamashita and Barreto 2004; Mollersten et al. 2003; Rhodes and Keith 2005)

In addition to advancing carbon management objectives, biomass could be used to reduce petroleum consumption. With sufficient external inputs of hydrogen and electricity, essentially all of the carbon in biomass feedstock could be converted to liquid fuels (Agrawal et al. 2007). This differs from conventional biofuels production, in which at most a third of the carbon content of the feedstock ends up in the fuel, with the remainder being oxidized to provide process energy or left as waste. In such a system, biomass is used to capture and recycle carbon from the atmosphere, while primary energy inputs are provided externally. Assuming these inputs are carbon-free, resulting liquid fuels can be (nearly) carbon neutral. Such systems could provide the largest displacement of petroleum-derived fuels per unit biomass, while biomass-CCS could provide the largest mitigation of CO_2 emissions per unit biomass—due to the double benefit of providing useful energy products and removing carbon from the active carbon cycle (Keith and Rhodes 2002).

Many technological pathways exist for integrating bio-energy and CCS. In principle, all the basic CCS technologies being advanced for fossil fuel systems, such as gasification and oxy-fuel combustion, could be applied to bio-energy systems, and additional opportunities exist from biological processes (e.g., ethanol fermentation) and potential soil enrichment with biomass-derived char.

The technical performance of such pathways remains uncertain. Some, such as capture of CO_2 off-gases from fermentation, could be deployed in the very near term, while others, such as those reliant on large-scale biomass gasification, may not be commercially viable for a decade or more, even in the presence of a strong carbon price. The mismatch between the scales of economically-viable bio-energy deployments and CO_2 capture, transport, and storage systems could be a challenge for biomass-CCS. However, supply chains supporting the current biofuel boom suggest that locally-available biomass supplies may not be fundamentally limiting, and biomass-fossil fuel co-utilization could help resolve this issue.

3 Land use

Biomass supply is limited both by technical limits to biomass yields (e.g., t ha^{-1} $year^{-1}$) and by competition with other uses for land, including food production and preservation of natural ecosystems. Table 1 presents illustrative calculations of the mitigation potential implied by several published estimates of feasible biomass supply capacity. Technological performance assumptions underlying these calculations are adopted from analysis of biomass-CCS systems (Rhodes 2007).

The upper end of estimates for potential biomass availability support the view endorsed by Read (2008) that biomass could provide the central mechanism for managing global climate and energy challenges. While the calculations in Table 1 are defined relative to transportation-sector emissions, their implications for economy-wide mitigation can be appreciated by considering that petroleum was responsible for 43% of 2004 energy-sector CO_2 emissions in the U.S. and that electric-sector mitigation from fossil fuel substitution is ignored in calculations of "offsets from bio-power" (Inventory of U.S. Greenhouse Gas Emissions and Sinks 2006).

While the uppermost estimates support the arguments by Read (2008), we remain skeptical because of (i) the deep uncertainty in the feedstock supply estimates; (ii) the environmental implications of maximizing production; (iii) the complex social and ethical issues arising from the required re-organization of global land use; (iv) the relative likelihood of success from advancing a single strategy rather than a diversified portfolio; and finally, (v) the potentially high costs of such a strategy.

Estimates of global supply capacity vary over more than an order of magnitude in each of the studies represented in Table 1. While more consistent studies would be useful, we doubt that analysis alone can substantively reduce deep uncertainties about biomass supply. Specifically, strong population growth, global adoption of meat-rich diets, and minimal gains in food production efficiency may leave little land for bio-energy feedstock production, while modest population growth, decreasing meat intensity of diets, and strong gains in food production efficiency may open substantial area for energy crops (Hoogwijk et al. 2003). Adaptive management strategies that exploit learning-by-doing should therefore drive decision making about biomass deployment rather than the kind of grand-scale deployment envisioned by Read (2008).

Large-scale biomass production will have important environmental consequences that may constrain optimal levels of production substantially below theoretical maximums. It may, for example, damage or reduce the extent of wilderness areas and native ecosystems, compromise the environmental services such ecosystems provide (e.g., regulation of clean water supplies), or reduce biodiversity.

Biomass production must be geographically distributed due to the intrinsic productivity of agricultural resources. This suggests that relatively large allocations of land in the developing world would be required to support the scales of bio-energy development implied by globally-aggressive biomass-based strategies. For example, the land availability estimates by Read (2008) indicate that 84% of arable land not in commercial use is in tropical regions of the world. Local food production capacity, which likely represents a more immediate concern in the developing world than carbon emissions, could be displaced. More generally, rural populations could be forced to adapt to radically changed local environments, including environmental consequences from large-scale biomass production. The notion that these disruptions should be absorbed by the developing world in order to mitigate carbon emissions in industrialized nations raises complex ethical issues of "biomass justice".

Read (2008) suggests a number of strategies to address these various issues: sequential deployment decisions beginning with land improvement and capacity building measures; fractionalizing feedstock into protein, cellulosic, and ligneous streams for alternate purposes; development of "sustainability conditionality" on biofuels trade, for example. We remain skeptical, however, as the validity of underlying assumptions, efficacy, and implications of such strategies remain unclear. Moreover, the constraints they imply for feasible timing and scales of production are not characterized.

Table 1 Estimates of potential bio-fuel supply

Projection basis								
Geographical area	United States		United States		Global		Global	
Biomass production estimate source	Walsh et al. 2003		Perlack et al. 2005		IPCC Working Group III T.S.U. 2000		Hoogwijk et al. 2003	
Time frame	5 years		2050		2050		2050	
Estimate type	Min	Max	Min	Max	Min	Max	Min	Max
Biomass supply								
Potential biomass supply (Mt year^{-1})	87[a]	171[a]	506[b]	1,236[b]	2,474[c]	32,143[c]	1,737[c]	80,714[c]
Potential biomass supply (EJ year^{-1})	1.2[c]	3.2[c]	7.1[c]	23.5[c]	47[d]	450[d]	33[e]	1,130[e]
Land dedicated to energy crop production (Mha)	7.9[a]	17.0[a]	0.0[f]	24.3[f]	0[d]	745[d]	430[g]	3,180[g]
Percent of current agricultural land	4%[h]	10%[h]	0%[i]	14%[i]	0%[j]	13%[j]	7%[j]	55%[j]
Bio-fuel supply								
Potential bio-fuel supply (EJ year^{-1})	0.5[k]	1.3[k]	2.8[k]	9.4[k]	18.8[k]	180.0[k]	13.2[k]	452.0[k]
Fuel demand (EJ year^{-1})	21[l]	21[l]	35.8[m]	35.8[m]	124[n]	496[n]	336[o]	336[o]
Percent of demand potentially met with biomass	2%[p]	6%[p]	8%[p]	26%[p]	15%[p]	36%[p]	4%[p]	134%[p]
Transportation sector mitigation potential								
Fossil CO_2 emissions (Mt CO_2 year^{-1})	1,313[q]	1,313[q]	2,287[r]	2,287[r]	7,936[q]	31,635[q]	20,604[s]	20,604[s]
Percent mitigated with substitution only	2%[t]	6%[t]	8%[t]	26%[t]	15%[t]	36%[t]	4%[t]	134%[t]
Percent mitigated with substitution and offsets (CCS)	8%[u]	21%[u]	28%[u]	86%[u]	44%[u]	148%[u]	12%[u]	565%[u]
Percent mitigated with (or H_2)[v]	11%[v]	21%[v]	37%[v]	89%[v]	51%[v]	168%[v]	14%[v]	646%[v]

[a] Considers only potential energy crops, as described in Walsh et al. (2003)

[b] The minimum value includes 124 Mt from currently unexploited forestry resources and 382 Mt from currently unexploited agricultural resources; the maximum value includes 332 Mt from forest resources – 129 Mt of which is currently used in the forest products industry – and 904 Mt from agricultural resources, as described in Perlack et al. (2005)

[c] Asssumes average heating values of 14 and 19 MJ/kg

[d] From IPCC Working Group III T.S.U. SRES Final Data (2000)

[e] From Hoogwijk et al. (2003)

[f] From Perlack et al. (2005)

[g] The minimum value includes only 430 Mha degraded agricultural land; the maximum value includes 2.6 Gha primary agricultural land plus 580 Mha degraded agricultural land, as described in Hoogwijk et al. (2003)

[h] Calculated by dividing the dedicated land area by 431 million acres of US agricultural land reported in Walsh et al. (2003)

[i] Calculated by dividing the dedicated land area by 449 million acres of US agricultural land reported in Perlack et al. (2005)

[j] Calculated by dividing the dedicated land area by 5 Gha global primary agricultural land and 760 Mha gobal degraded agricultural land reported in Hoogwijk et al. (2003)

Table 1 (continued)

[k] Calculated by multiplying the specified biomass supply by an assumed bio-fuel conversion efficiency of 40% Rhodes and Keith (2005)

[l] Reference projection for motor gasoline consumption in 2010 as described in Annual Energy Outlook (2005)

[m] 2× motor gasoline consumption in 2003, as described in Annual Energy Outlook (2005)

[n] Liquid fuel consumption, as described in IPCC Working Group III T.S.U. SRES Final Data (2000)

[o] 2× oil consumption 2002, as described in International Energy Outlook (2005); note that bio-fuels may not be suitable substitutes for all petroleum products

[p] Calculated by dividing the potential biofuel supply by the fuel demand

[q] Linearly scaled from fuel demand based on net emissions factor implied by the ratio of US 2003 motor gasoline consumption, as described in Annual Energy Outlook (2005), to US 2003 motor vehicle emissions as described in Inventory of U.S. Greenhouse Gas Emissions and Sinks (2006)

[r] 2× motor gasoline emissions as described in Inventory of U.S. Greenhouse Gas Emissions and Sinks (2006)

[s] 2× CO_2 emissions from oil in 2002 (table A11) from International Energy Outlook (2005)

[t] Set equal to the percent of demend potential met with biomass above

[u] Calculated by multiplying the potential biomass supply (Mt $year^{-1}$) by an assumed mass fraction carbon in biomass of 50%, multiplying by an assumed carbon capture rate in production of 50 to 60%, converting to Mt CO_2, dividing by the fossil CO_2 emissions (Mt CO_2 $year^{-1}$) and adding the percent mitigated with substitution only

[v] Calculated by multiplying the potential biomass supply (Mt $year^{-1}$) by an assumed mass fraction carbon in biomass of 50%, multiplying by an assumed carbon capture rate in production of 90%, converting to Mt CO_2, and dividing by the fossil CO_2 emissions (Mt CO_2 $year^{-1}$)

4 Long-run climate policy and abrupt climate change

The ability to generate negative emissions provides a mechanism for active management of atmospheric CO_2 concentrations over very long time horizons with consequent implications for long-term climate policy. In this regard, biomass with capture is similar to the direct capture of CO_2 from air by industrial means (Keith et al. 2005; Elliott et al. 2001; Parson 2006), and is related to other forms of intentional climate modification such as geoengineering accomplished by altering the global radiative forcing to counteract CO_2-driven warming (Keith 2000).

All of these methods partially counteract the effects of anthropogenic carbon emissions. Unlike geoengineering which directly affects the net radiative forcing to produce a rapid climatic response, negative emissions act on the derivative of atmospheric concentrations. Concentrations can only be reduced gradually, as the integral of globally-negative net emissions, once all emission sources have been mitigated. Moreover, implementation of air capture or biomass-CCS would require large capital expenditures making is difficult to achieve a rapid change in net emissions and even more difficult to rapidly alter net radiative forcing. It therefore seems somewhat implausible to us that biomass-CCS can play a major role in reducing the risk posed by abrupt climate change. Biomass-CCS is not a substitute for albedo geoengineering; rather it is more reasonably seen as a compliment. Geoengineering could rapidly reduce temperatures in the event of catastrophic climate change but will have little effect on CO_2 concentrations, whereas biomass-CCS allows reduction in concentrations albeit at a far slower pace.

Even so, the potential to actively manage atmospheric concentrations over time fundamentally changes both the range of emissions trajectories capable of stabilizing atmospheric CO_2 concentrations at desirable levels and the range of atmospheric concentrations that can be achieved—including, for example, pre-industrial levels.

5 Conclusions

Biomass-CCS could substantially change role of biomass-based mitigation. It alters the competitive balance of technologies for mitigating anthropogenic CO_2 emissions. Biomass-CCS may be capable of cost-effective indirect mitigation—through emissions offsets—of emission sources that are expensive to mitigate directly. For example, transportation-sector carbon emissions could be offset by negative emissions from electric-sector biomass-CCS deployments. The calculations presented in Table 1 indicate that the transportation-sector mitigation potential from such indirect strategies could be greater than that from biofuels applications. Heat and power applications do not provide energy security benefits comparable to liquid fuels; however the calculations suggest that a strategy leveraging biomass-CCS—or biomass-derived hydrocarbons, as discussed above—is at least as plausible as one based on hydrogen fuels, the latter of which is often presented as the dominant (if not only) option for carbon-neutral transportation (Abraham 2004).

More generally, the most expensive emissions to abate directly could be mitigated indirectly with offsets from biomass-CCS systems deployed wherever (in the world) they are least expensive. Such indirect mitigation could be part of a long-term mitigation strategy, as sustainably-produced biomass is a renewable resource. Alternatively, emissions offsets could simply provide flexibility in the transition to a carbon-neutral economy, balancing emissions from sources that are difficult to abate directly until cost-effective direct mitigation options can be developed and deployed.

Potential scales of biomass-based measures hinge on issues that are deeply, perhaps irreducibly uncertain, and are riddled with contentious value-laden trade-offs. To cite one example, with current productivity, large scale use of biomass energy will require substantial alteration to global land use patterns with consequently far-reaching impacts on rural society, food prices and the land that is set aside for nature; whereas, if attempts to use genetic engineering succeed in delivering dramatic increases in primary productivity then land requirements might be modest, but there might well be attendant risks from the release of such high-productivity organisms into the wild.

In this context, we make the following recommendations:

Policies supporting increasing bio-energy utilization should be implemented with an emphasis on adaptive management rather than fixed commitments. Specifically, economic, environmental, and social costs from bio-energy development should be evaluated and integrated into policy decisions on an ongoing or regular periodic basis.

Biomass-CCS and its unique attributes should be more deeply integrated in climate policy making. The implications of biomass-CCS are potentially large and are inadequately reflected in current climate policy debates.

Finally, policies should provide even treatment for comparable bio-energy systems. Current policies often favor dedicated biomass applications and discount both co-production with traditional harvests and co-utilization with fossil fuels (Energy Policy Act of 2005), where some of the most interesting opportunities may lie. Such biases undervalue the systematic advantages that co-production and co-utilization can provide for bio-energy development.

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