SINKS, ENERGY CROPS AND LAND USE: COHERENT CLIMATE POLICY DEMANDS AN INTEGRATED ANALYSIS OF BIOMASS

An Editorial Comment

The large natural carbon fluxes between atmosphere and terrestrial biosphere in combination with our substantial control over terrestrial biotic productivity (Vitousek et al., 1986) grants us a powerful lever for manipulating atmospheric CO_2. Proposals to use this leverage to offset CO_2 emitted from fossil fuels are roughly as old as modern knowledge of the CO_2-climate problem (NAS, 1977). More recently, modern biomass energy, which was first advanced as a solution to supposed shortages of fossil fuels, has emerged into the climate policy debate as an (almost) CO_2-neutral substitute for fossil fuels.

The use of terrestrial biotic productivity – either as a substitute for fossil fuels or as a carbon sink to offset their CO_2-emissions – is one of the few technical options that promises to slow rising atmospheric CO_2 concentrations at moderate cost. But that promise comes with substantial uncertainties with respect to cost, effectiveness, and environmental impact. These uncertainties have been well cataloged elsewhere (e.g. Smil, 1983; Giampietro, 1997); here, I focus on the problems that emerge from the lack of an integrated understanding of the manifold ways in which our leverage over the terrestrial carbon cycle may be exercised to mitigate the growth of atmospheric CO_2.

Integrated analysis is needed to account for the strong linkages between the use of sinks and the use of biomass energy, linkages that are inadequately addressed in most estimates of the cost of CO_2 mitigation, and in most integrated assessment models. Biomass energy and sinks are not, however, the only relevant ways to manipulate the carbon cycle. There are two other possibilities: the engineered remote sequestration of biomass and the use of biomass energy with capture and sequestration of CO_2. I first describe these four distinct methods for using biomass, and then summarize the economics of biomass as a means to CO_2 mitigation, providing comparisons with other estimates of the cost of mitigation. I next describe the basis and need for integrated analysis of biomass using two examples, one centered on spatially resolved economic modeling and a second drawn from engineering analysis of lifecycle costs and impacts. Finally, I sketch the challenges of integration and close with a cautionary note about the limitations of biomass for CO_2 mitigation.

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1. The Fourfold Way

There are four ways in which terrestrial biotic productivity, which I will call *biomass*, may be harnessed to retard the increase in atmospheric CO_2.

1. *Sinks.* Carbon may be sequestered *in situ* in soil or standing biomass. Although the distinction between the protection of existing carbon pools and actions intended to increase carbon storage (e.g., forest protection versus reforestation) is vital for policy implementation, the tight biological coupling between the protection and enhancement of sinks leads me to treat them jointly.
2. *Bioenergy.* Biomass may be harvested and used as fuel so that CO_2 emissions from the fuel's use are (roughly) balanced by CO_2 captured in growing the energy crops.
3. *Remote sequestration.* Biomass may be harvested and separately sequestered; for example, by burying the trees.
4. *Bioenergy with sequestration*. Biomass may be harvested and used as fuel with capture and sequestration of the resulting CO_2; for example, we may use biomass to make hydrogen and sequester the resulting CO_2 in geologic formations.

Sinks and bioenergy, the first two options, both figure prominently in contemporary climate policy analysis. While remote sequestration, the third option, was described in early climate assessments such as the National Academy's 'Energy and Climate' report (NAS, 1977), it currently attracts little attention, the article by Metzger and Benford (2001) being a notable exception. Unlike the first three options which have been analyzed for decades (however inconsistently), bioenergy with sequestration, the fourth option, is a newcomer. Though it was included in the IPCC second assessment (Watson et al., 1996, Chapter 19), it has received little subsequent analysis.

Climate policy assessments have generally treated biomass inconsistently, often in ways that overstate its potential for mitigation. Inconsistency often arises when the various ways of using biomass are treated separately, so that their essential linkage via the competition for scarce arable land is obscured. The IPCC second assessment, for example, treats options 2 and 4 in the chapter on 'Energy supply mitigation options' and treats option 1 in separate chapters on agricultural and forest management for the mitigation of greenhouse gas emissions.

Although there has been little explicit analysis of bioenergy with sequestration, there is nevertheless a significant body of relevant knowledge because it is a hybrid of two technologies that have separately been the subject of substantial analysis. First, the use of biomass for production of hydrogen or electricity using gasification or direct combustion (e.g. Williams and Larson, 1996; Hughes and Tillman, 1998). And, second, the use of fossil fuels without CO_2-emissions via the capture and sequestration CO_2 (e.g. Parson and Keith, 1998; Eliasson et al., 1999). These technologies might, for example, be combined to produce electricity from biomass using an integrated gasification combined cycle system in which the syngas was converted to hydrogen prior to combustion, and the captured CO_2 was sequestered in geological formations. The power plant would produce electricity with negative net CO_2 emissions, since CO_2 removed from the atmosphere in growing the biomass would then be removed from the active carbon cycle by burial deep underground.

All methods of exploiting biomass to regulate atmospheric CO_2 are bound by the limits of terrestrial ecosystem productivity. One can express this constraint in terms of energy or carbon. For example, if we wished to eliminate the *net* CO_2 emissions that now accrue from using 6 tC/yr of fossil fuels – the U.S. per-capita consumption – using biological systems with a productivity of 6 tC/ha-yr (a very high number) we would require about a hectare of land for each U.S. citizen, an amount roughly equal to current cropland per capita. Approximately the same area would be needed to mitigate a given quantity of emissions using any of the four methods described above.

The equal-area approximation serves as a rough guide to the total amount of land required to mitigate CO_2 emissions, and serves to emphasize the unity of biomass options for mitigation, but it is correct only as a crude approximation. Perhaps the most important departure from the equal-area approximation is that the use of sinks involves a balance between the flux of carbon into an ecosystem (its primary productivity) and process such as respiration and fire that oxidize carbon and generate a return flux to the atmosphere, whereas the other three options involve harvest of biomass and are thus not so susceptible to the instability of carbon in biological reservoirs. The effectiveness of sinks is controversial, and depends critically on the timescale and management regime considered (Schlamadinger and Marland, 1996; Borden et al., 2000; Schulze et al., 2000).

Efficient use of biomass, of course, requires analysis that breaks the equal-area approximation along two axes: The first is economic and geographic analysis of the competing demands for scarce and heterogeneous parcels of land, and the second is engineering lifecycle analysis of the costs and benefits of various strategies for managing a given parcel of land. Before examining these modes of analysis and describing the challenges of integration, I briefly review the role of biomass in the economics of CO_2 mitigation.

2. Biomass and the Economics of CO_2 Mitigation: A Brief Review

Biomass is one of few primary energy options that may allow significant reduction in global CO_2 emissions at moderate cost. Despite widespread discussion about a suite of alternative energy sources, there are currently few options for providing substantial supplies of energy with low CO_2 emissions. At current U.S. industrial prices the energy costs of coal, gas, and oil are roughly 1, 3, and 5 \$/GJ (EIA, 1999), while typical estimates for the price of biomass (supplied in large quantities) are roughly 2 to 3 \$/GJ (Walsh et al., 2000). All other large scale non-fossil sources of primary energy are substantially more expensive.

Moreover, our economies require not simply primary energy, but rather a mixture of electricity and fuels, and the economics of producing fuels with low net CO_2 emissions favors biomass over non-fossil alternatives. Wind, biomass, nuclear, and fossil fuels with CO_2 capture and sequestration (CCS), are all capable of supplying large quantities of electricity with minimal net CO_2 emissions at a producer cost of 15 to 20 \$/GJ (∼5-7 c/kWhr), within a factor of two above current costs.[⋆] The options for producing fuels are more limited: Given current technology biomass or fossil with CCS are the only reasonably priced technologies. The differences between fuels and electricity arise from the relative ease of thermochemically converting fuels from one form to another (e.g., biomass to hydrogen) compared to the difficulty of conversion between fuels and electricity. Hydrogen produced from wind or nuclear via electrolysis, for example, would cost 20–30 \$/GJ while the price of hydrogen produced from fossil fuels with CCS or from biomass would be 6–10 \$/GJ; a relative price advantage of roughly 1:3 for biomass or fossil hydrogen over wind or nuclear hydrogen. This cost differential emerges from the relative ease of thermochemical energy transformation and stands in sharp contrast to the approximate equality in the cost of electricity produced from all four sources. Biomass may also be advantageous for the production of the liquid fuels that are vital for transportation. Ethanol from biomass, for example, can serve as a transportation fuel with small net CO_2 emissions. While nuclear or solar power can – in theory – be used to synthesize carbonaceous liquid fuels from CO_2 it is hard to imagine this process becoming cost competitive.

Terrestrial carbon sinks promise low-cost mitigation of CO_2 while simultaneously protecting biotic resources. Consensus estimates suggest that a worldwide carbon flux of order 1 GtC/yr can be sequestered, and that many sequestration opportunities exist at costs significantly under 100 \$/tC (Bruce et al., 1996; Watson et al., 1996). The costs of sequestration are contentious, however, with some bottom-up technical estimates suggesting that there are significant opportunities at ∼10 \$/tC while other economic models showing supply curves that quickly exceed 100 \$/tC (Stavins, 1999). A decade ago the focus was on standing biomass in forests, but it has now broadened to include soils and non-forested systems such as croplands and open-canopy ecosystems.

The economics of biomass as a substitute for fossil fuels, as described above, imply mitigation costs of order 50–200 \$/tC for either electricity or fuels,[⋆⋆] a mitigation cost comparable to, but above the 10–100 \$/tC cost for offsetting CO_2

[⋆] These estimates apply to large power plants with current technology; other technologies are significantly more expensive, the cost of solar photovoltaic electricity, for example, is roughly a factor of 3 higher still.

[⋆⋆] The lower end of the range arises from the substitution biomass for coal in electricity generation while the upper end arises from use of bio-ethanol in transportation.

emissions using sinks. These costs are low compared to the peak marginal carbon prices of order 500–1000 $/tC that conventional economic models suggest will be necessary to stabilize CO_2 concentrations at ∼450 ppm.[⋆] The comparatively low cost of biomass based mitigation strategies, and the fact that, in contrast to other renewables, they are applicable beyond the electric sector, suggest that biomass will play a central role in a non-fossil, CO_2-constrained energy future. More specifically, assuming (i) that large quantities of biomass are available and, (ii) assuming that the use of fossil energy with CCS, an expansion of nuclear, or a drastic cut in the cost of non-fossil renewables are all ignored, then the energy economics described above dictate the large-scale use of biomass energy. Many energy modeling exercises have adopted these assumptions and illustrate this expectation (Nakicenovic et al., 1998, see Figure 5.9). While these conclusions follow from the assumptions, I do not believe that they represent the mostly likely scenario. Rather, I suspect that fossil fuels with CCS will play a significant role in a CO_2-constrained future, and, as I will argue below, that the costs of biomass based mitigation may be significantly underestimated.

3. Economic and Geographic Analysis

Now consider the challenge of an integrated analysis of biomass that moves beyond the simplistic equal-area and constant-cost approximations described above, turning first to integration that focuses on the scarcity of land. Recent economic analyses provides ample illustration of the need for integration. In a thorough study of biomass energy production, for example, Walsh et al. (2000) compute the supply of bioenergy in a model which sets a price for energy crops while allowing the quantity of biomass and the quantity and price of other agricultural commodities to adjust. They modeled the U.S. agricultural sector (divided into 305 districts) and found that 3 EJ/yr of primary energy (∼3% current US consumption) could be generated at a price of 2.5 $/GJ with use of 17 Mha of land and a ∼10% increase in prices for other crops. Other investigators have used similar models to predict supply curves for carbon sequestration in forests and cropland. But one cannot simply add the resulting supply curves when estimating the overall cost of CO_2 mitigation, because bioenergy, carbon sinks, and food production compete for (roughly) the same land.

Some aspects of this competition are explored by Newell and Stavins (1999) who analyzed the supply of carbon sinks using a model that predicts landowner’s management choices (crops versus forests) based on agricultural commodity prices and the price for sequestered carbon. Examining the Mississippi delta region, they found that a 10% increase in agricultural commodity prices produced a 7% decrease in carbon sequestration.

[⋆] Including other radiative forcings, 450 ppm CO_2 is approximately equivalent to a doubling of CO_2 over pre-anthropogenic levels.

There are systematic analyses of the tradeoffs between bioenergy and sinks on a given plot (e.g., Schlamadinger and Marland 1996), but there have been few attempts to synthesize an economic understanding of the competing demands for land with a biologically sophisticated understanding of the consequences of land management choices for carbon sequestration. Such analysis will be required to produce robust estimates of the supply curve for CO_2 mitigation using biomass.

4. Engineering and Lifecycle Analysis

Metzger and Benford's proposal (2001) to collect crop residues and sequester them in the ocean illustrates the need for systematic lifecycle analysis of biomass options. They assert that 400 Mt/yr of crop residues can be collected at a farm-gate price of 20 $/t (of residue) and then transported to ocean sequestration sites for an additional 30 $/t providing a total of 160 MtC/year of carbon sequestration at a cost of 100 $/tC. These estimates of the availability and price are somewhat optimistic compared to those produced by more exhaustive, spatially resolved inventories of crop residues; nevertheless, I accept them here, as uncertainties about price and availability were the subject of my previous example.

Given a specified price and availability of biomass, we must ask how it can most efficiently be used to reduce net CO_2 emissions. To illustrate the need for more systematic lifecycle analysis I present a highly simplistic estimate of the cost of CO_2 mitigation using bioenergy or bioenergy with sequestration. In each calculation I accept the Metzger and Benford (2001) assumption of farm-gate price, and assume that transportation to a power plant will cost $15/t, half of their 30 $/t cost for transportation and ocean disposal. First consider using biomass to partially substitute for coal in an existing power plant (Hughes, 1998). Coal costs 1 $/GJ and has a carbon content of 24 kg/GJ whereas at 35 $/t the biomass has an energy cost of 2 $/GJ and produces low net CO_2 emissions. Adopting these assumptions, the carbon mitigation cost of biomass co-firing is 40 $/tC, much less than the 100 $/tC computed by Metzger and Benford. To illustrate the point, assume the same 100 $/tC cost was applied as a carbon tax, then the effective cost of coal would rise from 1 to 3.4 $/GJ while the cost of biomass would remain at 2 $/GJ.

Now consider the use of biomass to produce electricity in a power plant that captures the CO_2 and sequesters it in geological formations. A crude engineering analysis suggests that cost of electricity from such a plant would be about 17 $/GJ and the net carbon emissions would be −55 kg/GJ (emissions are negative because the system sequesters carbon from the biomass). The current average producer cost of electricity is about 8 $/GJ and the U.S. average carbon intensity of electric production is 47 kg/GJ, therefore the carbon mitigation cost is ∼90 $/tC. Again, a 100 $/tC tax would favor this option over remote sequestration.

The cost analysis presented here is crude. My intent is merely to demonstrate the necessity for a systematic assessment of the multiple ways in which biomass can be used if robust, policy-relevant conclusions are desired. Nevertheless, assuming that these estimates are accurate to within a factor of two, it appears that remote sequestration (method 3) is inefficient when compared to using biomass energy with or without sequestration (methods 2 and 3). An integrated analysis of the optimal way to use crop wastes to mitigate CO_2 would have to examine many issues other than cost and CO_2 emissions including, for example, the lifecycle emissions of other greenhouse gasses, the required nutrient inputs, and the costs of transportation.

I suspect that the cost advantage of bioenergy or bioenergy with sequestration over remote sequestration of biomass is quite general, and is in no way limited to these specific cost assumptions. Remote sequestration buries carbon in a chemically reduced (rather than oxidized) form; it thus neglects the very embodied solar energy that is exploited in energy crops. In contrast, when biomass is used for fuel we forgo the sequestration but reduce net CO_2 emission by displacing fossil fuels; where we can use biomass with sequestration we extract (most of) the energy while simultaneously removing CO_2 from the atmosphere. In summary, I judge that the authors of *Energy and Climate* were correct in their comment about remote sequestration: ‘Its seems obvious that if large quantities of organic material were to be grown and collected, it would make more sense to use the material as an alternative source of energy’ (NAS, 1977, p. 13).

5. The Challenge of Integration

Robust understanding of the multiple strategies for exploiting our leverage over the terrestrial carbon cycle will require analyses that integrate knowledge from many disciplines. Systems ecology, for example, is required both to understand the carbon productivity of various management strategies and to understand the environmental impacts of biomass production; resource economics is needed to understand how the cost of biomass depends on competing demands for land; human geography is need to understand the multiple drivers of land use change; and, energy systems analysis is required to understand the trade-offs between various end products such as ethanol or hydrogen.

As described above, two broad axes of integration seem most pertinent: First, the extreme spatial heterogeneity of land, its essential scarcity, and its manifold social importance demand spatially explicit analysis that is grounded in economic rationality and yet is able to address the social dimensions of land use. Second, the complexity of costs and benefits arising from land management demand systematic lifecycle analysis.

The examples in the previous sections explored these two axes of integration, yet they were each restricted to economic analysis. Robust assessment of biomass will require analysis that grapples with the manifold non-market attributes of land use ranging from the value of lightly-managed landscapes and wilderness to the impacts of land use change on the fabric of rural societies.

Geographic assessment is needed to address questions such as: Given a specific policy mechanism to encourage biomass, where and how will land use change and how much mitigation will be affected? Lifecycle assessment is needed to address questions such as: Given a unit of land to be managed with the principal goal of mitigating net CO_2 emissions what strategy maximizes mitigation while minimizing costs? Or, given a required quantity of mitigation is it better to use a small quantity of land and manage it intensively or a larger quantity of land used more gently?

6. Limits to the Role of Biomass

While manipulation of the terrestrial carbon cycle grants us considerable leverage over atmospheric CO_2, that lever is puny in the face of our appetite for energy. Global energy use is now equivalent to more than 5% of terrestrial net primary productivity, and forecasts put this ratio as high as 10% by 2100 (Watson, 2000). If our appetite for energy is to be supplied by fossil fuels, the 21st century's consumption will exceed 1000 GtC, an amount comparable to the entire stock of terrestrial organic carbon, living and dead. Thus, while terrestrial sequestration can provide vital short-term mitigation, it cannot play a substantial role in the long-term stabilization of CO_2 concentrations absent a dramatic reduction in energy consumption.

The limits to biomass as a substitute for fossil fuels are illustrated by analysis of carbon fluxes: As noted above, providing the energy used by an average U.S. citizen would require more than a hectare of intensively managed land, an amount roughly equivalent to the average use of cropland per capita. Thus, providing all energy from biomass would require an approximate doubling of the area of intensively managed land.[⋆] Average European, and world average, per-capita energy use is of course less, but the ratio of cropland to energy use is roughly equivalent in each case. While such a doubling of cropland is possible, it seems likely that this cure for the CO_2-climate problem would wreak environmental havoc on par with the disease.

Biomass will of course provide only part of the solution: The point of the previous example is not that we might supply all the world's energy needs with biomass,

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[⋆] U.S. cropland and forest land occupy 180 and 210 Mha respectively. A hectare is 10^4 m^2, or $\sim$2.5 acres; a Mha is a million hectares. Representative productivities expressed in tons carbon per hectare per year (tC/ha-yr) are 2 for productive forests and 5 or more for intensively managed forests or annual grasses grown as energy crops. These numbers are approximate, my objective is merely to set a scale, to demonstrate that energizing industrial civilization with biomass would require roughly the same area and intensity of management as is now used for cropland. Less intensive management might be used, such as is the norm for North American timber production, but the productivity would then be smaller and the area required larger.

but that supplying (for example) one third of global energy needs would require (very roughly) an area equivalent to one third of global cropland. Robust analysis of biomass must address the consequences of this land use, and must determine what uses of biomass will provide the largest net benefits. Such analysis must confront a still harder and more value laden question, how much land ought we to spare for nature (Waggoner, 1997)? Resolving this question is one of the central challenges of climate and energy policy. It is my expectation that measured use of biomass that focuses on arresting or reversing some of the environmental damage wrought by recent exploitation – for example, by halting and reversing global deforestation and by improving denuded soils – will provide environmental and social benefits, but that large scale use of cropped biomass for energy will not.

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