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Bioenergy in the United States: progress and possibilities[1]

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Abstract

Concerns about global climate change and air quality have increased interest in biomass and other energy sources that are potentially CO_2-neutral and less polluting. Large-scale bioenergy development could indeed bring significant ecological benefits — or equally significant damage — depending on the specific paths taken. In particular, the land requirements for biomass production are potentially immense.

Various entities in the United States have performed research; prepared cost–supply assessments, environmental impact assessments, life cycle analyses and externality impact assessments; and engaged in demonstration and development regarding biomass crops and other potential biomass energy feedstocks. These efforts have focused on various biomass wastes, forest management issues, and biomass crops, including both perennial herbaceous crops and fast-growing woody crops. Simultaneously, several regional and national groups of bioenergy stakeholders have issued consensus recommendations and guidelines for sustainable bioenergy development.

It is a consistent conclusion from these efforts that displacing annual agricultural crops with native perennial biomass crops could — in addition to reducing fossil fuel use and ameliorating associated ecological problems — also help restore natural ecosystem functions in worked landscapes, and thereby preserve natural biodiversity.

Conversely, if forests are managed and harvested more intensively — and/or if biomass crops displace more natural land cover such as forests and wetlands — it is likely that ecosystem functions would be impaired and biodiversity lost. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Bioenergy: opportunities and risks

In the nine years since we explored potential impacts of biomass production in the United States on biodiversity [1], pressure has increased to reduce net CO_2 emissions that drive global climate change. The United States agreed in Kyoto to reduce its greenhouse-gas emissions to 7%

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below baseline levels — although the agreement will apparently not be presented to the Senate until developing countries have committed to participate significantly in global efforts to reduce emissions[2]. Proposed strategies for the United States include increasing energy efficiency, displacing fossil fuels with energy sources that are potentially CO_2-neutral, and carbon storage in forests and other ecosystems [2–5].

Pressure has also increased to address other pressing ecological and social challenges: (1) to improve air quality in urban and rural areas [6,7][3]; (2) to preserve ecological integrity and biodiversity on cropland [8] and in forests [9–15];[4] (3) to reduce the trade-deficit and national-security costs of petroleum [16,17]; and (4) to develop markets for waste wood [18] and low-quality forest wood [19]. An additional constraint will be pressure to produce food for a rapidly-growing human population [20–22].

Bioenergy systems could play important — and potentially synergistic — roles in addressing these challenges. Of the potentially CO_2-neutral and less polluting energy alternatives that are being seriously considered for large scale implementation,[5] biomass can both (1) readily supply base-load electrical power, and (2) be converted to liquid transportation fuels — and so it will likely be a key part of the solution.

Large-scale bioenergy development could bring significant ecological benefits — or cause equally significant damage — depending on the paths taken. In particular, the land requirements for large-scale biomass production could be immense. The nature and extent of the impacts of the resulting changes in land use will depend on the specifics (see Sections 1.1–1.3).

For example, integrating native perennial bioenergy crops with traditional crops on fertile cropland, and displacing annual crops with native perennial bioenergy crops on sensitive and marginal cropland, could bring at least three key benefits. Such a strategy could (1) slow global climate change by reducing net greenhouse gas emissions, (2) improve air quality and reduce acid deposition by reducing SO_X emissions, and (3) preserve natural biodiversity by restoring natural ecosystem functions in worked landscapes.

Conversely, if bioenergy facilitates intensive management of forests for extractive uses — or if biomass crops displace additional natural land cover such as forests and wetlands — it is very likely that ecosystem functions would be impaired and biodiversity lost. Indeed, implementation at a level sufficient to significantly displace current fossil fuel usage could destroy habitat for native wildlife on a scale not seen in the United States since the 1800s [1]. Also, primarily because of the time delay and/or uncertainty regarding forest regeneration, wood from existing forests is much less effective than energy crops at displacing CO_2 emissions from fossil fuels. We estimate (see Section 1.1) that wood from existing forests displaces only 100 ± 70 kg C mg^{-1} compared with 540 ± 280 kg C mg^{-1} for a range of perennial herbaceous and woody crops.

1.1. Impacts on global climate change

The main US sources of anthropogenic CO_2 emissions — accounting for about two thirds of the US total — are fossil-based power generation and transportation. Biomass will likely play key roles in reducing CO_2 emissions in both of these sectors, because it can readily supply base-load electrical power and be converted to fluid transportation fuels. Biomass can also displace fossil fuels indirectly as durable products that replace products made from such energy-intensive materials as steel, plastics and aluminum [4].

Generally speaking, the effectiveness of biomass in reducing CO_2 emissions from fossil fuels

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[2] These issues were discussed on 02/04/98 at a White House Briefing by Gene Sperling, Federico Peña, John Karl Scholz, Todd Stern and Peter Orszag.

[3] Further information and EPA regulations for each Clean Air Act Title are available at OAR Policy and Guidance Information <http://www.epa.gov/ttn/oarpg/amend.html>.

[4] Forest Service Chief Mike Dombeck, in a March 1, 1998 speech to Forest Service staff, said that "[c]onservation has moved from a 'special interest' to a national priority." Associated Press Online news report.

[5] The four major options appear to be biomass, wind, solar and geothermal. We do not address their comparative benefits and costs.

depends on two main factors: (1) the net effective greenhouse gas flux for the overall biomass production-use cycle, and (2) the relative efficiency of the biomass conversion or end-use process [2,4,23–26]. Although conversion and end-use efficiencies for biomass energy feedstocks are currently lower than those for fossil fuels, these may be transient symptoms of technological immaturity and small-scale implementation. Even now there are exceptions — for example, biomass can be co-fired in large and efficient coal-fired electrical power plants with minimal modifications and efficiency penalty [25]. For the longer term, new technologies — such as pre-drying, new combustion technologies, gasification, gas turbines and combined cycle systems — promise even greater efficiencies [25–27].

The net effective greenhouse gas flux for a particular biomass feedstock depends primarily on two characteristics of the biomass production-use cycle: (1) the net greenhouse gas flux, and (2) the order and timing of the component source and sink terms [4,28]. Fluxes of CO_2 and other greenhouse gases for bioenergy systems involve several sources and sinks. The principle ones are (1) CO_2 fixation during biomass growth, (2) changes in the organic matter content of the soil, and (3) CO_2 emissions during biomass conversion and/or use. Other greenhouse gas emissions for bioenergy systems include (1) CO_2 emissions from fossil-fueled equipment used to manage, harvest, process and transport biomass, (2) CO_2 emissions from fossil energy used in the production of fertilizers and pesticides, and (3) N_2O emissions from nitrogen-fertilized soil [4,29–32]. Results are expressed, where possible, both in terms of the mass of carbon per mass of biomass and in terms of the mass of carbon per area of land used to produce the biomass [33].

1.1.1. Changes in the organic matter content of the soil

Generally speaking, the conversion of land from natural cover to intensive annual crop production progressively decreases the organic matter content of the soil. The major factors are (1) decreased detrital inputs, and (2) increased erosional and metabolic losses caused by increased soil temperature and aeration. For organic-rich soils, this loss of organic matter can result in obvious subsidence. However, we will assume for this analysis that most cropland has already lost the most labile component of its soil carbon, and that ongoing losses are therefore *minimal*.

Conversely, the conversion of land from intensive annual crop production to perennial herbaceous species progressively increases the soils' organic matter content. For example, the conversion of land from annual crops (cotton, wheat and corn) to native perennial grasses (as part of the Conservation Reserve Program) added an average of 1.1 Mg C ha^{-1} yr^{-1} to the soil [34]. Bransby and coworkers obtained similar results for the conversion of land from annual crops to switchgrass [35]. Zan and coworkers have reported much greater below-ground biomass for switchgrass than for corn — 7.2 Mg ha^{-1} compared with 1.6 Mg ha^{-1} — implying a one-year addition of 2.2 Mg C ha^{-1} yr^{-1} to the soil [36].

It has been reported that the conversion of land from annual crops to fast-growing woody crops added an average of approximately 1–2 Mg C ha^{-1} yr^{-1} over the course of the rotation, although there was a transient loss of soil carbon from increased erosion and mineralization until canopy closure at approximately 6 years [37]; also see [38]. Other workers have failed to find an increase [39]. Additional studies of soil carbon changes are planned for larger scale (12–120 ha) hybrid poplar plantings near Alexandria, Minnesota, USA [40].

Projected yields of harvestable biomass on good agricultural sites are 15–20 Mg dry biomass ha^{-1} yr^{-1} for perennial herbaceous crops and 10–15 Mg dry biomass ha^{-1} yr^{-1} for woody crops [29]. Assigning the net increase in soil carbon to the harvested biomass crop — as a negative component of its net carbon flux — yields 55–150 kg C Mg^{-1} for perennial herbaceous crops and 0–200 kg C Mg^{-1} for short-rotation woody crops.

1.1.2. Fossil energy inputs

The major fossil energy inputs for biomass crop production are fertilizers (mostly nitrogen) and fuel (for planting, management and harvesting). Nitrogen fertilizers are made from natural gas.

Shapouri and coworkers estimated that fossil energy inputs for corn production currently average 2.3 GJ Mg^{-1} — with 0.9 GJ Mg^{-1} as nitrogen fertilizer and 0.5 GJ Mg^{-1} as fuel [41]. Lorenz and Morris estimated a current average of 2.8 GJ Mg^{-1} — with 1.2 GJ Mg^{-1} as nitrogen fertilizer and 0.3 GJ Mg^{-1} as fuel [42]. These estimates are equivalent to 30–40 kg C Mg^{-1} based on the CO_2 emissions from the mix of fossil feedstocks used. Including most of the stover with the harvest reduces the estimate to approximately 20 kg C Mg^{-1}.

Projected fossil energy inputs for perennial crop production are considerably lower: 0.72 GJ Mg^{-1} for switchgrass and 0.48 GJ Mg^{-1} for hybrid poplar [29]. Although projected fuel requirements are 0.30 GJ Mg^{-1} for both crops, switchgrass is projected to require more nitrogen fertilizer than hybrid poplar: 0.34 GJ Mg^{-1} vs 0.16 GJ Mg^{-1}. These estimates are equivalent to 12 kg C Mg^{-1} for switchgrass and 8.3 kg C Mg^{-1} for hybrid poplar based on the CO_2 emissions from the mix of fossil feedstocks used. The values for other woody crops are presumably similar.

1.1.3. Order and timing of CO_2 fixation and emission

Woody crops sequester CO_2 during growth, serving as a transient carbon sink. Taking the carbon content of dry wood to be approximately 540 kg C Mg^{-1}, assuming linear tree growth and using a discount rate of 3% per year for CO_2 uptake [28] reduces the net effective CO_2 flux by 30 kg C Mg^{-1} for a three year rotation (e.g., willow) and 90 kg C Mg^{-1} for a 10 year rotation (e.g., hybrid poplar).

In contrast, for wood harvested from standing forests and used for energy, the released carbon is gradually removed from the atmosphere as the forest regenerates. Assuming linear tree growth and a 3% discount rate — and indeed, that the forest does in fact regenerate to its initial state [43] — *increases* the net effective CO_2 flux by approximately 370 kg C Mg^{-1} for a 100 year rotation — approximately 70% of the total carbon content (540 kg C Mg^{-1}). Failure to return to the initial state — a likely outcome for the harvesting of mature and old-growth forests — will further increase the net effective CO_2 flux, although this can be offset somewhat by long-term storage of some harvested wood as structural materials [38] and associated displacement of energy embodied in such structural materials as aluminum, steel and concrete [4]. Including these offsets, and assuming linear tree growth and a 3% discount rate, the net effective CO_2 flux is increased by approximately 460 kg C Mg^{-1} if the total effective carbon storage stabilizes at 50% of its initial value after 100 years. Alternatively, the net effective CO_2 flux is increased by approximately 500 kg C Mg^{-1} if the total effective carbon storage returns to its initial value after 400 years.

1.1.4. Fossil-fuel displacement

Marland and coauthors have argued that, with current conversion efficiencies, 1 kg carbon in biomass can displace only 0.6 kg carbon in fossil fuels [28]. Given the transitional role of cofiring and the potential for high-efficiency biomass conversion systems, an upper limit of 1 kg fossil carbon displaced per kg biomass carbon seems reasonable.[6]

1.1.5. Summary of impacts on global climate change

The results of these calculations are summarized in Table 1. The estimated CO_2-emission reduction for using perennial biomass crops to displace fossil fuels is 400 ± 140 kg C Mg^{-1} for switchgrass, 550 ± 210 kg C Mg^{-1} for willow, and 600 ± 220 kg C Mg^{-1} for poplar. These estimates can presumably be generalized to other perennial biomass crops with similar rotation length and growth characteristics — and this assumption is reflected in Table 1. The corresponding estimate for corn is 300 ± 80 kg C

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[6] We assume relatively-efficient combustion, and so we do not include the potent climate-forcing impacts of CH_4 and other products of incomplete combustion (see discussion in Akbari et al. [44] at p. 723).

Mg^{-1}. We emphasize that the estimated reduction in CO_2 emissions for perennial biomass crops — and especially for woody crops — may be greater than the carbon content of the biomass. That is, the reduction in anthropogenic climate forcing via transient CO_2 sequestration during growth and/or CO_2 fixation as soil organic matter may be appreciable compared to that from direct fossil fuel displacement.

These estimates can be expressed in terms of the land area used for biomass production by using the projected yields of harvestable biomass on good agricultural sites of 15–20 Mg dry biomass ha^{-1} yr^{-1} for herbaceous crops and 10–15 Mg dry biomass ha^{-1} yr^{-1} for short-rotation woody crops [29]. Doing so, we obtain estimates of 5.4 ± 2.2 Mg C ha^{-1} yr^{-1} for corn, 7.4 ± 3.4 Mg C ha^{-1} yr^{-1} for perennial herbaceous crops, 7.4 ± 4.0 Mg C ha^{-1} yr^{-1} for woody crops on a three-year rotation, and 8.0 ± 4.3 Mg C ha^{-1} yr^{-1} for woody crops on a ten-year rotation. The greater productivity of switchgrass compensates for its lower carbon content.

In contrast, the estimated CO_2-emission reduction for using wood from existing forests to displace fossil fuels is much smaller, primarily because of the time delay and/or uncertainty regarding regeneration: 100 ± 70 Kg C Mg^{-1} for a range of forest harvesting-use-regeneration cycles.

1.2. Impacts on air quality and acid precipitation

Biomass feedstocks contain little sulfur compared with oil and coal, and varying amounts of nitrogen. Uncontrolled SO_X emissions from biomass combustion are negligible compared to uncontrolled SO_X emissions from coal and oil combustion, but uncontrolled NO_X emissions can be comparable — and are dependent on the conversion process and nitrogen content of the biomass [45]. NO_X emissions comprise fuel-bound NO_X and thermal NO_X. Generally, wood contains less nitrogen (i.e., protein) than perennial herbaceous crops or crop residues. Fluidized bed boilers generate less thermal NO_X than grate-fired boilers or gasifier-based boilers and gas turbines because of their lower and more uniform temperatures.

1.3. Impacts on land use

The ecological effects of growing large quantities of biomass for energy — the effects on wildlife habitat and biodiversity, on soil fertility and erosion, and on water quality — will depend

Table 1
Estimated CO_2-emission reduction for displacing fossil fuels with various types of biomass

Type of Biomass. All values in this table are given as kg of carbon per Mg of biomass	Carbon content of dry biomass	Change in soil organic matter content during biomass growth	Fossil energy inputs during biomass growth	Order and timing of CO_2 fixation and emission	Estimated total CO_2-emission reduction[a]
Corn	400	–	−20 to −40	–	300 ± 80
Perennial herbaceous crops	400	55–150	−12	–	400 ± 140
Short-rotation woody crops					
Three-year rotation	540	0–200	−8	30	550 ± 210
Ten-year rotation	540	0–200	−8	90	600 ± 220
Wood from existing forests					
100-year rotation[b]	540	–	–	−370	140 ± 30
400-year rotation[b]	540	–	–	−500	30 ± 10

[a] The total has been adjusted to account for an estimated range of 60–100% in displacement efficiency.

[b] These estimates assume that total carbon storage in the forest returns to its initial value over the time period specified.

on the specifics. The ecological implications of this land use change would very likely be positive — as long as perennial biomass crops displaced annual agricultural crops. However, the ecological implications of displacing more natural land cover (such as forests and wetlands) with energy crops would very likely be negative [1,40,46–48].

1.3.1. Soil erosion and water quality

It has been projected that displacing annual crops with perennial biomass crops would reduce runoff — decreasing soil erosion and improving water quality [29,47]. Even so, runoff during crop establishment could be comparable to or greater than that from annual row crops, especially for tree crops treated with herbicides to suppress competing vegetation. Field-scale comparisons of annual crops and perennial biomass crops have been under way since 1995 at three Southeastern universities: (1) no-till corn and sweetgum, with and without cover crops, at Alabama A&M University; (2) cotton and cottonwood at Mississippi State University; and (3) no-till corn and sycamore at the University of Tennessee [49]. In 1997, a watershed-scale study began in eastern South Carolina comparing sycamore, sweetgum, and sweetgum with a cover crop [49].

Steady state infiltration rates do not appear to increase with tree crop age, with comparable rates for one year old sycamore, soybean and corn [50]. First year data from a series of switchgrass and tree crop trials in the Southeastern USA [51] show little difference between the perennial crops and annual crops (corn and cotton) — although runoff from one of the cottonwood plots began to decrease dramatically by Spring of the second year [52,53]. Although cover crops (winter rye grass, tall fescue, crimson clover and interstate sericea) do appear to reduce first year erosion in sweetgum, they also inhibit tree growth [54].

Displacing annual crops with perennial biomass crops would significantly reduce net pesticide use — and could also reduce net fertilizer use, depending on which biomass crops were deployed and what agricultural uses they displaced [29,47].

1.3.2. Habitat and biodiversity

Displacing annual agricultural crops with perennial biomass crops could also improve habitat for native wildlife — especially if native crop species were used in ecologically-appropriate locations. Perennial energy crops could also be integrated with annual crops as buffers around remnant natural areas — perennial herbaceous crops around grassland remnants and woody crops around forest remnants — and as filter strips along streams. The introduction of such crops in worked landscapes could improve wildlife habitat, preserve natural biological diversity and restore natural ecosystem functions — and simultaneously diversify the income mix of landowners.

Results from field research in hardwood plantations [55–60] support the hypothesis that replacing row crops with native woody biomass crops (or native-foreign hybrids) in formerly forested regions will help increase populations of some forest-dependent bird species whose habitat has been — and continues to be — eliminated and fragmented by human activities.

Bird density and species diversity in hardwood plantations during breeding season are increased by the presence of understory vegetation and/or contrasting habitat inclusions (such as fencerows or stream corridors) that contain mature trees and associated understory vegetation [58,60]. Significant use of hardwood plantations by small mammals also seems to depend on the presence of understory vegetation and/or other contrasting habitat inclusions [56,59,61].

These results support the recommendation that such woody crops be sited to surround and fill gaps between remaining forest fragments, buffering them from cleared areas, reducing habitat fragmentation and increasing the availability of valuable forest-interior habitat. They also indicate that the habitat value of such woody crops for birds and small mammals is increased by the presence of understory vegetation and/or contrasting habitat inclusions that contain mature trees and associated understory vegetation.

Initial results from field research in large switchgrass plantings [55,62] support an analogous possibility — that native perennial grasses grown as energy crops in former grasslands may provide suitable habitat for some prairie-dependent bird species. This could be a lucky break for grassland songbirds, many of which are in very serious condition (with declines of 90–95% being not uncommon). More generally, this might also benefit many other species native to tall-grass prairie, which have lost almost all of their original habitat.

Efforts are underway at the US Department of Agriculture to evaluate biomass crops as an alternative to Conservation Reserve Program (CRP) set-asides for controlling soil erosion and chemical runoff. Although farmers have commonly planted perennial grasses (and trees) on CRP set-aside lands, harvesting has not been permitted. It appears that biomass crops can provide many of the wildlife habitat benefits of CRP management if they are managed and harvested appropriately [8,63].

2. The response: research, negotiation and demonstration

2.1. Research

The US Department of Energy (DOE) Biofuels Feedstock Development Program (BFDP) at the Oak Ridge National Laboratory (ORNL) has explored a wide variety of annual and perennial plant species — 34 herbaceous species and 125 tree species — as potential biomass crops [48]. US DOE BFDP efforts have focused in recent years on switchgrass (*Panicum virgatum*) — a perennial grass native to the US prairie — and several fast-growing woody crops — hybrid poplar (*Populus* spp), willow (*Salix* spp), sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*) and maple (*Acer* spp) — as model species for testing at larger scales. The US paper industry is also exploring fast-growing woody crops as an ecologically-sound fiber resource [64,65].

DOE's National Renewable Energy Laboratory (NREL) has focused on research, development and demonstration of biomass conversion technologies. Working with private-sector partners, NREL has developed technologies for: (1) hydrolysis and fermentation of lignocellulosic feedstocks to produce ethanol and other products [66]; and (2) biomass gasification [67][7] and integration with aeroderivative gas turbines [25,68,69].

Various entities in the United States have done cost–supply assessments [70–72], environmental impact assessments [1,29,40,45–49,60,73,74], life cycle analyses [31,69] and externality impact assessments [75,76] for biomass crops and other potential biomass energy feedstocks. Most of these efforts have focused on perennial herbaceous crops and fast-growing woody crops — and have addressed such issues as energy and greenhouse-gas budgets, soil health and erosion, surface water and groundwater pollution, biodiversity and landscape ecology, and emissions from conversion facilities. Other studies have explored biomass production as an alternative to the Conservation Reserve Program for ecologically-sensitive cropland [8,63].

2.2. Negotiation

Given the uncertainty and the potential for conflict, the best strategy appears to be joint fact finding and negotiated conflict resolution [77–79]. A wide range of bioenergy stakeholders — farmers, utilities, fuel producers, environmental nongovernmental organizations and government agencies — have convened workshops and roundtables to share concerns and engage in a process of joint fact finding, negotiation and consensus building. These efforts have resulted in recommendations and guidelines for developing and implementing bioenergy technologies in ways that are economically viable, socially beneficial and ecologically sustainable [80–83]. As bioenergy development proceeds, these efforts can evolve into jointly implemented adaptive environmental assessment and management [84–87].

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[7] This fact sheet describes scale-up gasification projects that the Biomass Power Program is cost-sharing with industry in Hawaii and Vermont.

This process began in the United States with an informal workshop sponsored in late 1990 by DOE's Biofuels Feedstocks Development Program — where members of the principal stakeholder groups met and got most of the main issues out on the table. The process continued with a workshop that was jointly sponsored in mid-1991 by National Audubon and Princeton University's Center for Energy and Environmental Studies. This workshop — which brought together engineers, ecologists, foresters and policy makers to consider the implications of large scale bioenergy development for biodiversity — revealed the outlines of broadly acceptable guidelines for energy crop production [80].

Building on these efforts, the National Biofuels Roundtable — a diverse group of bioenergy stakeholders that met from late 1992 to early 1994 — negotiated a comprehensive set of guidelines for energy crop production [81]. However, the group was unable to reach substantive agreement on any of the issues associated with forest harvesting for energy. Also, it was impossible for the group to go beyond generalities at the national level, given the regionally specific nature of bioenergy resources and issues.

Information sharing and negotiation efforts began in the North Central States with the RENEW Wisconsin Conference in early 1993 [88] and continued with the Wisconsin Biomass Energy Infrastructure Workshop in mid 1994 [89] and the Biomass Ecological Workshop: Defining the Agenda for the North Central States in early 1995 (proceedings not published).

In mid 1994, the Coalition of Northeastern Governors (CONEG) — at the request of Vermont's Governor Dean — convened a Governors' Biomass Roundtable to recommend actions for the region's governors to take regarding bioenergy. After several months of negotiation, the group had reached substantive agreement on many issues — and not on issues associated with harvesting forests for energy feedstocks. To help break the impasse, the roundtable held a Forest Ecology and Biomass Harvesting Workshop in early 1995 with invited panels of foresters and ecologists. The workshop clarified two key points: (1) forest harvesting for energy is a minor component of current forest harvesting by wood products industries; and (2) the ecological implications of the increased harvesting of low quality wood for energy are unclear and probably mixed.

Following this workshop, the CONEG roundtable agreed that, while no additional oversight is needed currently regarding the ecological impacts of harvesting the region's forests for energy, the states should monitor harvesting levels. The roundtable recommended that, if and when forest harvesting for energy production becomes significant compared to current forest harvesting for wood products industries, the states should begin to monitor the ecological impacts of energy harvesting [82].

The Southeast Bioenergy Roundtable, initiated in early 1995 by DOE's Southeastern Biomass Energy Program (SERBEP), included representatives from a wide range of regional stakeholders from commercial, governmental, environmental and academic sectors. After several meetings, the group issued a report that reviews the potential for bioenergy in the Southeast, identifies issues and concerns, and presents consensus strategies for bioenergy development that is environmentally, economically and socially responsible [83].

The group concluded that bioenergy development in the Southeast could bring environmental, economic and social benefits. The ecological implications of displacing annual row crops with biomass crops would likely be positive. Conversely, the ecological implications of significantly increasing forest harvesting could be negative, and the ecological implications of displacing forests and wetlands with biomass crops would be negative. The group also identified issues that currently limit bioenergy development in the Southeast.

Approximately 1.7 EJ of biomass is currently used for energy in the Southeast, primarily fuelwood and residues from the forest-products industries — and the potential supply was estimated to be ~7.5 EJ, including ~3 EJ from the region's forests and ~4 EJ from energy crops. Although the region's energy demand is expected to increase, competition from low-cost natural gas and other fossil fuels will limit the demand for biomass. Also, the use of forest biomass for energy is likely, at least in the short term, to be limited largely to residuals from higher-value products. Lastly, it will be necessary to create a demand, and address economic concerns regarding the longer crop-production cycle, before farmers will commit to growing perennial biomass crops.

The Southeast roundtable presented consensus strategies to address the issues that currently limit bioenergy development: (1) minimize environmental costs and maximize environmental benefits by focusing on the use of biomass residues and the sustainable development of the region's biomass crop potential; and (2) promote bioenergy market development. These strategies are expressed as recommendations to the region's private, government, research and public-interest sectors.

In related work relevant to the use of forest management and harvesting residues for fuelwood in the US Northeast, the National Audubon Society and the Procter and Gamble Company have cooperatively studied plant and animal responses to timber harvesting on non-industrial private lands in northeastern Pennsylvania [90]. National Audubon has also cooperated with International Paper on wildlife studies at their short-rotation hardwood plantations in South Carolina — work that is directly relevant to energy crops.

2.3. Demonstration

DOE's Regional Biomass Energy Program has for many years funded the creation of resources to facilitate bioenergy development, focusing mainly on biomass residues and wastes. Cost-shared demonstration projects have generally been the primary focus. Informational resources, such as directories, feedstock-supply assessments and technology assessments, have also been created.

DOE, through NREL and in partnership with the Electric Power Research Institute, invited proposals and funded feasibility studies for several Integrated Bioenergy System Demonstration Projects. DOE has subsequently funded project planning for three such projects: (1) a project in Minnesota to process alfalfa into leaves for cattle feed and stems, and to produce electricity from the stems; (2) a project in New York to grow short-rotation willow and produce electricity by cofiring with coal; and (3) a project in Iowa to grow switchgrass and produce electricity by cofiring with coal.

2.3.1. Minnesota

The Minnesota Valley Alfalfa Producers cooperative has contracted to supply 75 mW of biomass electricity generation to the Northern States Power Co. by late 2001. The cooperative, with cost-shared DOE funding, will build facilities to process alfalfa into leaves for cattle feed and stems, and a plant to produce electricity from the stems. This is the most conservative of the three DOE-funded Integrated Bioenergy System Demonstration Projects, in that it employs a crop that is familiar to the region's farmers, and that it depends on a high-value coproduct for economic viability.

2.3.2. New York

The New York State Energy Research and Development Authority has funded research on the bioenergy potential of short-rotation willow at the State University of New York College of Environmental Science and Forestry since 1987 [91]. Efforts have focused on: (1) identification and field-testing of promising willow clones; (2) research on the ecological aspects of short-rotation willow production; (3) demonstration of farm-scale production; (4) development and demonstration of conversion technologies; and (5) study of the economic feasibility of integrated bioenergy systems.

The clonal-development component has proceeded in close cooperation with the University of Toronto. The DOE/ORNL Biofuels Feedstock Development Program began funding field trials of promising willow clones in 1992, and four small-scale short-rotation willow farms were planted in 1993–1995. The program established a 40+ hectare demonstration farm in 1996 with funding from the USDA Cooperative States Research, Education and Extension Service.

Several studies have explored ecological aspects of short-rotation willow production and identified ways to improve ecological sustainability, and additional studies are under way [92].[8] Studies have explored alternatives for site preparation and crop management to improve soil ecology and reduce non-point source pollution. Other studies have explored impacts on avian biodiversity at field scales, and landscape-scale studies are planned as larger plantings are established.

The conversion-system focus shifted in 1989 from gasification to direct combustion and cofiring with coal for electricity production. The New York State Electric and Gas Corporation joined the project in 1992, and in late 1994 demonstrated 10% cofiring with sawmill waste in its pulverized-coal unit at Greenridge [93].

The study funded by DOE/NREL and EPRI in 1994 concluded that it would be economically feasible to cofire pulverized-coal units with short-rotation willow, supplemented with forest and mill residues. Planning for a demonstration project is under way with DOE funding.

2.3.3. Iowa

Chariton Valley Resource Conservation and Development Inc. — together with IES Utilities and many other public and private interests — has been exploring the potential of switchgrass production for bioenergy to provide ecological and economic benefits to the region [94]. It appears that switchgrass is a sustainable crop that is both ecologically appropriate for the region's CRP-like lands (lands with high erosion potential and low row-crop productivity) and likely to help the region's economy, given ongoing changes in crop support and CRP programs. Efforts have included research and development for crop establishment, management, harvesting and transportation, and technology transfer to the region's farmers.

The study funded by DOE/NREL and EPRI in 1994 concluded that it would be economically feasible to cofire pulverized-coal units with switchgrass [94]. The study further concluded that this would be a low-risk strategy for the utility — given the low-cost of converting a pulverized-coal unit to cofire switchgrass and the expectation that cofiring at 5% would have minimal impacts on performance — and one that would provide such environmental benefits as displacing SO_X and CO_2 emissions. An additional benefit would be the establishment of a long-term market for switchgrass, which would encourage expanded production and thereby the commercialization of more-advanced conversion technologies such as gasification. Planning for a demonstration project is under way with DOE funding.

3. Synthesis

Biomass residues and wastes are generally attractive as energy feedstocks from both economic and ecological perspectives. They are commonly the least expensive feedstocks available for producing electricity or fluid fuels — less expensive even than coal in some cases [82]. Furthermore, using these low-cost biomass feedstocks to displace coal and oil is generally beneficial from an ecological perspective, and it seems likely that they will be increasingly used as their advantages are appreciated.[9] Although insufficient biomass residues and wastes are available — approximately 3 exajoules (EJ) per year — to significantly displace the more than 80 EJ of fossil fuels used in the United States each year, their increasing use may help to ease some of the institutional and infrastructural barriers to the use of biomass energy feedstocks.

More plentiful biomass feedstocks will be required for bioenergy to significantly displace current fossil fuel use in the United States, and

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[8] Tim Volk, State University of New York College of Environmental Science and Forestry, personal communication.

[9] There are serious concerns regarding hazardous air and ash emissions from facilities using wood contaminated with toxic metals or organic compounds — especially lead-painted wood and wood preserved with pentachlorophenol or chromated copper arsenate. However, separation of contaminated wood from clean wood at the source would minimize the risk. Also, new technologies may permit the ecologically-acceptable production of clean fluid fuels from such contaminated feedstocks.

there are two main possibilities — wood from existing forests and energy crops. Unfortunately, economic and ecological interests are not in alignment here. Wood from existing forests is significantly less expensive than energy crops. Also, there are major institutional and infrastructural barriers to large scale energy crop production.

In contrast, although there are major uncertainties due to knowledge limitations, it appears that the net ecological implications of biomass crop production are neutral to positive, while the net ecological implications of forest harvesting are neutral to negative. For example, we estimate that the CO_2-emission reductions for using biomass crops to displace fossil fuels are 300 ± 80 kg C Mg^{-1} for corn, 400 ± 140 kg C Mg^{-1} for switchgrass, 550 ± 210 kg C Mg^{-1} for willow and 600 ± 220 kg C Mg^{-1} for poplar. In contrast, the estimated CO_2-emission reduction for using wood from existing forests to displace fossil fuels is much smaller, 100 ± 70 kg C Mg^{-1} for a range of forest harvesting–use–regeneration cycles, primarily because of the time delay and/or uncertainty regarding regeneration.

This conflict of economic and ecological interests is probably the major factor inhibiting the development of a significant bioenergy sector in the United States. Economic forces might be sufficient to drive the development of a forest-based bioenergy sector in regions of the country with significant forest resources — primarily the New England States, the Southeast, the Great Lakes States, the Mountain West and the Pacific Northwest. However, such large scale forest-based bioenergy development would very likely be opposed by citizens who are already concerned about the ecological impacts of current forest harvesting by the wood products industry.

Conversely, ecological considerations appear to favor the development of a bioenergy sector based on energy crops in regions of the country with significant surplus cropland — primarily the Midwest, the Southeast, the Mid-Atlantic States and the Great Lakes States. However, given the high cost of energy crops compared to fossil fuels — especially natural gas for electrical power production — and the institutional and infrastructural barriers associated with energy crop production, the prospects for near term implementation might seem problematic.

Given this situation, a two-pronged approach seems appropriate. First, as the CONEG Governors' roundtable recommended, states should begin to monitor the ecological impacts of forest harvesting for energy production if harvesting levels become significant compared to current forest harvesting for the wood products industries [82].

Second, it will also be necessary to close the gap between the costs of energy from energy crops and fossil fuels [25]. The DOE strategy in this area has three components: (1) exploiting multiple niche markets and providing incentives to support scale-up of energy crop production [25]; (2) ongoing energy-crop research to reduce production costs and maximize net ecological benefits [74]; and (3) commercial-scale demonstration of high-efficiency conversion technologies [25,67].

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