Chapter 1

Forest Biomass Sustainability and Availability

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This chapter provides a synthesis of information on potential supply of forest biomass given needs for sustainable development of forestry. Sustainability includes maintenance of water supply, biodiversity, and carbon storage as well as timber products, community development, and recreation. Biomass removals can reduce fire hazard and insect and disease attack, restore forest composition and structure, enhance forest growth, provide revenue for treatments and communities, and offset greenhouse gas emissions. Biological limitations vary by forest condition, ownership, and how stands are regenerated. Limitations maintain water supply, soil nutrients, and biodiversity. There are economic limitations because costs for removals may exceed revenue. One analysis suggests U.S. forest-based biomass supply could be 45 million dry tons per year or more, depending on biomass price. Social targets and limitations are given in federal and state legislation. These include a federal cellulosic fuel target with biomass source restrictions, state-level renewable energy portfolio standards, and state-level forest practice guidelines. Understanding of biological and economic limitations and benefits is developing, particularly at local levels. Social targets and limitations could change. Increases in fossil fuel prices would accelerate efforts to develop understanding of biological limitations and could result in changes to social and economic targets and limitations.

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Introduction

To assess availability and sustainable use of forest biomass for the United States, we suggest accepting the "Brundtland report" (*1*) view of sustainable development. This report defines sustainability in relation to satisfying human needs though sustainable development: *Humanity has the ability to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits—not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities.* This definition indicates that sustainability needs to account for (1) human needs, current and future, (2) limitations in meeting these needs based on technological capabilities, social organzation, and environmental resources, and (3) the ability of the biosphere to absorb the effects of human activities.

We also suggest that sustainable development of forest biomass needs to be part of a broader sustainable development of forestry that seeks to meet a wide range of social, product, and environmental needs for people. Specifically the sustainable development of forest biomass must consider how to accommodate sustainable development of forest timber products, forest-based recreation, forest non-timber products, forest-based community development, and forest environmental services such as biodiversity and carbon storage (*2*).

Efforts to establish sustainable levels of forest biomass use need to consider the potential biological supply and a range of environmental, economic, and social limitations. The sustainable development of biomass, although subject to many limitations, also potentially provides benefits that can promote sustainable development of forestry. This chapter provides synthesis of current understanding about the factors that will determine the sustainable levels of biomass supply. First, we provide three example analyses that estimate potential sustainable supply given current understanding of economic and environmental constraints. The first example estimates of potential biomass supply are driven by physical and biological limitations. The second example estimates add economic limitations and estimate supply available at different prices at forest roadside or mill gate. The third example estimates add limitations on biomass supply due to competition with agricultural biomass and limitations of transportation and technology to produce biofuels in specific locations across the western United States. In progressing through the examples, there is a progression of added constraints that will determine supply of forest biomass. Each example has similar but not identical biological limitations on supply. Second, we discuss environmental benefits and limitations associated with forest biomass supply. Third, we discuss the social (institutional) support and limitations on biomass supply—which may not be included in the economic/environmental estimates—including current and emerging regulations and policy concerning renewable energy, and forest practice guidelines.

Our second and third biomass supply estimation examples focus on estimating biomass supply for biofuels production. In addition to the factors that determine biomass supply in these examples, the amount of wood biomass actually available in a location for a particular user will be influenced by competition for biomass from electric power plants, thermal energy producers, biochemical producers, and users of pulpwood to make paper and wood panels. Even though our examples focus on estimating biomass for biofuels production, they are in fact estimates of supply available for all wood biomass users.

Table I shows key estimation results for the three examples and the key drivers used to make the estimates.

Table I. Comparison of three estimates of forest-based biomass supply

Study	*Key Estimate*	*Key drivers of biomass supply estimates*
"Billion Ton Supply" Study	Nationwide estimate—137 million odt/year of forest-based biomass supply physically available in the near term	• Physical and biological limits on logging residue removal • Need for and biological limits on forest health thinnings
BRDI Feedstock Study	Nationwide estimate—45 million odt/year of forest-based biomass supply available for a cost of about $44/odt at forest roadside or mill gate in the near term	• Cost to harvest and chip progressively larger amounts of logging residue or biomass from forest thinnings • Limitations on amounts logging residue or thinnings obtained due to required co-production of sawlogs/pulpwood
WGA Biofuel Plant Siting Study	Western U.S. estimate—11 million odt of forest-based biomass supply out a total supply of 130 million odt of all forest and agricultural feedstock; total biomass would make 11 billion gallons of biofuels at a demand price of $2.40 per gallon gasoline equivalent	• See drivers for BRDI Feedstock Report • Spatial distribution of biomass in relation to candidate locations for biofuels plants • Transportation networks and costs • Capital and operating costs for conversion technologies • Offered price of biofuels at wholesale fuel terminals

Potential Biological Supply from Forest-Based Biomass Resources

A general definition of forest biomass is all forest plant and forest-plant-derived materials. We limit forest biomass to parts of trees on, or derived from, forest land. This definition includes all trees on two categories of forest land—timberland and other forest land. Timberland can grow 20 cubic feet per acre per year on the main stem of trees, whereas other forest land (such as pinyon-juniper forest in the western United States) produces less. It also includes wood and bark residues generated at primary mills (sawmills, panel mills, or pulp mills) or secondary mills (e.g., flooring, furniture).

We do not discuss wood that may come from growing short-rotation woody crops (SRWCs) on agricultural land because this is covered in another chapter. Our focus is on the level of sustainable supply from forest-based sources. Factors that determine biological potential for SRWCs, economic limitations, and social limitations differ from factors for forest-based sources. Sustainable supply of wood from SRWCs is influenced by many factors, including rates of improvement in genetic stock and growth and the amount of shift of agricultural land to SRWC and associated decrease in food production that is acceptable. The total amount of wood biomass available for biochemicals and bioenergy will be the total available from SRWC and forest-based sources.

Estimates of wood biomass supply from forest-based sources often focus on amounts not currently used for lumber, panels, or paper. Specifically, unused forest biomass resources can include (1) logging residue left after conventional harvesting operations, (2) "other removals" from land clearing or pre-commercial thinning operations, (3) fuel treatment thinnings to reduce fire hazard or insect and disease damage, (4) unused mill residue from primary wood processing mills, and (5) unused mill residue from secondary processing mills. It is sometimes the convention to include several other sources as forest-based sources, including urban wood residue, construction and demolition waste, and tree trimmings, and we include them for that reason. Physical and biological availability from sources (1) to (5) is driven by different factors. Logging residue availability is driven by (co-produced with) harvest of sawlogs and pulpwood and limited by need to leave nutrients on logging sites. In a similar way sources (2), (4), and (5) are co-produced with other activities. Forest treatment thinnings are driven by forest restoration objectives and programs. Each of these estimates excludes use of biomass supply that would require diverting wood from its current uses. Diverted sources include (1) pulpwood, (2) sawlogs (at a very high cost), (3) fuelwood (used primarily for home heating), (4) currently used wood residue from forest products mills, and (5) black liquor from pulp mills. Diverted biomass sources are discussed separately.

Our first estimation example is from the USDA/DOE "Billion Ton Supply" report (*3*), which estimated sustainable biomass use to determine if U.S. land resources can produce biomass sufficient to displace 30 percent of the country's 2005 petroleum consumption, or about 1 billion dry tons of biomass per year. The report estimated potential supply of 1.3 billion dry tons of biomass by the mid-21st century and that forest biomass may provide up to 368 billion dry tons. However, for forest sources, if we exclude amounts currently used and amounts based on assumed growth of the forest products industry (e.g., more logging residue and mill residue) then additional near-term forest biomass potential is 137 million dry tons (Tables II and I). If we take into account amounts of biomass generated with increased production by the forest products industry, then biomass potential is 225 million dry tons.

An increase of forest biomass supply of 137 million dry tons, or with industry growth to 225 million dry tons, would be an increase over 2006 U.S. wood harvest (225 million dry tons) (*3*, *4*) by 60–100 percent. The biomass increase with industry growth assumes all increases in fuelwood, wood residue at mills, and black liquor would be available for new bioenergy and biochemicals. There is a good case for the sustainability of these additional biomass levels based on

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limitations built into the estimates. These include (1) current conventional harvest and projected future harvest that produce logging residue are well below forest growth, (2) it is likely that leaving behind 35 percent of logging residues would provide nutrients and habitat needed to sustain forest ecosystems and wildlife, (3) additional biomass from fuel treatments to reduce fire hazard is based on estimated possible thinning removals of wood from currently overstocked forest stands and would be removed over 30 years, after which additional growth could allow additional thinnings, and (4) currently unused mill residue is excluded from supply. Note that these estimates, by excluding diversion of currently used biomass (pulpwood, mill residue, fuelwood, pulp liquor) would also allow for sustaining a growing forest product industry to meet needs for increasing domestic consumption of wood and paper products.

Table II. Potentially available forest biomass for the United States from the "Billion Ton Supply" report (10^6 dry tons)

	Unused	*Existing use*	*Growth*	*Total*
Logging residue	**32**	—	**15**	**47**
Other removal residue	9	—	8	17
Fuel treatments (timberland)	49	—	—	49
Fuel treatments (other forest land)	11	—	—	11
Fuelwood	—	35	16	51
Wood residue (forest products)	8	46	16	70
Pulping liquor (forest products)	—	52	22	74
Urban wood residue	28	8	11	47
Total	137	141	88	366

If the constraint is removed to avoid diverting currently used mill residue, fuelwood, or pulp liquor, then some fraction of the exiting biomass use of 141 million dry tons (includes black liquor) could be diverted to new bioenergy or biochemical production.

The "Billion Ton Supply" report does not include potential biomass supply from either (1) additional pulpwood harvest or (2) diversion of current pulpwood harvest from pulp mills and composite panel mills. The amount of U.S. pulpwood harvest in 2008 was about 74 million dry tons, down from about 93 million dry tons in 1998 (*5*, *6*). Therefore, pulpwood harvest could be increased by at least the difference between the 1998 and 2008 harvest levels, or 19 million dry tons. Such increased pulpwood harvest would also generate logging residue that could be partially removed.

Using a conversion factor of 80 gallons of ethanol per dry ton of biomass or the potential sustainable ethanol production using additional biomass sources—without industry growth and without substantial diversion—wood from

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current uses could be ((137 + 19) × 80) = 12 billion gallons. These estimates of *potential* biologically sustainable supply could be increased with diversion of wood from current sources and additional pulpwood harvest. However, total *available* supply will also be limited by economic (cost) and social (e.g., regulatory) constraints.

Example Estimates of Supply Given Economic and Environmental Constraints

A number of national and regional studies have estimated forest biomass supply considering economic synergies and limitations. In addition to the physical and biological limitations identified in the "Billion Ton Supply" report, there are economic limitations on total supply that include (1) assumptions about markets or programs that will provide forest biomass, (2) costs to purchase, harvest, and chip biomass for roadside pickup, and (3) cost to transport biomass to using facilities. One determinant of the cost to harvest is the expected level of special equipment owned by harvesting companies to efficiently remove biomass, chip, and transport wood biomass. The limitations on supply to a particular user in a region will also include competition for biomass from other users—for biofuels, bioelectricity, thermal energy, and pulpwood use for pulp or panels. These economic limitations are all on the supply side—the amount of biomass that may be supplied at a given price at a plant gate. The amount of biomass a plant can consume in a particular location depends on the price it can pay—a limitation on the demand side. The amount the plant can pay will be determined by other non-feedstock costs of production and by the price of fossil fuel that could be used as an alternative to biomass. Increases in price for fossil fuels will be a key factor in determining the speed of development of bioenergy plants (*7*).

Our second and third examples of estimates of biomass supply include economic constraints. The first focuses on estimates of forest biomass or mill residue available at increasing roadside or mill gate costs. The second adds limitations on biomass supply due to competition with agricultural biomass and limitations of transportation and technology to produce biofuels in specific locations across the Western United States.

Economic Estimates of National Forest Biomass Supply for Biofuels Including Economic Constraints

An analysis commissioned by the U.S. Federal Biomass Research and Development Initiative (BRDI) (*8*) shows how assumptions about operation of wood products markets and allowable cost levels for forest-based biomass and competition with agricultural biomass supplies will result in limited amounts of biomass being available for biofuels and chemicals production.

The BRDI analysis determined the agricultural and forest-based biomass sources and cost levels required to produce 21 billion gallons per year of advanced biofuels (e.g., cellulosic ethanol or biodiesel) (*8*). The 21-billion-gallon production target for advanced biofuels in 2022 is specified by the 2007 Energy

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Independence and Security Act. The analysis assumed 1 billion gallons of the total would be biodiesel from soybeans. The remaining 20 billion gallons would be provided using a combination of agricultural feedstocks, forest-based feedstocks, and imported biofuels.

Note that the BRDI analysis assumed that all forest-based and agricultural biomass would be available for biofuels. In reality, these biomass sources could also be used for increased electric power production or increased heat energy production, so not all the amounts estimated by the BRDI report would necessarily be available solely for biofuels. If competition with electric power producers for biomass were included in the analysis, the amount of biomass available for biofuels at a given price would depend on biomass demand by electric power producers.

The first step in the BRDI evaluation was to estimate quantities of agricultural and forest-based biomass that would be provided at forest roadside or farm gate at progressively higher costs. To provide enough forest and agricultural biomass feedstock to produce 20 billion gallons, it was determined that the roadside/farm gate cost would need to be about $44 per ovendry ton (odt). At this price level, about 45 million odt of forest-based biomass would be provided that could make 4 billion gallons of ethanol. Agricultural biomass feedstocks or imports would be used to provide the other 16 billion gallons of biofuels. The study did not estimate the cost to provide biomass delivered to biofuels plants. The delivered cost would depend on local factors, including spatial distribution of the biomass, transportation infrastructure, and biofuels plant size (these factors are included in our next example).

The estimated supply of forest-based biomass of 45 million odt at $44/odt (Table I) is substantially less than the potential supply identified by the "Billion Ton Supply" report—where the estimate of current potential was 137 million odt/year and the estimate of potential with an increase in harvest of traditional products was 225 million odt/year. There are two key reasons why the BRDI estimate is much lower. First, the "Billion Ton Supply" report assumed that it may be possible to collect biomass from logging residue at conventional logging sites and, in addition, conduct thinning operations on separate forest land to reduce fire hazard and insect and disease damage. However, the BRDI analysis needed to be explicit about the markets or programs that would provide biomass for biofuels. To obtain logging residue requires integrated harvesting operations providing both sawlogs/pulpwood plus biomass. To obtain biomass from separate thinning operations requires that either they be integrated harvesting operations that provide both sawlogs/pulpwood plus biomass, or that there would be quite expensive subsidized operations that would remove only small trees and biomass suitable for biofuels or bioenergy. For the BRDI report, it was assumed that thinning operations would integrate harvesting operations where sawlogs/pulpwood are harvested along with biomass. The estimated amount of biomass provided in total by logging and thinning operations is limited by the expected demand for sawlogs and pulpwood in each region.

The second main factor limiting supply is the cost to provide forest-based biomass at roadside. Amounts of biomass from integrated forest harvesting operations have a stumpage cost (cost of biomass resting in the forest) plus cost to harvest and chip at roadside. While logging residue currently has a stumpage

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cost about $3 per odt, the cost increases toward pulpwood stumpage prices (e.g., $15–$25 per odt) as removals increase. The price would increase as available residue becomes more scarce. Harvesting and chipping costs increase as more stands are harvested that have a lower density of trees or greater haul distance to roads.

Table III indicates the effect of the integrated harvesting and cost restrictions on availability of forest-based supply sources. Logging residue and forest thinnings could provide 40 and 21 million odt/year, respectively, but after imposing a limit that (1) integrated logging to provide only as much sawlogs and pulpwood as currently demanded and (2) a roadside price of $44/odt, then supply from these sources is limited to 20 and 11 million odt, respectively. Higher prices for logging residue and thinnings bring higher supply because it allows access to biomass with higher harvest (as determined by simulation of thinnings and harvest operations) and stumpage costs. Other removal residues (from land clearing and pre-commercial thinnings) are limited to half the total potential—6 million versus 12 million odt. Urban wood residue is limited to about 10 percent of the total estimated residue generated of 28 million odt. The upper limit of supply, at any price, is judged by half the amount generated. Conventionally sourced wood (pulpwood) is estimated to contribute about 4 million odt to meet the goal to produce 20 billion gallons of biofuel, whereas the potential at higher prices is at least 15 million odt/year.

Table III. Forest biomass available at about $44 per ovendry ton and at cost over $100 per odt for the United States from the BRDI feedstock report (10^6 dry tons)

	Supply at $44/odt	*Upper limit on supply >$100/odt*
Logging residue	20	40
Other removal residue	6	12
Fuel treatments (timberland)	11	21
Fuel treatments (other forest land)	0	0
Wood residue (forest products)	1	1
Urban wood residue	3	14
Conventionally sourced wood (pulpwood)	4	15
Total	45	103

As prices increase above $44/odt, supply would increase above 45 million odt as more is supplied particularly from conventionally sourced wood and urban wood waste, which could add at least 30 million odt (Table III). With increased price, the increased supply would vary notably by source. Supply of biomass from logging residue and thinnings may not increase much with price to the extent that

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supply is limited by sawlog and pulpwood harvest levels. Supply from new or diverted pulpwood harvest can continue to increase with price as limited by owner willingness to sell and harvest costs. Supply from urban sources will increase in price as limited by wood waste amount and collection and processing costs. The amounts from logging residue and thinnings could most readily increase with increased levels of sawlog and pulpwood harvest, which would be required to get the higher levels of logging residue and thinning supply shown in Table III at prices over $100/odt. In projections of harvest made in 2005, conventional sawlog and pulpwood harvest was projected to increase by 29 percent over the 2006 level by 2030 (*9*). A revision to these projections would take into account the decrease in recent economic activity due to the recession and the impact of any increased demand for pulpwood use for energy.

The estimates prepared for the BRDI report exclude supply of forest biomass from federal lands in recognition that the Energy Independence and Security Act of 2007 excludes use from most federal land to meet biofuels production targets. However, the analysis does not apply the EISA 2007 restriction to use only forest biomass from planted forests. Such a restriction would substantially reduce supply (see discussion on social limitations below). There is currently no federal legislation promoting electric power production or thermal power production that restricts biomass supply to come from planted acres.

The estimate of 15 million dry tons for pulpwood supply from the BRDI report does not include the effect of increasing supply due to increases in forest inventory over time nor the supply of biomass from pulpwood diverted from current pulp or panel production. A study by Abt et al. (*10*) estimated that over half of 30 million dry tons of wood biomass needed to provide 10 percent of the fuel for coal electric power plants in the South would come from additional pulpwood harvest or pulpwood diverted from current supply to pulp and panel mills. In this case, half or more of biomass supply would come from pulpwood sources as opposed to logging residue sources. Compared to the BRDI study, this study for the South estimates greater proportion of supply from pulpwood sources as opposed to logging residue sources.

Example Estimates of Western Biofuels Supply Including Competition with Agricultural Sources and Limitations of Infrastructure and Technology

Our third example is from an analysis commissioned by the Western Governors Association (WGA) and shows how the use of forest-based biomass will be limited not only generally by wood product markets and allowable cost levels (as for the BRDI analysis) but also by amounts close to specific geographic locations. That is, the amount of forest-based biomass available for a specific plant will be limited by the amount of material available at a certain cost within a certain transportation radius. There will be a tradeoff between the higher cost of obtaining greater supply at greater distances and the lower capital cost of a larger capacity biofuels plant.

The WGA study determined the amount of biofuels that could be produced in the western United States using forest-based and agricultural resources for given prices of biofuels at existing fuel terminals. Given an offered price for biofuels

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at fuel terminals across the West, an optimization model was used to select the optimal location of biofuels plants from candidate locations and simultaneously select the amount of feedstocks to be used from a given local area, the conversion technology to be used, and the capacity of the plant. Optimal locations were ones that provided the highest profit level given the biofuel price offered at terminals. A key finding was that biofuels could provide between 5 and 10 percent of the projected transportation fuel demand in the region with fuel price between $2.40 and $3.00 per gasoline gallon equivalence (gge) at fuel terminals, and exclude costs to deliver fuel to local gas stations and taxes (*11*). At $2.40 per gge 11 million odt of forest biomass would provided in the West or 8.6% out of total feedstock of 130 million odt from all sources. Total biofuels production at $2.40 per gge would be 11.3 billion gallons (Table I).

Figure 1 (from the WGA report) indicates how estimated capital cost to produce a gallon (gasoline equivalent) using Fisher–Tropsch conversion declines with increasing capacity. The WGA study identified the size and technology of plants that would produce biofuels at lowest cost in given candidate locations when considering both the possible size of plant (which determines capital cost per gallon) and aggregate demand for biomass (which determines transport distance and cost per unit of biomass).

The WGA study allowed wood biomass to be converted to liquid fuel using three technologies: hydrolysis and fermentation to ethanol, gasification and Fisher–Tropsch conversion to middle distillates, and upgrading pyrolysis oil to gasoline. Efficiencies to convert wood to biofuels for these processes were assumed to be 90, 42, and 22 gallons per dry ton, respectively. Given these conversion efficiencies and associated costs of production by capacity size, only the first of these technologies was selected by the optimization model to convert wood to biofuels at biofuel prices up to $3 per gge.

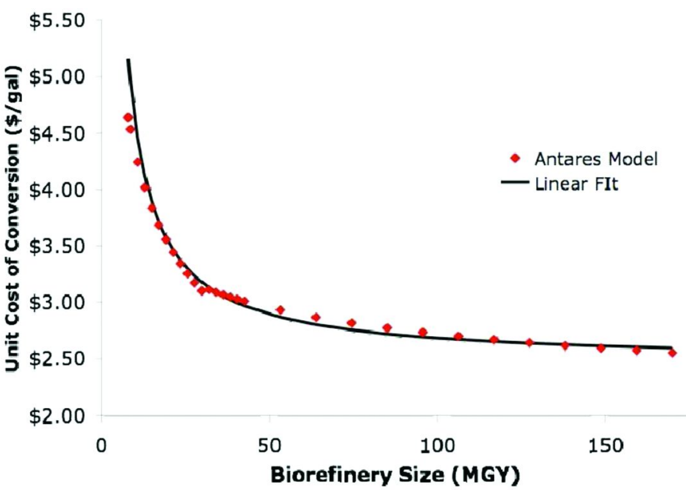

Figure 1. Capital cost per gallon (gasoline equivalent) to produce biofuel by Fisher–Tropsch conversion by biorefinery size. (reproduced with permission from reference (11)).

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For a biofuels price of \$2.40/gge, the capacity of plants converting wood to ethanol was limited to sizes from 35 to about 100 million gallons per year, depending on the local abundance of forest-based biomass. For example, plants in Northern California at Eureka, Redding, Chico, and Fort Bragg ranged in size from 55 to 98 million gallons (Figure 2). At a conversion efficiency of 90 gallons per dry ton, the annual wood consumption would range from 610,000 to 1,090,000 dry tons per year. The fact that there are four limited-scale lignocellulosic plants chosen by the optimization model also illustrates that in forest areas it may be most profitable to have several smaller scale plants that each obtain biomass from a limited distance to obtain forest biomass, rather than one or two large plants that go a longer distance to obtain biomass.

There are additional caveats to understanding the effect of local forest biomass supply on capacity size. As prices for forest biomass increase above the current price for pulpwood, then pulpwood-size material can be purchased for biofuels, and not just logging residue. When pulpwood may be purchased within an area, then the total biomass available in the area will increase. This would increase the economic viability of constructing a higher capacity biofuels plant. In addition, if prices increase above recent pulpwood prices, then it may be economical to invest in growing short-rotation woody crops within a short distance of a biofuels plant, which could also increase the viability of constructing a higher capacity biofuels plant.

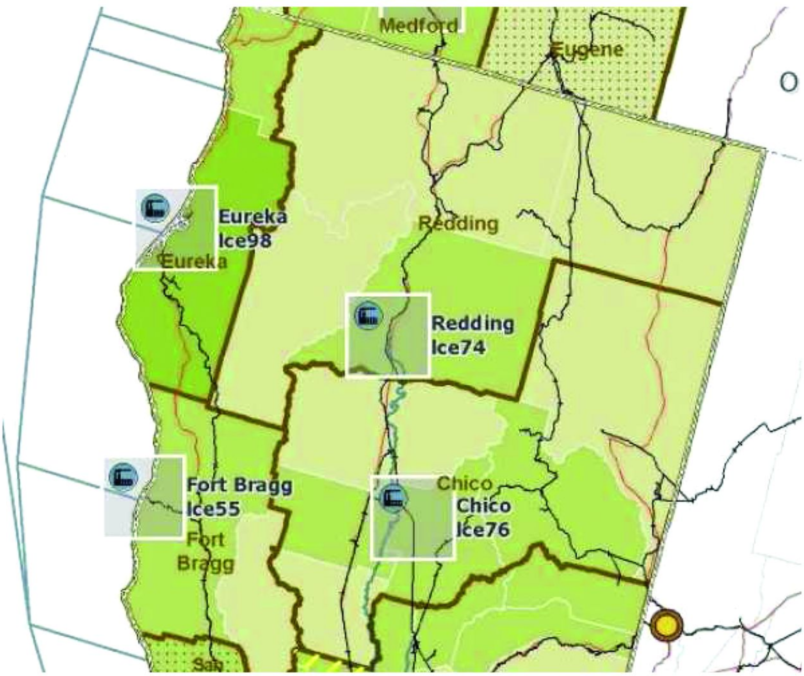

Figure 2. Potential lignocellulosic ethanol plant locations in Northern California. (reproduced with permission from reference (11)).

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Environmental Benefits and Limitations Associated with Forest Biomass Supply

Removal of biomass from forests may have positive or negative effects on site productivity and forest sustainability as determined by what (and how much) is removed and by how biomass is removed (*12*). Sustainability criteria (*13*) include protecting the resource base (*14*, *15*) and maintaining biodiversity (*16*), maintaining carbon storage, and reducing or eliminating net greenhouse gas (GHG) emissions in producing wood-based energy (*17*). Protecting the resource base requires attention to maintaining productivity and avoiding off-site impacts from pesticide or nutrient movement (*18*). Potential negative effects are very specific to management systems and the machinery used to harvest and gather material (*19*). The main environmental concerns are whether high levels of removals and more trafficking by machinery would reduce future productivity by removing too many nutrients, lowering levels of soil organic matter, compacting soil, and increasing soil erosion (*20*). The total effects on carbon balance (*21*) and energy efficiency depend not only on the production and harvesting of biomass but also on the energy it produces, which depends on the efficiency of the conversion technology and products that result as well as offsets of other fuel sources; these aspects require a full life cycle analysis that is beyond the scope of this chapter (*17*).

As noted above, the most likely scenarios for providing biomass are (1) increased residue removals integrated with harvesting timber products (*3*, *19*); (2) removals of biomass to reduce fire hazard (e.g., (*22*)); or (3) harvest on additional areas primarily to provide biomass for bioenergy (*23*). In addition, locally significant amounts of biomass may be available after major disturbances, including wildfire, insect or disease attack, and wind storms. In all cases, the limitations and methods used to remove biomass with lowest impact will be determined by the nature of the existing forest stands. The most salient features of forest stands that will guide limitations and methods are whether they are publicly or privately owned and whether they are planted versus naturally regenerated. Most forest land in the eastern United States is privately owned, and the reverse is true in the West where public ownership predominates (*4*). The main areas of planted forests are the southern pines and the Douglas-fir stands of the Pacific Northwest. The limitations and methods will also be determined by the details of the kinds of wood material that are removed.

Limitations on removals and acceptable removal methods vary in part because of differences in the major management objectives of public and private landowners. Public land tends to be managed for a wider range of resource values than private land. Private landowner objectives tend to include obtaining revenue from timber and other resources. Non-industrial private forest (NIPF) landowners have the most variation in management objectives. Some surveys of NIPF landowners suggest interest in non-timber values can be high and may limit interest in removal of wood for revenue (*24*).

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What Material Is Removed

Logging residue is a broad category that includes cut material from conventional harvesting that is not removed (tops, limbs, some green but rotten wood boles) and standing dead and green material that is not harvested because it is unusable (standing dead and rough or rotten stems of merchantable diameter; non-desirable species; and small-diameter stems of commercial species). For planted stands, residues tend to be tops and limbs. For naturally regenerated forests, it is also possible to remove a portion of the non-desirable stems (non-commercial species) and a portion of small-diameter stems of desirable species. The number of small-diameter trees of desirable species that are left standing may have significant effects on the successful regeneration of the stand. Regrowth of the forest with desirable species will be faster if some small trees of desirable species are left standing after harvest. Leaving behind non-desirable trees may hinder successful regeneration of desirable species by competitive exclusion. Currently pulpwood and sawlog harvest from federal forest land is low, so almost all logging residue from integrated harvesting will come from non-federal lands, probably private lands (*3*). Harvest of additional forest areas primarily for biomass will likely be similar to current pre-commercial thinnings or may be similar to current practices to harvest pulpwood with additional removal of some residue.

Biomass from forest treatments to reduce fire hazard is primarily unmerchantable trees and shrubs that have accumulated as a result of altered fire regimes (*25*, *26*). The alteration in fire regimes (frequency of fire) is primarily due to many years of fire suppression. Although there are tens of millions of acres in need of treatments to reduce fire hazard and restore natural fire regimes, available treatment methods are costly and sometimes resisted by the public. Although fuels reduction treatments that provide biomass for bioenergy could overcome some of the financial constraints, the dispersed nature of the biomass imposes significant transportation costs. Financial and logistical concerns place limitation on the number of acres that can be treated per year. The "Billion Ton Supply" report (*3*) assumed that the backlog of needed treatments would occur over 30 years. As a result of assumptions such as no road construction and other operating, the amount of biomass for fire hazard reduction thinnings included in that report as available for bioenergy uses is less than 1 percent of the material that has been identified for fuel treatment removal. The National Forests are projected to furnish about 20 percent of the hazardous fuel removals available for bioenergy from timberlands and from other forest land. Most (73 percent) of the hazardous fuel biomass removals from timberlands and 58 percent of the removals from other forest land will come from privately owned forests. Other publicly owned land makes up the remainder.

Biomass may also come from salvage operations after major disturbances . Wildfire, hurricanes and other wind events, and insect and disease outbreaks, such as bark beetles or exotic organisms, can affect large areas; these disturbances effectively represent unplanned harvests. Salvage logging is conducted to recoup financial value, limit spread of infestation, reduce wildfire risk, or allow for reforestation. While salvage logging is contentious (*27*), such events could

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provide locally significant biomass supply. Additionally, major wind events such as Category 3 and higher hurricanes cause blowdown and breakage that blocks roads, highways, and commercial sites, and the removed material is usually piled and burned or placed in landfills but could be available to produce bioenergy.

How Forest Biomass Is Removed

Methods to remove biomass can be adapted to help obtain the most biomass, meet environmental impact limitations, and lower costs. Conventional harvesting methods are numerous and depend on forest type, regeneration method, sizes of materials to be removed, site conditions such as slope, drainage, trafficability, and costs of operation. In general, direct effects of harvesting are minimized by matching machinery to the site, including use of low ground pressure tires or tracks and minimizing machinery movement on the site. Protecting water resources by delineating buffers around streams and controlling water movement and other site-specific protection practices also minimize direct harvesting impacts. Some form of voluntary Best Management Practices or Forest Practices regulations (discussed below) have been adopted in all states to protect water and other resources, and many address these issues (*28*). Integrating biomass removals with conventional harvesting may use standard harvesting equipment (for example, small-diameter stems or unmerchantable stems may be felled and transported with merchantable stems to a landing or roadside where they are separated and transported).

Unconventional biomass removal methods are being developed to minimize handling and transportation costs of tops, branches, and limbs (*29*). One method gathers, compresses, and bundles this material into a form resembling a standard log, which can then be transported by conventional methods. Besides bundling machinery, in-woods chippers and masticators are available for fuel reduction treatments, particularly in the wildland–urban interface (*30*). In Southern Pine plantations, adding a small chipper to conventional harvesting appears to work better on clearcut sites than in partial harvests (*31*). Specialized machines have been developed in Scandinavia to remove greater forest biomass by lifting stumps and root systems from the soil (*32*). While not currently in general use, they have the potential to increase biomass removal by 25 percent or more of the aboveground removal. If biomass removals are conducted as separate operations and not integrated with conventional harvests, such as mechanical fire hazard reduction treatments, they represent an additional entry into a stand and may be contaminated with more soil and rock and have more or different impact than integrated operations. Additionally, biomass produced may be contaminated with more soil and rock than is typical of conventional harvests.

Effects of Biomass Removals

Potential negative effects of biomass removals require limitations and are primarily a function of how much and what is removed (nutrients, deadwood) and ground disturbance (soil compaction, erosion, and impacts on regeneration and ground layer diversity). Biomass removals may also have positive effects on forest health and assist to restore degraded ecosystems. Potential negative effects

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ACS Symposium Series; American Chemical Society: Washington, DC, 2011.

are very specific to management systems and the machinery used to harvest and gather material. The main environmental concerns relate to impacts on soil's physical and chemical properties, particularly maintenance of fertility. Fertility reduction is a concern because nutrient concentrations are higher in leaves, twigs, and small branches than in bolewood, and there is an argument that over time more nutrients would be removed with entire removal of tops and branches than could be replenished from natural sources. Similar concerns about removals from planted forests have been addressed by research, particularly for intensively managed pine plantations. Generally, we know how to avoid significant impacts, and nutrients are routinely added to raise productivity in plantation systems. In a nationwide study of long-term (10-year) soil productivity impacts of carbon removals conducted on 26 sites, even complete removal of all aboveground organic matter, including the forest floor, had no consistent effects, with the single exception of a reduction in the 10-year growth of aspen stands as compared to bole-only removal (*33*). Effects of removals on soil carbon sequestration are less clear. A review and meta-analysis of harvesting studies found that harvesting generally had little or no effect on soil carbon, although whole-tree harvesting caused a slight decrease (*34*). Fertilization and invasion by native N-fixers significantly increased soil carbon. It seems reasonable that more complete biomass removals could have a greater negative effect on the soil carbon pool, but this would likely vary by levels of removals, types of equipment used, as well as soil, site, and stand characteristics. Thus, further research is needed to identify the forest type and soil combinations where potential deficiencies may exist that could be triggered by biomass harvesting at certain levels of intensity and frequency of removal.

Deadwood serves important ecological functions in forest ecosystems (*35*). The amount of deadwood is affected by harvesting. Deadwood serves as habitat for a variety of organisms, including fungi, mosses, liverworts, vertebrates, and invertebrates, as well as regenerating plants. Deadwood alters site water balance and water quality, both through storage and release of water and by reducing runoff and erosion. Deadwood may also support biological nitrogen fixation, and it contains nutrients that are cycled back into the soil. Because of the important roles played by deadwood, some level of deadwood should be retained to protect these functions (*20*). The roles played by deadwood differ substantially among forest types and regeneration systems, making it unlikely that a universal standard for leaving deadwood on-site would serve all combinations. Nevertheless, recommendations seem to be settling on 30–35 percent retention (*20*) without regard for potential fire hazard.

There is also concern that biomass removals can reduce biological diversity. In planted forests this could result from more complete biomass removals or from greater ground disturbance. Retaining standing dead and downed stems can provide habitat for diverse ground-level flora and fauna (*36*, *37*). More complete removals in naturally regenerated forests could remove non-commercial yet ecologically valuable tree and shrub species; this concern can be addressed locally by appropriate retention guidelines. Also addressed in guidelines (see below) is the rule to avoid removals entirely from areas of high conservation value, such as old forests, wetlands, and rare habitats (*20*).

Benefits from Biomass Removals

Fire hazard can be reduced and the vigor of remaining trees can be increased by biomass removals from overstocked stands resulting from fire suppression (*22*), cessation of grazing, or abandoned management. The financial value of forests can be increased by providing markets for thinnings (*38*), especially by removing small-diameter and non-merchantable stems and by improving growth on otherwise suppressed stems, particularly in naturally regenerated eastern hardwoods. Removals can also aid in forest restoration efforts where there are goals to alter stand composition or structure. Biomass harvest can provide revenue that can offset restoration costs (*39*) but may be more costly than other methods (e.g., pile and burn treatments to reduce hazardous fuels). Revenue for biomass can also help fund restoration following wildfire, insect or disease outbreaks (*40*), or weather-related disturbances such as ice or windstorms (*41*).

Social (Institutional) Support and Limitations on Forest Biomass Supply

Policies and Regulations Influencing Renewable Energy Production [Some text adapted with permission from the 2009 and 2010 ECE/FAO Forest Products Market Review (*61*, *62*).]

A key factor that will be a driver in markets for wood feedstock for energy is the definition of "biomass" in legislation, which determines what materials can obtain an incentive for energy use. As a result, depending on the legislation, wood from different kinds of stands and different forest ownerships will or will not qualify for incentives to produce wood-based liquid fuels, heat, or power. The definition varies between the 2007 Energy Independence and Security Act (EISA 2007) (*42*); the Food, Conservation, and Energy Act of 2008 (PL 110-234, Farm Bill) (*43*); and numerous pieces of draft legislation currently being debated.

EISA 2007, which promotes biofuels production and sets a target for the United States to produce 21 billion gallons of advanced biofuels by 2022, allows wood biomass feedstock only from non-federal land—with the exception of material adjacent to buildings or public places. Allowable wood from non-federal land includes previously established actively managed tree plantations and slash or pre-commercial thinnings.

The Farm Bill, which supports biomass supply for energy and investments in biomass energy production, allows use of wood from federal lands taken to reduce fire hazard or improve forest health and any wood from non-federal land available on a renewable basis.

The 2008 Farm Bill and 2007 EISA have different nationwide restrictions on biomass that can be used. An analysis by the USDA Forest Service (*44*) for the U.S. South, for example, indicates that the biomass definition in the 2008 Farm Bill would allow forest biomass to be supplied from 189.7 million acres of forest land. The 2007 EISA would allow biomass from planted forest area, or 44.4 million acres. The 2007 EISA excludes biomass from 17.3 million acres of federal land and 145 million acres of non-planted forest land. The sources allowed by a prospective federal renewable electricity standard have not yet been determined. Discussion is ongoing on how to reconcile these and other definitions of forest biomass that could qualify for various federal incentive programs.

State-level policies also promote or limit forest biomass use for bioenergy. Common policy instruments used by state governments that influence wood biomass use for energy include (1) rules and regulations including renewable portfolio standards, (2) financial incentives, and (3) programs supporting research, outreach, and education (*45*). In addition, states have policies to support sustainable use of wood biomass, including (1) definitions of biomass that can be used for energy to meet regulatory targets or qualify for subsidies, (2) establishment of mandatory or voluntary best forest management practices for supplying wood biomass, and (3) requirement for a professional forest management plan before biomass can be removed and used to meet regulatory targets or qualify for subsidy.

Financial incentives are the most common policy instrument and used by at least 40 states, most commonly to support feedstock demand or supply or to lower cost of capital investments. Almost all are designed to support a range of renewable energy sources including wood or agricultural biomass, wind energy, or solar energy and do not focus exclusively on wood. For example, Georgia exempts agricultural and wood biomass from the state's sales and use taxes (*46*).

Rules and regulations are the second most common type of instrument. Thirty-six states and the District of Columbia have Renewable Portfolio Standards (RPS) or Renewable Fuels Standards (RFS) (*47*) that set targets for the percentage of energy generated (or publicly purchased) in the state that must come from renewable sources by certain dates. These targets are most commonly for percentage of electric power (RPS) from renewables but sometimes represent the percentage of transportation fuels (RFS) from renewables. In most cases they are fixed percentages for given years. In some cases targets are flexible. In 2010, governors of 25 states have endorsed the vision of the 25 by '25 organization to provide 25 percent of electric power from renewables by 2025, although individual state legislation varies. For example, Missouri requires 2 percent for 2011–2013, 5 percent for 2014–2017, 10 percent for 2018–2020, and 15 percent for 2021 and thereafter (*48*).

Public service programs including education, research, and outreach are provided by 18 states, are least common, and are not specifically directed to support wood bioenergy. Support is given to develop a range of technologies and for programs to provide technical assistance to a range of businesses.

State policies supporting sustainability of wood biomass supply include biomass definitions that are intended in part to limit competition for wood inputs with the forest products industry and to support use of underutilized material. A minority of states have developed wood biomass harvesting best management practices, including Maine, Michigan, Minnesota, Missouri, and Wisconsin. For example, guidelines for Wisconsin are to retain tops and limbs (with <4-in. diameter) from 10 percent of trees in the harvest area and to not remove the forest litter layer, stumps, or roots (*49*).

In Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass; Zhu, J., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2011.

Regulations on Forest Practices

Amounts of biomass supply will be influenced by forest practice regulations that are specified by most state governments. These regulations currently focus on harvesting for conventional products and often derive their legal standing from federal water quality legislation (*50*, *51*), although some states have gone further in prescribing practices (*52*). According to Shepard (*28*), 12 states have regulatory procedures with mandatory Best Management Practices (BMPs) or require permits for timber harvest, and most others have voluntary BMPs and enforcement against polluters. The states with the most prescriptive regulations are California, Oregon, and Washington (*53*). With high rates of compliance to voluntary BMPs (*54*), this system is sufficient for conventional forest practices (*28*). States vary in their emphasis on what to protect in BMP guidelines, partially a reflection of diverse forest ecosystems, land ownership, and levels of timber harvesting. In the eastern United States, for example, northeastern states emphasize the influence of harvesting on nutrient depletion and stormflow; BMPs in mountainous states (Appalachians and Ouachita) focus more on stormflow, erosion, and sedimentation; in the low relief Lake States and Coastal Plain, maintaining site productivity is of greater concern (*51*).

The most common restrictions on harvesting within BMPs relate to water quality protection and focus on defining buffers around water bodies and limiting activity within the buffer zone. Most attention has been directed toward perennial streams and rivers, wetlands, and lakes with less attention to headwaters and ephemeral streams (*55*).

Several states have developed additional guidelines for biomass harvesting in existing forest stands; Maine, Minnesota, Missouri, Pennsylvania, and Wisconsin have published at least draft versions. The primary concern addressed in these guidelines is the potential effect of removing greater amounts of biomass than would be removed in conventional harvest, and the common remedy is to specify what and how much material should be left on-site. Because the state forest lands in Pennsylvania are certified by the Forest Stewardship Council (FSC), their guidelines reference the FSC Appalachia Regional Standard but with greater specificity.

Evans and Perschel (*56*) reviewed the various state biomass removal guidelines and concluded that they all addressed issues of dead wood, wildlife and biodiversity, and water quality and riparian zones. Generally, these guidelines called for retention of 15–30 percent of slash on-site, with various amounts of snags and cavity trees retained. All called for avoiding sensitive areas (e.g., shallow soils, unique habitats, areas of conservation value). Water quality and riparian zones were assumed to be protected by existing BMP guidance for conventional harvesting, although several states reiterated the guidance for biomass harvests. Where differences arose they related to local or regional concerns for silviculture (for example, regeneration was mentioned by Minnesota, Pennsylvania, and Wisconsin) and disturbances; several states proscribed biomass removals where dispersal of harmful insects or diseases was a concern. Maintaining soil fertility and site productivity was addressed specifically in the guidelines from Maine and Wisconsin; in the first case, reference is made to soil

In Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass; Zhu, J., et al.; ACS Symposium Series; American Chemical Society: Washington, DC, 2011.

drainage classes, and in the second case, 17 specific nutrient-poor soils where removals are to be avoided. Maine, Minnesota, Pennsylvania, and Wisconsin guidelines all protect the forest floor and root systems from removal.

Thus, most biomass BMPs focus on restricting the amount of biomass that can be removed from the site. Three states (Minnesota, Missouri, Pennsylvania) place restrictions on re-entry to the site for biomass removal following conventional harvest, thereby favoring integrated operations. As biomass harvesting becomes more commonplace and more biomass-fueled power plants are proposed, it is likely that more states will adopt biomass harvesting guidelines, although more than likely, guidance will be along the lines already promulgated by these five eastern states. The effect of these BMPs on biomass supply is difficult to estimate because of the wide variability in stand conditions (biomass potentially available), harvesting methods, and differences among the state BMPs. We expect that restrictions on re-entry and retention requirements for snags and deadwood will have the most effect on biomass supply. The amount of slash removed will probably be more sensitive to costs of handling and transport than BMP restrictions. These assumptions should be tested to refine future estimates of biomass supply.

In addition to the influence of state BMPs on biomass removals, there will be the influence of the major voluntary forest certification systems in limiting biomass removals. Certification under the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI) both require monitoring and avoidance of loss of soil nutrients among other factors that will limit biomass removals from forest land (*57*, *58*). In North America, SFI and FSC have certified 181 and 109 million acres, respectively (*59*). SFI also recognizes an additional 202 million acres certified by the Canadian Standards Association (CSA) and American Tree Farm System (ATFS). The idea of certifying well-managed private forests in the United States began with creation of the American Tree Farm System in 1941 based on a set of forest management principles and inspections each 5 years. In 1993, FSC was created to prevent deforestation globally, with an initial focus on tropical deforestation. SFI was created by the U.S.-based American Forest and Paper Association—an industry trade group—to respond to the FSC and address public concerns about sustainability (*60*). SFI has since become an independent non-profit organization with third-party auditing, as has FSC. Forest landowners benefit from certification by obtaining market access and market share, depending on the credibility of the system's environmental claims. Because these certification systems call for monitoring of soil effects of wood biomass removal of all types, they will inevitably play a role in limiting such removals as demand for wood biomass from forest land increases.

Summary

For biomass supply from forests to be sustainable, it needs to contribute to the broader sustainable development of forestry. Sustaining forestry includes maintenance of environmental services such as water, biodiversity, and carbon storage as well as timber products, forest-based community development,

In Sustainable Production of Fuels, Chemicals, and Fibers from Forest Biomass; Zhu, J., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2011.

forest-based recreation, and forest non-timber products. Biomass supply can contribute, depending on forest area and conditions, in several ways. These include reducing fire hazard and insect and disease attack, aiding in restoration of forest composition and structure, enhancing forest growth, providing revenue to support treatments, providing revenue to support communities, and offsetting net greenhouse gas emissions. But there are biological, economic, and social limitations on amounts of supply. Biological limitations on amounts and kinds of biomass that can be removed vary by forest type and condition, by ownership (public, private), and by how stands are regenerated (planted, natural). Biological limitations are needed to maintain water supply, soil nutrients, and biodiversity. There are economic limitations that depend on the forest type, condition, and biomass to be removed, and removals may be more or less costly or could exceed expected revenues. Improvement and adaptation of harvesting technology can help address both biological and economic limitations. Estimates of U.S. total forest-based biomass supply given current understanding of biological and economic limitations suggest supply of about 45 million dry tons per year or more at $44/dry ton at forest roadside or mill gate. This estimate assumes there are no restrictions on forest sources of biomass that can be used. With increased price, the supply increase would vary by source. The increase from logging residue and thinnings would be limited by harvest for sawlogs and pulpwood as well as harvest costs, whereas the increase from pulpwood would be limited by owner stumpage price, harvest costs, and demand of pulpwood for pulp and panels. Social (institutional) targets and limitations in the form of federal and state legislation will support or limit wood biomass supply. These actions include a federal renewable cellulosic fuel target that includes biomass source restrictions, state-level renewable energy portfolio standards that may support biomass use for electric power production, and state-level forest practice guidelines that influence the kinds and amounts of biomass that can be removed from particular forest types and conditions. Understanding of biological and economic limitations and benefits is still developing, particularly at regional and local levels. Social targets and limitations could also change. A factor that could help accelerate development of understanding or change in social targets and limitations would be substantial increase in prices for fossil fuels that could be replaced by wood bioenergy or biofuels.

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