Biomass Energy from Crop and Forest Residues

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Summary. Residues remaining after the harvest of crop and forestry products are being proposed as a substantial energy source for the nation. An estimated 22 percent of the residues might be utilized, providing a renewable source of high-grade energy with the potential of supplying 1 percent of the current U.S. gasoline consumption as ethanol or 4 percent of the total electrical energy used. These net energy benefits are limited by high energy costs to collect, transport, and process the residues. Environmental threats include soil erosion, water runoff, and nutrient loss.

Development of alternative energy sources is of major importance in the United States as high consumption continues to deplete fossil energy resources. Conversion of plant biomass offers potential as one such energy source (*1, 2*). Of the plant biomass produced yearly in the United States through photosynthesis, approximately one-third is harvested as agricultural and forest products (*3*). Residues remaining after harvest amount to 17 percent of the total annual biomass production and may be one of the most abundant resources available for conversion into energy (*4*). These residues (*5*) amount to an estimated 540 million metric tons (Mt) in the field (dry) and have a gross heat energy equivalent of about 12 percent of the fuel consumed annually in the United States.

There is a need to assess the direct and indirect costs and benefits of using crop and forestry remains for conversion into energy, since they are valuable when left on the soil because they maintain a productive agriculture and forestry and a quality environment. In this article we analyze these costs and benefits and discuss several soil conservation technologies that could be used to maintain the productivity of agriculture and forestry if plant residues are systematically harvested.

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Biomass Energy Analysis of Crop and Forest Residues

The sources of crop and forest residues are varied, and there are differences between crops and forest types in the amount of biomass remaining after harvest. A total of about 430 Mt of crop residues remains on agricultural land after harvest and about 110 Mt remains after trees are harvested for lumber and pulpwood (Table 1) (*6*). Not all crop and forest residues are readily available, and the energy and environmental costs of collecting and using some of them are significant.

Collection, transport, and processing. The density of crop and forest residues per square meter is low (Table 1); hence a significant energy input is necessary to collect and transport them. With crop residues, one harvesting strategy would be to collect and stack the corn stover, wheat straw, or other crop residue in the field. The total energy required to collect 1 ton of corn residues is calculated to be 43,100 kilocalories (*6*). Collecting wheat straw, which is less dense than corn stover, requires an estimated 50,500 kcal/ton (*6*).

Collection of forest residues requires larger equipment than collection of crop residues, and greater quantities are harvested per hectare. Employing a chipping technology requires an energy input of 135,000 kcal/ton (*6, 7*). Energy costs for round-trip transportation of forest and crop residues by truck are 1310 kcal/ton per kilometer (*8*).

After collection and transport to a central processing plant, residues can be converted into high-quality forms of energy by several different methods. The three technologies included in this assessment are ethanol production, electricity generation, and methane gas production.

A dry ton of biomass (4.7×10^6 kcal) can be converted into about 227 liters of ethanol, which has an energy value of 1.1×10^6 kcal (*6*). The heat energy inputs for fermentation and distillation are assumed to be supplied by burning the lignin and other residues remaining after processing, so that a net efficiency of 12 percent is possible (*9*).

Another method of converting biomass into high-quality energy is through burning to produce electrical power. Conversion to electrical power has several advantages: (i) electricity is high-quality energy; (ii) electric power plants can be located near the source of the combustible materials; (iii) electrical energy can be more easily transported to the consumer than raw biomass energy; and (iv) crop and forest residues burn cleanly compared with coal.

The conversion of biomass into electrical energy has an efficiency of 25 percent (*6*). This might be improved by using hot combustion gases to partially dry the incoming feedstock. A 100-megawatt power plant produces about 457×10^6 kilowatt-hours annually (*10*) and will supply electrical energy to a town of about 50,000 people (*11*). A total of 1.57×10^{12} kcal, or 135,000 ha of corn residues (50 percent moisture on a dry weight basis), would be required to fuel this electric plant (assuming no energy inputs for residue collection and transport, fertilizer replacement, and land degradation caused by the removal of corn residues) (*6*).

Crop and forest residues that are ground and mixed with water (80 percent) can produce methane, a clean-burning gas that can be stored under pressure (with added energy input). From 1 ton of dry biomass, about 785,000 kcal of methane can be produced. The processing energy input is 558,300 kcal. Based on the input of 1 ton of biomass (4.7×10^6 kcal) plus the

Table 1. Potential energy from crop and forest residues.

Source	Hectares harvested ($\times 10^6$)	Crop yield[a] (ton/ha)	Residues (ton/ha)	Total yield (tons $\times$ 10^6)	Amount readily usable[b] (tons $\times$ 10^6)	Potential net heat energy[c] (kcal $\times$ 10^9)	Potential net electrical energy[d] (kcal $\times$ 10^9)	Potential net ethanol energy[d] (kcal $\times$ 10^9)
Barley	3.8	2.4	3.5	13.3	3.6	6,940	2,652	758
Corn	28.3	5.6	5.6	158.5	39.6	71,874	19,800	9,308
Cotton	5.4	0.6	0.5	2.7	0	0	0	0
Oats	5.4	2.0	4.0	21.6	6.5	12,513	4,789	1,368
Rice	0.9	4.9	7.4	6.7	5.2	10,010	3,832	1,095
Rye	0.3	1.5	2.3	0.7	0	0	0	0
Sorghum	5.7	3.5	1.2	7.4	0	0	0	0
Soybeans	23.4	2.0	3.0	70.2	0	0	0	0
Wheat, winter	19.6	2.1	3.5	68.6	18.6	35,805	13,705	3,916
Wheat, spring	7.2	1.8	2.3	16.6	0	0	0	0
Other	56.0		1.1	62.0	0	0	0	0
Total crops	156.0[e]			428.3[f]	73.5	137,132	44,778	16,445
Total forest[g]	4.5		24.7[f]	111.2[h]	44.0	71,032	20,307	8,372
Grand total				539.5	117.5	208,164	65,085	24,817

[a]Yield data are from (*51*). [b]It is assumed that 40 percent of the land area in row crops is on a slope from 0 to 2 percent and that 50 percent of the land area in other crops is on a slope from 0 to 5 percent (*52*). An estimated 2000 kg of corn stover and 1600 kg of straw are left in the field to protect the soil from erosion and to maintain soil organic matter. [c]Heat recovered from combustion of the biomass is calculated at 55 percent (*54*). [d]Conservation tillage was assumed on all land and the ethanol or electrical energy yield from conversion of residues of all small grain crops was assumed to be similar to the yield from conversion of wheat residues (*6*). [e]Datum is from (*51*). [f]Calculated by multiplying yield data by dry weight ratio of residue to yields (*26*). [g]Data are from (*55*). [h]Datum is from (*53*).

processing energy, the net energy return is about 5 percent (*6*). Various crop residues produce similar yields (*12*).

Energy inputs to offset the environmental consequences of biomass removal. Removal of crop residues increases soil erosion rates and changes the quality and productivity of the land. The energy inputs needed to offset the productivity loss due to crop residue removal provide one measure of some of the environmental costs of residue removal.

It is difficult to make general statements about the effects of increased soil erosion on crop production because they depend on crop type, soil nutrients, soil structure, topsoil depth, drainage, temperature, and moisture. The evidence suggests, however, that corn yields are reduced by an average of about 4 percent (220 kilograms per hectare) for each 2.5 centimeters of topsoil lost from a base of 30 cm or less (*13, 14*). Wheat yields may be reduced about 5 percent (108 kg/ha) for each 2.5 cm of topsoil lost (*14*). This reduced productivity can be partially offset by agricultural inputs requiring fossil energy. The energy inputs needed to produce 1 kg of corn and 1 kg of wheat are 1210 and 1370 kcal, respectively (*15*). Although for some production inputs, such as fertilizers and pesticides, there are diminishing returns, we will assume a linear relation at normal yields and a value of 1000 kcal to offset a reduction in yield of 1 kg of corn or wheat per hectare.

Similarly, changes in soil structure can be measured in terms of energy inputs required to offset soil degradation. Reducing soil carbon content from 2.15 to 1.0 percent (3.8 to 1.8 percent organic matter) is reported to reduce the calculated yield of corn about 25 percent (*16*). Such reduction in soil tilth increases the power and energy required to till the soil. For example, reducing soil organic matter from 1.05 to only 0.13 percent increases the energy input for deep plowing under moist conditions more than twofold (*17*).

Crop and forest residues contain nutrients that must be replaced if removed from the land. For example, corn and forest residues contain about 1 percent nitrogen (*18*), and each ton of topsoil that is eroded contains about 5 kg of nitrogen and 1 kg of phosphorus (*19*). Note that no energy inputs for establishing and maintaining the agricultural and forest crops are charged against the use of biomass residues, because these are an assumed cost of producing the crops.

Alternative crop management systems to offset environmental degradation. Various methods of tillage can be used to reduce or prevent soil erosion and water runoff. Although these cultural practices require an energy investment, in general they return that investment several times over (*20*). These conservation tillage practices include contour planting, crop rotation, planting cover crops, and no-tillage culture.

Planting a cover crop of rye and vetch after harvest, for example, reduces soil erosion (*21, 22*). Growing rye and vetch between corn crops reduced soil loss by 43 percent (*23*). This combination of cover crops provided about 8 tons of vegetation by early spring (*22*). The rye is particularly good in this mix because it provides a persistent mulch that does not decay as rapidly as vetch. The vetch in the cover crop combination provided an equivalent of 112 kg of nitrogen per hectare (*22*). Winter cover crops offer no soil erosion advantage over heavy residues of chopped stalks or straw but are essential if the crop residues are removed (*24*).

No-tillage culture refers to planting directly in crop residues, including chopped stalks, small grain residue, chemically killed winter cover crops, and meadowland (*24*). Corn residues left on the surface of the land in no-tillage culture generally reduce soil erosion to about one-third that in conventionally tillaged corn grown continuously on a 4- to 5-degree slope (*25*); combining no-tillage culture with a corn-corn-oats-hay rotation would reduce soil erosion to about one-ninth that in conventional tillage (*25*). No-tillage planting in sod killed with a herbicide reduces soil loss to 1/20th that of conventionally plowed sod (*24*). This technology also has some associated environmental problems (*6*).

Net energy benefits of converting crop residues. Here we evaluate the use of corn, wheat, soybean, and cotton residues for conversion to electricity, ethanol, and methane.

The slope of cropland restricts the use of crop residues for energy production (*26*). While the slopes of the most productive cropland generally range from 0 to 12 percent, on a silt loam a 1 percent slope is the maximum at which erosion

Table 2. Net energy benefits from 1 ha after 30 years of harvesting corn residues for energy conversion (annual rainfall, 90 cm).

Management system	Residues harvested (tons)	Potential energy (kcal × 10^6)	Land slope (percent)	Annual soil loss (ton/ha)	Added annual soil loss (ton/ha)	Collection energy (kcal × 10^3)	Transport energy (kcal × 10^3)	Energy to offset 30-year soil loss (kcal × 10^3)	Energy to offset added annual soil loss (kcal × 10^3)	Energy to replace nutrients in residue (kcal × 10^3)	Cover crop energy (kcal × 10^3)	Electrical energy (kcal × 10^6)	Biogas energy (kcal × 10^6)	Ethanol energy (kcal × 10^6)	Net energy (kcal × 10^6)
Conventional tillage	3.5[a]	11.6[b]	6 to 12	45[c]	9[d]	151[e]	183[f]	1,100[g]	689[h]	588[i]		2.9[j]			0.2
Conventional tillage	3.5[a]		6 to 12	45[c]	9[d]	151[e]	11[k]	1,100[g]	689[h]	258[l]			0.8[j]		−1.4
Conventional tillage	3.5[a]		6 to 12	45[c]	9[d]	151[e]	183[f]	1,100[g]	689[h]	588[i]				1.9[j]	−0.8
Conservation tillage[m]	3.8[n]	12.5[b]	0 to 2	4[c]	2[d]	156[e]	199[f]	100[o]	153[h]	639[i]		3.1[j]			1.9
Conservation tillage[m]	3.8[n]		0 to 2	4[c]	2[d]	156[e]	11[k]	100[o]	153[h]	259[l]			0.9[j]		0.2
Conservation tillage[m]	3.8[n]		0 to 2	4[c]	2[d]	156[e]	199[f]	100[o]	153[h]	639[i]				2.1[j]	0.9
No tillage, contour, cover crop[p]	5.5	18.2[b]	3 to 5	4[c]	0[d]	184[e]	288[f]	100[o]	0[h]	924[i]	240[q]	4.6[j]			2.8
No tillage, contour, cover crop[p]	5.5		3 to 5	4[c]	0[d]	184[e]	288[f]	100[o]	0[h]	924[i]	240[q]			3.1[j]	2.8

[a]Corn stover yield per hectare was assumed to be 5500 kg; 2000 kg was left on the land to maintain soil carbon. [b]The corn stover was assumed to contain 50 percent moisture (dry weight) (*30*) and had an energy value of 3300 kcal/kg (*56*). [c]Estimated from (*26*). [d]Removing some of the stover was calculated to increase soil erosion by 20 percent for conventional tillage (*25*), 50 percent for conservation tillage (*57*), and 0 percent for no-tillage with adequate cover crop (*24*). [e]See text for an explanation for 151,000 kcal; the 156,000 kcal is based on an added 0.3 ton of stover collected in conservation tillage and the 184,000 kcal is based on an added 2.0 tons of stover collected in the no-tillage, contour, and cover crop systems. [f]Transported an average distance of 40 km at 1310 kcal/ton-km. This includes the return trip (*8*). [g]A soil loss of 12 cm over 30 years (54 ton/ha × 30 years) would, by the end of the period, reduce annual corn yield by an estimated 1056 kg. Assuming an energy input of 1000 kcal to maintain corn yield at the original level, a total input of 1.1 million kcal is required to offset soil degradation over 30 years. [h]About 5 kg of N and 1 kg of P are removed per ton of added annual soil loss (*19*). [i]The nutrient content of corn residue was assumed to be as follows: N, 1.0 percent; P, 0.1 percent; K, 0.9 percent; and Ca, 0.6 percent (*18*) (N = 14,700 kcal/kg; P = 3000 kcal/kg; K = 1800 kcal/kg; and Ca = 315 kcal/kg) (*58*). [j]See (*6*) for details on biomass conversion into electricity, methane, and ethanol. [k]Transported an average distance of 2.5 km at 1310 kcal/ton (dry)-km. This includes the return trip (*8*). [l]The calculated fertilizer value of biogas residue for 3.5 ton/ha is 588,000 kcal. For conversion to biogas, crop residue must be chopped and water added to bring the proportion to 80 percent water. The energy cost for hauling and applying the biogas residue to the land within 2.5 km is about 20,000 kcal/ton (*59*). Thus, the total required input would be about 350,000 kcal (3.5 ton/ha). [m]A total of 1700 kg of corn residues is left on the surface of the land. Tillage is carried out with a chisel plow. [n]About 1700 kg of crop residues was left on the soil to maintain soil carbon and protect the land from erosion (*26*). [o]A soil loss of 1.1 cm over 30 years (5 ton/ha × 30 years) would, by the end of the period, reduce annual corn yield by 97 kg. Assuming an energy input of 1000 kcal to maintain corn yield at the original level, a total input of 100,000 kcal is required to offset soil degradation over 30 years. [p]Total corn residues of 5500 kg/ha were harvested at the same time that the grain was harvested. The corn field was seeded with annual ryegrass during late August. The rye growing during the fall and spring months produced at least 4500 kg of biomass (*22*). No-tillage culture was employed and corn was planted on the contour. [q]A total of 20 kg of annual rye seed was planted (*60*) (20 kg × 12,000 kcal/kg = 240,000 kcal). Seeding was done after harvest.

can be controlled (*27*) with conventional tillage and no remaining residues (*19*, *26*).

In addition to the limits established by the maximum slope of the land, the residues of some crops, such as soybeans and cotton, should not be harvested. Although soybean residues amount to about 3 ton/ha, they degrade rapidly [95 percent by spring (*28*)] and are essential to help control the severe erosion problem associated with soybeans (*29*). With cotton the quantity of residues is small (0.5 to 1 ton/ha) and erosion rates are high (*20*).

If corn stover is removed for energy conversion, additional fertilizer is required to offset the nutrients removed. Corn yields about 5500 kg of grain per hectare and an equal amount of stover with about 50 percent moisture on a dry weight basis (*30*). The stover contains about 1 percent nitrogen, 0.1 percent phosphorus, 0.9 percent potassium, and 0.6 percent calcium (*18*). In terms of energy, the amount of fertilizer in 5500 kg of stover is about 1×10^6 kcal (*31*).

In corn production on land with a slope of 6 to 12 percent and conventional tillage (fall moldboard plowing), soil erosion is assumed to be 45 ton/ha per year (*20*, *32*). If 3500 kg of stover were removed in early fall along with the grain, it is estimated that erosion would increase about 20 percent, or nine additional tons per hectare (*25*). With conventional tillage, this additional erosion would also remove 45 kg of nitrogen and 9 kg of phosphorus (*19*). This loss alone would require an additional 0.7×10^6 kcal of energy annually in fertilizer (Table 2).

Over a 30-year period, the increased loss of topsoil (and subsequent degradation of the land) would lead to a reduction in corn yields of about 1056 kg/ha per year (*20*). Removing the stover for conversion to energy would increase the annual loss of soil from about 45 ton/ha to 54 ton/ha (*25*). Since about 1000 kcal of fossil energy is necessary to offset a 1-kg reduction in corn yield, a 1056-kg reduction would require 1.1×10^6 kcal. Summing these added energy inputs, the removal of corn stover over a 30-year period would necessitate the input of at least 2.4×10^6 additional kilocalories per hectare annually to offset the deleterious effects (environmental degradation external to the crop hectare is not included) (Table 2). This amounts to a 37 percent increase in energy inputs for corn production over time (*15*), compared to normal inputs of 6.4×10^6 kcal.

With 50 percent moisture (dry weight), 3.5 tons of stover from conventional corn production is calculated to contain 11.6×10^6 kcal (Table 2). Conversion of this amount of stover into electricity yields 2.9×10^6 kcal. The total energy cost, including land degradation over a 30-year period, results in an annual net gain of only 200,000 kcal/ha. This land degradation does not include sedimentation and possible flood damage that would result from the removal of the corn stover residue.

If the stover from conventional corn production is converted into methane, there is a net annual energy loss of about 1.4×10^6 kcal/ha (Table 2). This includes using the residue from the conversion process for fertilizer. If the stover were converted into ethanol, the net energy loss would be about 0.8×10^6 kcal/ha (Table 2).

The net return for conversion to electricity of corn residues on a 0 to 2 percent slope with conservation tillage is 1.9×10^6 kcal/ha (Table 2). With this net return per hectare, a regional area of 650,000 ha (2500 square miles) would be needed to supply a community of 157,000. Several assumptions are made in this case: (i) all of the region is farmland with a 0 to 2 percent slope; (ii) the region is producing only corn grain; and (iii) all the corn stover present (3.8 ton/ha) is being harvested and transported to a 75-MW power plant. Seldom would all of these assumptions be met in any region of the United States.

Even on a slope of 0 to 2 percent, the conversion of corn residues into methane results in a net energy gain of only 200,000 kcal/ha (Table 2). This includes using the residue from the conversion process for fertilizer. The reason for this small net return is the high cost of conversion, including storage. Conversion of corn residues into ethanol results in a calculated net energy benefit of 900,000 kcal/ha (Table 2).

Employing no-tillage culture, contour planting, and an annual rye cover crop increases the yield of residue to 5500 kg/ha if moisture is not limiting (Table 2). In addition, these conservation technologies increase the range of slope from which residues can be harvested to 3 to 5 percent. The net energy return with this technology is greater than conventional tillage even on a 0 to 2 percent slope (Table 2).

With wheat production, soil degradation is primarily due to wind erosion and is independent of slope. About 3.5 tons of wheat straw are produced per hectare, but this straw can only be harvested from a relatively small percentage of the Great Plains region (*33*). In the areas where some wheat straw can be harvested, a maximum of only 1.9 ton/ha can be removed. Sufficient straw must be left to protect the soil and maintain essential soil organic matter. In the regions where wheat straw can be harvested, the soil erosion problem is less than with corn. The net energy gain from wheat residue with conventional tillage is slightly higher than that from corn residue, although the cumulative effects of soil erosion over 30 years would eventually make the net energy return negative (*6*).

Net energy benefits of converting forest residues. Forest residues hypothetically available total 110 Mt annually (Table 1), with only 44 Mt estimated as readily available (*3*). Readily available residues include slash located on slopes of 0 to 12 percent and within 2000 km for electrical power transfer of a community (*33, 34*).

Roadways used to obtain timber and pulpwood account for about 90 percent of the soil erosion problems associated with the harvesting of forests (*35, 36*). The erosion is generally severe (*37*); soil losses range from 0.01 to 3.9 ton/ha per year (*38, 39*). The accelerated surface erosion due to roads would continue for only 2 to 6 years if regrowth of vegetation were allowed on roads, skidways, and landings after harvest (*35, 39*). However, mass wasting of soil in mountainous terrain would continue for longer periods (*35, 40*).

For this analysis we assume that good forest roadway practices are employed in removing slash (Table 3). Since nutrients would be removed with the slash, a compensatory energy input of about 3.9×10^6 kcal/ha would be required (Table 3). Although environmental problems are associated with harvesting slash, there are also some advantages, including reduced threats from fire, insects, and diseases (*41*).

Conversion of forest residues into electricity provides a net energy gain of 11.4×10^6 kcal/ha (conversion into ethanol provides only 4.7×10^6 kcal) (Table 3). Even so, a power plant using forest residues to produce electricity for a community of about 15,400 might require a completely forested area of 2500 square miles.

The potential electrical energy from the 44 Mt of U.S. forest residue readily available is calculated to be 20.3×10^{12} kcal (Table 1). Together, forest and crop residues could provide 208×10^{12} kcal, or about 1.1 percent of the current fossil fuel consumption in the United States. This net energy return would occur with minimal environmental degradation if appropriate technologies were employed.

Other Environmental Consequences

In addition to soil degradation, as discussed in terms of energy costs, other serious environmental problems are associated with the harvesting of crop and forest residues. These problems are not easily measured in either energy or dollar units. Some specific environmental aspects of biomass energy conversion are considered in this section, with emphasis given the ecological benefits of biomass residues and the consequences of sedimentation and runoff.

Ecological benefits of crop and forest residues. Crop and forest residues play a vital role in the ecology and protection of agricultural and forest ecosystems. By maintaining soil fertility, organic matter content, and structure, they help to control erosion, sedimentation, and flooding.

Residues control erosion by reducing the impact of water and wind on soil particles. If biomass residues were totally removed from agricultural and forest lands, erosion would increase significantly (*3, 19*). In turn, the increased erosion would reduce soil fertility by carrying away nutrients in the soil sediments (*19, 42*).

For centuries agriculturalists have related crop production potential to soil organic matter content. Organic matter improves soil structure and water-holding capacity, increases cation exchange capacity, and stabilizes mineralization rates of nitrogen. Because organic matter is lightweight, it is significantly more susceptible to erosion than other soil components.

Nutrients in crop and forest residues are valuable in maintaining soil fertility, and residues left to decay in the field replace substantial amounts of the nutrients removed from the soil during the growing season. If the residues are removed, large quantities of supplemental fertilizers must be applied.

Sedimentation and water runoff. Runoff from agricultural land carries an estimated 2.7×10^9 tons of topsoil annually to streams and other deposition areas, while an additional 1×10^9 tons is eroded by the wind (*20, 25, 43, 44*). Erosion rates in cultivated soils average more than 20 ton/ha annually (*25*). An estimated three-quarters of soil erosion takes place in agricultural land (*45*). Since the advent of agriculture in this country, about one-half of the original topsoil has been lost from one-third of the nation's croplands (*43*).

Sedimentation depletes reservoir volume; silts harbors and navigation channels; increases flood damage; reduces

Table 3. Net energy benefits from 1 ha after harvesting forest residues for energy conversion. The land slope was about 10 percent; the annual rainfall, 90 cm.

Quality of collection practices	Residues harvested (tons)	Potential energy (kcal $\times 10^6$)	Annual soil loss (ton/ha)	Added annual soil loss (ton/ha)	Collection energy (kcal $\times 10^6$)	Transport energy (kcal $\times 10^6$)	Energy to offset 6-year soil loss (kcal $\times 10^6$)	Energy to replace nutrients in residue (kcal $\times 10^6$)	Electrical energy (kcal $\times 10^6$)	Ethanol energy (kcal $\times 10^6$)	Net energy (kcal $\times 10^6$)
Poor[a]	24.7[b]	81.5[c]	4[d]	1[e]	3.3[f]	1.3[g]	2.2[h]	3.9[i]	20.4[j]		9.7
Poor										13.7[j]	3.0
Good[k]	24.7	81.5	<1[l]	0[l]	3.3[f]	1.3[g]	0.5[h]	3.9[i]	20.4[j]		11.4
Good										13.7[j]	4.7

[a]Mechanical collection equipment similar to that described in text is used, but roadways, skid trails, and landings are poorly managed and thus erosion is high (*35, 39*). [b]Estimated yield of slash per hectare (*55*). [c]Slash harvested and chipped is assumed to contain 50 percent moisture (dry weight). Thus, the energy content would be 3300 kcal/kg (*56*). [d]With poor harvesting practices, it is estimated that this problem would last for about 6 years (*39*). [e]The added erosion caused by using a tractor to remove slash was estimated to be 20 percent. [f]Collection of the slash and chips is assumed to require an estimated 3.3×10^6 kcal per hectare. This includes protection and maintenance of machinery plus fuel. [g]With the wood chips containing 50 percent moisture, the energy required to transport 1 ton 1 km is calculated at 1310 kcal. This includes the return trip (*8*). The central processing plant for electrical generation or ethanol would service an area of about 650,000 ha. The average distance required to transport residues to the plant would be 40 km. [h]The erosion problem is assumed to last about 6 years. About 5 kg of N and 1 kg of P are removed per ton of added soil loss (*19*). [i]The nutrient content of the slash was assumed to be as follows: N, 1 percent; P, 0.01 percent; K, 0.5 percent; and C_a, 1 percent (*61*). [j]See (*6*) for details on biomass conversion into electricity, methane, and ethanol. [k]Mechanical collection equipment similar to that described in text is used and roadways, skid trails, and landings are properly managed (*35, 39*). [l]With proper harvesting technology, soil erosion should be minimal. This includes removing slash.

the recreational value of streams and lakes; raises the costs of water treatment, hydroelectric power generation, and water distribution; and obstructs drainage and irrigation ditches (*46*). Sediments washed into the nation's waterways cause an estimated damage of $500 million annually (*47*).

Soil sediments, associated nutrients (for example, nitrogen, phosphorus, and potassium), and pesticides have an ecological impact on stream fauna and flora. The added nutrients may increase aquatic productivity, resulting in eutrophication; in contrast, suspended sediments reduce light penetration and hence decrease the productivity of aquatic ecosystems (*48*).

Crop and forest residues reduce the rate of runoff from agricultural and forest land and increase water infiltration rates (*49*). This conserves water, increases the moisture-holding capacity of the soil, raises ground water levels, and helps prevent flooding (*6*). Rapid runoff and erosion, in addition to degrading the quality of agricultural and forest lands, also pollute streams, lakes, and reservoirs and contribute to flood losses. Therefore, any program in which crop and forest residues are converted into energy must employ sound conservation technology to protect agricultural and forest land and water resources.

Conclusion

Although the total of 540 Mt of crop and forest residues (dry) in the field has a gross thermal energy equivalent of about 12 percent of the fossil fuel consumed in the United States, the readily available residues could provide net energy equal to either 1.3×10^9 gallons of high-grade liquid fuel (about 1 percent of current U.S. gasoline consumption), 4 percent of the electrical energy now used, or 1 percent of the energy consumed as heat energy. Even if this contribution is relatively small, it is renewable (assuming no environmental degradation) and therefore has value to the U.S. energy program and especially to certain rural regions of the nation.

The indirect environmental and energy costs of removing crop and forest residues significantly reduce the net energy return and put limiting constraints on the availability of residues. Although crop and forest lands in the United States are extensive, only an estimated 20 percent of the total residues remaining after harvest could be used for conversion because of environmental vulnerability and the difficulty of harvesting some areas of land. Even with proper management practices, severe soil degradation problems can result from residue removal.

Investigations should be carried out before any large-scale biomass energy program is adopted. Related to research needs is the new Soil and Water Resources Act, requiring federal agencies to review their policies to encourage soil conservation (*50*). Especially with current agricultural practices, it is unrealistic to emphasize crop residues as an energy source. While there is a need to develop our biomass energy resources, with current crop and forest management practices such development would only add to environmental problems associated with soil loss and land degradation. The Soil and Water Resources Act may lead to improved management practices, allowing an opportunity for efficient, large-scale conversion of plant residues.

References and Notes

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