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Renewable Energy in the United States

Is There Enough Land?

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Abstract

A review of studies of biomass potential in the United States finds a wide variation in the estimates. A number of specific policy-relevant questions about the potential of biofuels in the United States are answered. A recently published global analysis of the potential conflict between land needed for bioenergy and land needed for food is extended to the situation in the United States. A renewable energy supply scenario, capable of meeting the 2001 US energy demand, indicates that there is enough land to support a renewable energy system but that the utilization of biomass would be limited by its land requirement.

Index Entries: Agriculture; forest; postfossil; renewable energy; scenario; land requirements.

Introduction

Oil production in the United States peaked in 1970 and many expect world oil production to peak by 2020. Odell *(1)* expects that natural gas will fill in for oil, and peak about 2060, followed by unconventional oil and gas, which in his projection will peak about 2080 and 2100. This allows the global oil and gas consumption rate to increase from the current rate of 263 EJ/yr at a rate of 1.6%/yr for the first half of the present century, to a level of 702 EJ/yr, then level off, and finally decrease rapidly at the beginning of the next century. At this point, the use of coal, nuclear breeder energy, and/or some forms of renewable energy must expand rapidly to fill in for the declining production of oil and gas. In a similar vein, Turton *(2)* projects a rapid expansion in the use of biomass for fuels beginning in 2050 and reaching 180 EJ in fuels, requiring 320 EJ in raw biomass by 2100. What role can we expect biomass and other forms of renewable energy to play in this postpetroleum age? Will land availability limit the ability of renewable sources to meet the demand? Will biomass energy become a big new customer for land, reducing the availability of land for food?

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Review of Studies of the Bioenergy Potential in the United States

According to the following five studies, the potential amount of liquid fuel from cellulosic biomass in the United States ranges from less than 10 to 30 EJ. Lynd et al. *(3)* estimate 30 EJ of ethanol from 160 Mha devoted to energy crops. Ethanol productivity is assumed to increase to 168 GJ/ha because of improved biomass productivity (18.0 Mg/ha) and process yield (0.53 J ethanol/J biomass). Hoogwijk et al. *(4)* estimate 20 EJ largely from agricultural land no longer needed for food production because food productivity is assumed to outpace population growth, but the land area is not specified. Green et al. *(5)* estimate 15 EJ from 37 Mha plus the use of corn stover. They assume that by 2050 ethanol productivity will increase to 335 GJ/ha. This study calls for the unusual measure of replacing soybeans with switchgrass, justified on the claim that much more ligno-cellulosic biomass can be produced while producing the same amount of protein. Perlack et al. *(6)* estimate a potential of about 8.5 EJ of liquid biofuels, largely from residues of existing biomass operations and improved agricultural yields. They require only 22 Mha of land exclusively for energy crops. McLaughlin et al. *(7)* base their estimate on the modeled economic response to prices paid for switchgrass; at 44 US$/Mg they find only 1.4 EJ of ethanol is produced. This requires 16.4 Mha, reducing crop production and increasing the price of corn, wheat, and so on, by 10–15%. This study is particularly important because it is the only study that examines the economic effect of energy crop production on food production. In none of these studies is the role of biomass in a total renewable energy system of the country considered. The section entitled "A Renewable Energy Scenario to Produce the Energy Used in the United States in 2001" in this article is an attempt to rectify this situation; it calls for 16 EJ of liquid fuel and 3.1 EJ of solid fuel from biomass.

Biomass Energy, is There Enough Land in the United States?

The question is a little vague. Is there enough land to do what, with what technology, and on whose land? Let us begin by examining some more specific questions.

Is There Sufficient Cropland in the United States to Provide Enough Ethanol From Corn to Make a 10% by Volume Blend, Often Referred to as E-10, of All the Gasoline Used in 2001?

The gross ethanol yield per acre from corn is taken to be 74.2 GJ/ha (equivalent to 3516 L of ethanol/ha) *(8)*, and it is the *gross* land-energy productivity that should be used in this case because we just want to know whether biomass can supply enough ethanol, regardless of the source of the energy to produce it. (The net energy will come later.) In 2001, 479 GL (126.6 billion gal) of gasoline were used in the United States *(9)*. Hence, for a 10% volume blend, 13.7 Mha (33.8 million acres) would be required. Inspection of the United States land use *(10)* indicates that this amount could be met from the idled and reserve program land. However, note that this amount of land area is half the total land currently allocated to corn *(11)*. Hence, corn might be able to support the current effort to promote E-10 but not much more, and E10 replaces only 10% of the gasoline.

How Much Could the Required Land Area be Reduced by Converting Some of the Corn Stover to Ethanol?

Kim and Dale *(8)* analyzed the case in which 70% of the stover as well as the corn grain, was converted, and wheat was grown as a winter cover crop to offset the loss of the organic matter as a result of the removal of a portion of the stover. In their study the corn grain yield was 8.12 Mg/ha-yr and the corn stover 5.70 Mg/ha-yr. From the corn they obtained 2.88 Mg/ha-yr of ethanol; and from the stover, 1.68 Mg/ha-yr. Important byproducts included corn gluten meal, 0.46 Mg/ha-yr; corn gluten feed, 1.96 Mg/ha-yr; and corn oil, 0.36 Mg/ha-yr. In addition 1.28 MWH/ha of electricity was obtained.

In this case they found the gross land-ethanol productivity to be 122 GJ/ha (617 gal/a). The energy inputs for the corn grain are summarized as follows, in GJ/ha: agricultural processes, 22.7; wet-milling, 42.5; and energy avoided owing to coproduct production, –49.5. The energy inputs for the corn stover, in GJ/ha, are for corn stover conversion, 5.0; and avoided electricity, –15; for a subtotal of 5.7 for both aspects of the process. Thus, the overall net land-ethanol productivity is 122 – 5.7 = 116.3 GJ/ha, or 588 gal ethanol/acre.

Note the importance of the avoided energy of the byproducts in reducing the energy required to produce the ethanol. The stover adds not only cellulose to increase the ethanol output, but also adds thermal energy to power the process and supply excess electricity. The *net* ethanol land productivity is 116.3 GJ/ha (588 gal/acre), whereas without the stover, the *gross* land ethanol productivity is only 74.2 GJ/ha (375 gal/acre). Hence, the land required to make the ethanol for a 10% blend is reduced from 13.7 to 8.66 Mha. In this case the energy required to grow and process the ethanol is supplied by process residuals (largely lignin) and a portion of the product ethanol.

How Much Energy is Saved When Ethanol is Made From Corn?

Ferrell et al. *(12)* have reviewed a number of conflicting papers and come to the following conclusions.

For Corn Ethanol

Per amount of energy in the ethanol, the nonrenewable energy inputs are: 0.05 of petroleum, 0.3 of natural gas, 0.4 of coal, and 0.04 of hydro and nuclear for a total of 0.79. Per unit of energy in gasoline the energy inputs

Table 1
Land Requirements for Food and Energy

Item	World		United States
	Poor	Rich	
Arable land (m^2/person)	2500		6140
Forests and pastures (m^2/person)	12,400		15,300
Food consumption (Kg wheat equivalent)	200	800	800
Food production (Kg wheat eq./m^2)	0.2	1.0	0.233
Arable land needed for food (m^2)	1000	800	3400
Energy consumption (GJ/person-yr)	35	200	330
Biomass production (Mg/ha)	1.0	15	15
Energy production (GJ/ha-yr)	18	270	270
Land required for energy (m^2/person)	19,000	7400	12,200
Land required for food and energy (m^2/person)	20,000	8200	15,600

Sources from ref. *13* and this work.

are: 1.1 of petroleum, 0.03 of natural gas, 0.05 of coal, and 0.011 of hydro and nuclear, for a total of 1.191. So when one unit of gasoline energy is replaced with one unit of corn ethanol energy, 1.1 – 0.05 = 1.05 units of petroleum energy are saved. However, 0.3 – 0.03 = 0.27 units of natural gas energy are expended and 0.4 – 0.05 = 0.35 units of coal are expended. Regarding the total energy when one unit of corn gasoline energy is replaced with one unit of corn ethanol energy, 1.19 – 0.79 = 0.40 units of energy are saved. So, if corn ethanol is used in an effort to reduce petroleum imports, it is quite effective; the reduction in imported petroleum energy is 105% of the energy in the ethanol. However, if corn ethanol is used to reduce fossil fuel use, such as would be the case when greenhouse gases are of concern, it is much less effective; the reduction in fossil fuel use is only 44% of the energy in the ethanol. And the reduction in total nonrenewable energy is only 40%.

For Ethanol From Cellulosics

The substitution of one unit of energy in cellulosic ethanol for one in gasoline saves 1.09 units of nonrenewable energy. Not only does the use of cellulosics greatly expand the resource base, it is far more energy efficient than corn.

Can Biomass Supply the Primary Energy Consumption Without Compromising Food Production?

The global analysis, summarized in the first three columns of Table 1, taken from Nonhebel *(13)*, is based on the current world population of six billion; the extension to the United States in the fourth column is based on the current United States population of 300 million. The analysis distinguishes between so-called "poor" and "rich" societies. Food consumption (line 3) in "rich" societies is high owing primarily to the inclusion of meat in the diet. Food productivities (line 4) are based on the world average for the "poor" and Holland's maximum for the "rich". The corresponding land requirements for food (line 5) are nearly the same for "rich" and "poor," the higher productivity of the "rich" being offset by their greater consumption. Note that if the average United States wheat yield, 0.233 kg/m^2 *(10)*, had been used for the "rich" food productivity, the land requirement would be much higher, specifically, 3433 m^2, as shown in the United States column. This does not exceed the United States arable land per capita but it does exceed the world average of 2500 m^2, indicating that the rich diet and the United States wheat productivity cannot be shared by all. Assumptions concerning energy consumption are presented in row 6; as indicated, the US energy consumption exceeds Nonhebel's rich level. Biomass productivity is given on lines 7 and 8. The value of 15 Mg/ha is based on the performance of plantations of short-rotation woody biomass. The value of 1 Mg/ha seems low. The author indicates a value of 2 Mg/ha for unfertilized plots earlier in the article; and values of 3–8 are given in the literature *(14).* However, the productivity of a typical Swedish forest is 1 Mg/ha-yr *(15).* Furthermore, many who use biomass for fuel live in areas of poor rainfall. Hence, the biomass productivity has not been changed. Even if it were as high as 3 Mg/ha there still would not be enough arable land. The energy productivity (line 8) is based on the heat content of biomass with no consideration of product yield or processing and harvesting requirements. Thus, it is an upper limit. The corresponding land requirements for primary energy are given in line 9. In all three cases the land required for food and biomass greatly exceeds the arable land indicating that food production would have to be reduced if sufficient arable land were allocated to bioenergy to meet the full primary energy demand.

What can be Expected From the United States Forests?

From forest surveys *(16)*, the total live biomass in the 202 Mha (500 million acres) of US Timberland, including Alaska, is 21.9 Pg (24,120 million dry t). The gross growth rate is 3.55% of live biomass. This is partially offset by the death rate, 0.75%, and the removals rate, 1.9%, leaving a net accumulation rate of 0.9% *(17).* Thus, the annual increase in live biomass is 0.197 Pg/yr (217 million dry t/yr). In addition Perlack et al. *(6)* estimate that 0.260 Pg/yr. (287 million dry t/yr) could be obtained from residues and fire hazard reduction. (*see* Review of Studies of the Bioenergy Potential in the United States section) Adding this to the net annual increase in live biomass yields 0.457 Pg/yr (503 million dry t/yr) for the total. The energy content of this (using 17.6 MJ/kg) is 8.0 EJ (7.5 quads), which would yield about 3.7 EJ of liquid biofuel. However, at present some residues are in use for direct heating and the generation of electricity.

The aforementioned figures are based on surveys of only 206 Mha (500 million acres) of "productive unreserved forest" whereas the total forest area is 309 Mha (750 million acres). However, the remaining 103 Mha (250 million acres) consists of low-productivity forest in the west and in the interior of Alaska, and protected acres in wilderness areas and national parks *(18)*. The availability of cheap oil has been a disincentive to producing fuels from cellulosic biomass. Without this restraint and with improved technology for converting cellulosic biomass to liquid fuels, regulation to preserve the sustainability of forest growth may well be even more important than now.

How Much Additional Liquid Fuel Could be Made if Animal Production Were Reduced by 50%?

According to the mass flow diagram of Heller and Keoleian *(19)*, 177 Tg/yr (390e9 lbs/yr) of grains are fed to animals. This is slightly more than the 162 Tg (356e9 lbs) exported, which required 37.2 Mha (92 million acres) (*see* Appendix A). This indicates that approx 41 Mha (100 million acres) are used to produce grain to be fed to animals, not counting the extensive land used for pasture. In addition to the land used for grain production and pasture, 42 Mha (103 million acres) are used to grow hay (Appendix A). Hence, if animal production were reduced by 50% there would be about 41 Mha (100 million more acres) for biomass, which according to the value of 116.3 GJ/ha (588 gal/acre) *(8)*, would yield 4.77 EJ ethanol (58 billion gal ethanol), about 30% of the gasoline (on an energy basis) used in 2001.

How Does the Land Productivity for Photovoltaic Hydrogen Compare With That of Biomass?

Long-term photovoltaic (PV) efficiency based on insolation on the horizontal is assumed to be 10%. Average insolation in the United States is taken to be 59,000 GJ/ha-yr. (*Source:* Inspection of insolation contour plots from de Jong *[20]*). This is supported by the fact that a typical year's insolation in Madison, WI is 51,500 GJ/ha-yr *(21)*. The land-PV electricity productivity = 0.1 × 59,000 GJ/ha-yr = 5900 GJ-electric/ha-yr. Electrolysis efficiency is assumed to be 80%. The land-hydrogen energy productivity = 0.8 × 5900 = 4720 GJ-hydrogen/ha-yr. (23,883 gal/acre ethanol equivalent). Note how much greater this is than the current value of 49 GJ/ha-yr or even the optimistic value of 335 GJ/ha-yr *(5)* presented in Section "Review of studies of the Bioenergy Potential in the United States".

What is the Land-Energy Productivity for Biodiesel Compared With Bioethanol?

For biodiesel made by esterification of oil from soybeans grown in a corn-soybean rotation, soybean production was 2.60 Mg/ha-yr, yielding 0.46 Mg/ha-yr of diesel fuel *(8)*. Based on 37.8 MJ/Mg this corresponds to a land-energy productivity of 17.4 GJ/ha-yr. The aforementioned figure of 2.60 Mg/ha-yr is supported by the value of 2.51 Mg/ha-yr found in Table A1, which is drawn from total United States production data. The result of 17.4 GJ/ha-yr is in rough agreement with the value of 25 obtained independently *(22)*. Hence, the gross land liquid-fuel productivity is much smaller than that obtained for corn ethanol, 74.2GJ/ha-yr *(8)*. However, a recent study *(23)* found that without byproducts considered, the net energy in biodiesel was 73% of the gross, and 20% in ethanol from corn. Hence, the net land liquid-fuel productivity would be 12.7 GJ/ha for soy diesel and 14.8 GJ/ha for corn ethanol.

Is There Enough Cropland in the United States for Ethanol From Biomass to Replace all the Gasoline Used in the United States in 2001?

On an energy equivalent basis, it would require 727 billion L (192 billion gal) of ethanol to replace the 480 billion L (126.6 billion gal) of gasoline used in 2001 *(9)*. Using the land-ethanol productivity of 116 GJ/ha (588 gal/acre), (developed in the answer to question 2) this would require 132 Mha (326 million acres). This is greater than the currently harvested cropland; however, this land might be found if one looked hard:

1. From reserve programs, cropland used for pasture, and 'other' land, 65 Mha *(10)*.
2. By eliminating export grains, 37 Mha (Appendix).
3. By reducing animal production by 50%, 40 Mha (*see* above discussion).
4. By replacing soybeans with switchgrass, 29 Mha (*see* Review of Studies of the Bioenergy Potential in the United States section and ref. *5*), for a total of 171 Mha.

A Renewable Energy Scenario to Produce the Energy Used in the United States in 2001

The extent to which biomass energy is used will depend on how much is needed, and this means that the energy demand and other sources of supply need to be spelled out in detail. The following scenario is based on the energy used in the United States in 2001 and the constraint that neither fossil fuel nor nuclear power be used. The underlying rationale is to determine whether an energy system using only renewable energy sources available in the United States is possible, or better expressed, what the land requirements might be. It is based on a set of plausible assumptions, and is meant to give a rough sketch of the role biomass might play.

The land-energy productivities on which the scenario is based, are presented in Table 2. The nonelectrical 2001 demands are presented, along with renewable means of satisfying them, in Table 3. The 2001 electrical demands are presented, along with the renewable means of satisfying

Table 2
Land Renewable Energy Factors

Technology	Solar efficiency (%)	Factor (GJ/ha-yr)	Sources
Wind electric	n. a.	416	*24*
Photovoltaic	10	5886	*29*
Solar–thermal–electric (STE)	11.5	6771	*30*
Solar–thermal	34.5	20,371	Based on three times's the output of STE
Liquid biofuel	0.19	113	Corn and 70% stover *(8)*
Switchgrass, advanced	0.56	331	Dependent on R&D *(5)*
Wind hydrogen	n. a.	354	Based on wind-electric and 85% electrolysis efficency
Biomass solid	0.30	180	Based on 282 GJ/ha for less 15% loss in harvesting and 25% loss in combustion

n. a., not applicable.

Table 3
Renewable Energy Scenario to Cover 2001 Nonelectric Energy Use

Type of use	In 2001 EJ/yr	Renewable energy scenario EJ/yr	TWh/yr	Energy source
Transportation				
Aviation fuel *(31)*	3.0	3.0	–	Hydrogen
Gasoline *(10)*	15.4	7.7	–	Biomass liquid
	–	7.7	725[a]	Electricity
Diesel fuel *(10)*	5.0	4.0	–	Biomass liquid
	–	1.0	98	Electricity
Other fuel *(10)*	4.4	3.2	314	Electricity
	–	1.2		Biomass liquid
Total transportation *(32)*	27.8	27.8	–	–
Nonfuel (Chemicals and so on) *(33)*	6.2	3.1	–	Biomass liquid
	–	3.1	–	Hydrogen
Residential, commercial, and industrial nonfuel *(32)*	28.3	3.1	–	Biomass solid
	–	14.7	–	Solar thermal
	–	10.5	–	Conservation
Electric storage loss[b]	–	–	284	–
Total	62.3	62.3	1421	–

[a]Based on 10.6 MJ/kWh rather than 3.6 to account for thermal conversion.
[b]It is assumed that 50% of the electricity is stored and that 25% of this is lost because of electrochemical conversions.

Table 4
Renewable Energy Scenario to Cover 2001 Electrical Energy Use

Source	2001[a] TWh	Renewable energy scenario TWh	Land (Mha)
Fossil	2677	0	–
Nuclear	769	0	–
Hydro	217	434	–
Biomass	35.2	0	–
Waste (MSW)	21.8	30	–
Geothermal	13.7	137	–
STE	0.25	943	0.57
Photovoltaic	0.25	313	0.21
Wind	6.7	1883	20.8
Other	4.7	5	–
Storage loss[b]	–	936	–
Total	3737	4460	21.6

[a]DOE Annual Energy Review, Table 8.2a *(34)*.
[b]It is assumed that 50% of the electricity is stored and that 25% is lost in electrical conversions. Supply divided among STE, 30%; PV, 10%; and Wind, 60%.

Table 5
Summary of Land Requirements

Item	Energy content EJ	Energy content TWh	Land factor GJ/ha	Land factor MWh/ha	Land Mha
Biomass liquid	16.0	–	113	–	142
Biomass solid	3.16	–	180	–	17.5
Hydrogen (wind)	6.12	–	354	–	17.2
Solar–thermal	14.7	–	20,371	–	0.7
Electricity	–	5881	–	–	–
Wind (60%)	–	3529	416	116	30.4
STE (30%)	–	1764	6771	1882	0.93
PV (10%)	–	588	5886	1636	0.36
Total	40.0	5881	–	–	209.1
	–	21.1 EJe	–	–	–

Note. This scenario calls for 15.7 EJ (14.9 quads) of biomass liquid. According to Lynd et al. *(3)* this option would also produce 349 TWh of electricity. Using the land wind electrical energy factor of 116 MWh/ha (0.47 e5 kWh/acre), this would reduce the wind land requirement by 3.0 Mha (7.4 million acres).

them, in Table 4. Finally, the amounts of the various forms of renewable energy and their land requirements, are presented in Table 5.

This scenario calls for a great deal of wind energy; it requires 6.0% of the land in the lower 48 states to be used for wind power. There is enough land if some class 3 sites are used. Elliot and Swartz *(24)* conclude that, while avoiding all environmentally sensitive areas, class 3 and above wind sites occupy 18% of the land area and have a potential of 14,300 TWh/yr. Class 4 characteristics were used to compute the average wind energy land productivity in this study. One of the desirable aspects of wind power is that the use of an area of land for wind power does not preclude its use for agriculture. In fact, combining a biomass plantation with a wind farm makes good sense. *(25)*

156 Mha (385 million acres) for biomass is also very large but some of the studies reviewed in previous sections indicate that this might be possible, especially, if exports were reduced, agricultural and dietary practices were changed, forest and agricultural residues were utilized, and/or bioenergy technology improved as expected. Several alternatives (solar–thermal, solar–thermal–electric, wind–electric, and hydrogen from electricity) that are less land intensive, are available if necessary.

Obviously many other menus of energy supply are possible. Wind energy is emphasized over photovoltaic conversion because it is less expensive and does not cover the land. Hydrogen was selected for aviation fuel because of its high energy density, and the fact that there is some experience with hydrogen as an aviation fuel *(26).* I chose a mixture of biofuels and electricity for vehicles over hydrogen because of the low cost and efficiency *(27)* and the promise of hybrid vehicles.

The storage requirement (50% of electrical generation to be stored and 25% of this lost owing to conversion) is speculative. I have assumed that electro-chemical batteries would be used but hydrogen could be used for electrical storage; however, the energy loss is very large, although the cost of storage is less *(28)*. Hydrogen in this scenario is for uses that do not require it to be converted back into electricity.

The land-energy productivity used in this scenario for biomass liquid fuel, 116 GJ/ha, is based on corn kernels plus 75% of the stover *(8).* Although it is higher than the current technology of using only corn kernels, it does not represent a particularly optimistic value. A more optimistic value, projected to occur by 2050 in Green et al. *(5)* on the basis of improvements in switch grass productivity, which have been achieved in experimental plots, the use of Fischer–Tropsch synthesis as well as fermentation, and expected fermentation improvements, is 331 GJ/ha. This would reduce the land required for biomass liquid fuels from 142 to 48 Mha, obviously a much more accessible amount.

Hopefully, the scenario puts biomass energy into context and begins to lay open the nature of a sustainable renewable energy system at the 2001 level of demand in the United States. The study indicates that there

Table A1
Agriculture Land Use

	Units	Area (Mha) *(11)*	Production (M units) *(11)*	Average yield (units/ha)	Density (kg/unit) *(11)*	Producsts (Tg)	Yield (Mg/ha)
Corn for grain	bu	27.62	8807.0	318.9	25.4	223.7	8.10
Corn sillage	tons	2.7	97.3	36.0	907	88.2	32.67
Sorgum for grain	bu	2.73	333.6	122.2	25.4	8.5	3.10
Wheat for grain	bu	18.43	1577.8	85.6	27.2	42.9	2.33
Oats for grain	bu	0.81	110.0	135.8	14.8	1.6	2.01
Barley for grain	bu	1.62	214.4	132.3	21.8	4.7	2.89
Rice	cwt	1.3	210.4	161.8	45.3	9.5	7.33
Soybeans for beans	bu	29.3	2708.8	92.5	27.2	73.7	2.51
Peanuts for nuts	Lbs	0.49	3134.0	6395.9	0.454	1.4	2.90
Dry edible beans	Lbs	0.68	32.0	47.1	27.2	0.9	1.28
Cotton	bales	5.04	17.3	3.4	218	3.8	0.75
Tobacco	Lbs	0.17	870.0	5117.6	0.45	0.4	2.30
Potatoes	cwt	0.51	451.0	884.3	45.35	20.5	40.10
Sugarbeets	tons	0.55	27.8	50.5	907	25.2	45.84
Sugarcane	tons	0.4	35.3	88.3	907	32.0	80.04
Forage used for hay	tons	25.92	211.3	8.2	907	191.6	7.39
Alfalfa hay, (dry)	tons	9.16	68.8	7.5	907	62.4	6.81
Small- grain hay (dry)	tons	1.76	7.8	4.4	907	7.1	4.02
Tame hay (dry)	tons	10.89	52.4	4.8	907	47.5	4.36
Wild hay (dry)	tons	2.72	8.1	3.0	907	7.3	2.70
Haylage from alfalfa (green)	tons	1.44	23.3	16.2	907	21.1	14.68
Other haylage (green)	tons	0.72	11.2	15.6	907	10.2	14.11
Total	–	145.0	–	–	–	884.2	–

Table A2
Agriculture Land Use

	Export *(1)* 1e6 Mg	Export land Mha	Int. land Mha	Net Int. use 1e6 Mg	Residue yield kg/kg *(3)*	Residue 1e6 Mg
Corn for grain	47.06	5.81	21.81	176.6	1	223.7
Corn sillage	–	0.00	2.70	88.2	–	–
Sorgum for grain	3	0.97	1.76	5.5	–	–
Wheat for grain	25.4	10.91	7.52	17.5	1.23	52.8
Oats for grain	1	0.50	0.31	0.6	1.16	1.9
Barley for grain	2.56	0.89	0.73	2.1	1.45	6.8
Rice	3.54	0.48	0.82	6.0	0.78	7.4
Soybeans for beans	36.88	14.67	14.63	36.8	–	–
Peanuts for nuts	–	0.00	0.49	1.4	–	–
Dry edible beans	–	0.00	0.68	0.9	–	–
Cotton	2.21	2.95	–	–	–	–
Tobacco	0.16	0.07	0.10	0.2	–	–
Potatoes	–	0.00	0.51	20.5	–	–
Sugarbeets	–	0.00	0.55	25.2	0.95	24.0
Sugarcane	–	0.00	0.40	32.0	–	–
Forage used for hay	–	0.00	25.92	191.6	–	–
Alfalfa hay (dry)	–	0.00	9.16	62.4	–	–
Small-grain hay (dry)	–	0.00	1.76	7.1	–	–
Tame hay (dry)	–	0.00	10.89	47.5	–	–
Wild hay (dry)	–	0.00	2.72	7.3	–	–
Haylage from alfalfa (green)	–	0.00	1.44	21.1	–	–
Other haylage (green)	–	0.00	0.72	10.2	–	–
Total	121.8	37.2	105.6	760.9	6.57	316.5

is enough land for a sustainable renewable energy system at the level of demand experienced in 2001, and that the utilization of biomass, although quite significant, would be limited by its land requirement.

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Appendix A Agriculture Land Use

The following worksheets, Tables A1 and A2, are based on data from the 2002 Census of Agriculture *(11)* and other references as indicated on the worksheet. It contains information on crop production, crop yields, acreage, exports, acreage used for exports, and residue production. In Table A1, values for the area, production in terms of the units given in the units column, and density are entered directly. This allows the yields and the production in Mg to be computed. In Table A2 the exports and residue yields are entered directly. This allows the land area required for exports to be computed from the known yield given in Table A1. Similarly, the land left for internal use can be computed and along with it the production used internally. Finally the amount of residue can be computed from the residue yield and the total production.

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