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Crop residues as soil amendments and feedstock for bioethanol production

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Abstract

Traditional solid fuels account for more than 90% of the energy supply for 3 billion people in developing countries. However, liquid biofuels (e.g., ethanol) are perceived as an important alternative to fossil fuel. Global crop residue production is estimated at about 4 billion Mg for all crops and 3 billion Mg per annum for lignocellulosic residues of cereals. One Mg of corn stover can produce 280 L of ethanol, compared with 400 L from 1 Mg of corn grains; 1 Mg of biomass is also equivalent to 18.5 GJ of energy. Thus, 3 billion Mg of residues are equivalent to 840 billion L of ethanol or 56×10^9 GJ of energy. However, removal of crop residues exacerbates soil degradation, increases net emission of CO_2, and aggravates food insecurity. Increasing the SOC pool by 1 Mg C ha^{-1} yr^{-1} through residue retention on soil can increase world food grain production by 24–40 million Mg yr^{-1}, and root/tuber production by 6–11 million Mg yr^{-1}. Thus, identifying alternate sources of biofuel feedstock (e.g., biofuel plantations, animal waste, municipal sold waste) is a high priority. Establishing biofuel plantations on agriculturally marginal or degraded lands can off-set 3.5–4 Pg C yr^{-1}.

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1. Introduction

Biomass has been used for millennia as a source of residential energy. It is still the main source of energy for about 3 billion people in developing countries of Asia and Africa (RWEDP, 1997; Amous, 1999; Lefevre et al., 1997; Hoogwijk et al., 2005), often with severe adverse impacts on air quality and human health. However, the modern use of biomass as biofuel is through the production of ethanol or hydrogen as a renewable alternative to fossil fuel. Modern biofuels are high-quality energy carriers which can be used for generating electricity or transport, as a substitute for fossil fuel (Giampietro et al., 1997). These are also called “green gold” fuels, because their feedstocks can be grown on farmland over and over again (Vorholz, 2006). Modern biofuels include ethanol, methanol, methane and triglyceride oils. The interest in modern biofuels and other renewable sources of energy is increasing because of the rapid increase in atmospheric concentration of CO_2 and the attendant global warming because of fossil fuel consumption (WMO, 2006).

With regards to using crop residues as potential feedstock for ethanol production, some questions which need to be addressed include the following: Should crop residues be used for carbon (C) sequestration and soil quality improvement or producing energy? Should the answer to this question be determined by short-term economic or the long-term sustainability of natural resources? Should the need for fuel to run industry and vehicles override the urgency to achieve food security for almost a billion people around the world who are food insecure and threatened by hunger? Answers to these serious global issues must be based on objective analyses of the facts. Two issues which require a critical appraisal are: (i) sequestration of atmospheric CO_2 into long-lived pools, and (ii) development of C-neutral fuel sources. Both issues are important to addressing the global climate change. The strategy of C sequestration in terrestrial ecosystems, a natural process, is energy efficient and a cost-effective option because the process of capturing, concentrating, transporting and

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injecting industrial CO_2 into geological strata are themselves energy intensive (Turner, 1999).

This paper describes the global energy demand, discusses the importance of biofuel as a renewable alternative to fossil fuel, outlines the potential sources of biofuel feedstock, explains the significance of crop residue to sustainable management of soil and water resources, and deliberates the impact of biofuel plantations on the global C cycle. The focus is on developing biofuel feedstock production systems in synergy with those of food production systems needed to feed the world population of 6.5 billion in 2006 and expected to reach the 10 billion mark by 2050.

2. Global energy demand and the role of biofuels

The global energy demand is about 424 EJ yr^{-1}, of which the current US energy consumption is about 106 EJ yr^{-1} (Weisz, 2004) (Fig. 1). Primary energy consumption worldwide increased 40 times between 1860 and 2005 (Vorholz, 2006). The future energy demand will increase at the rate of 1–2% yr^{-1} for the world, and 1.5% yr^{-1} for the US (Weisz, 2004). Global energy demand increased by 93.2% from 219 EJ in 1970 to 424 EJ in 2000, at an average rate of 6.8 EJ yr^{-1} or 3.1% yr^{-1} (Table 1). The future energy consumption is projected to increase from 424 EJ in 2000 to 660 EJ in 2025 at an average rate of increase of 9.45 EJ yr^{-1} or 2.2% yr^{-1} (Table 1). The global potential of primary renewable energy has been estimated at 2800 EJ yr^{-1}, which is more than the forecast for the world energy requirement by 2100 (Moreira, 2006). There will also be an attendant increase in global CO_2 emission from 6.1 Pg of CO_2–C in 1990 to 9.8 Pg in 2020, along with an increase in global population from 6.0 billion in 2000 to 7.5 billion in 2020 (DOE, 2003).

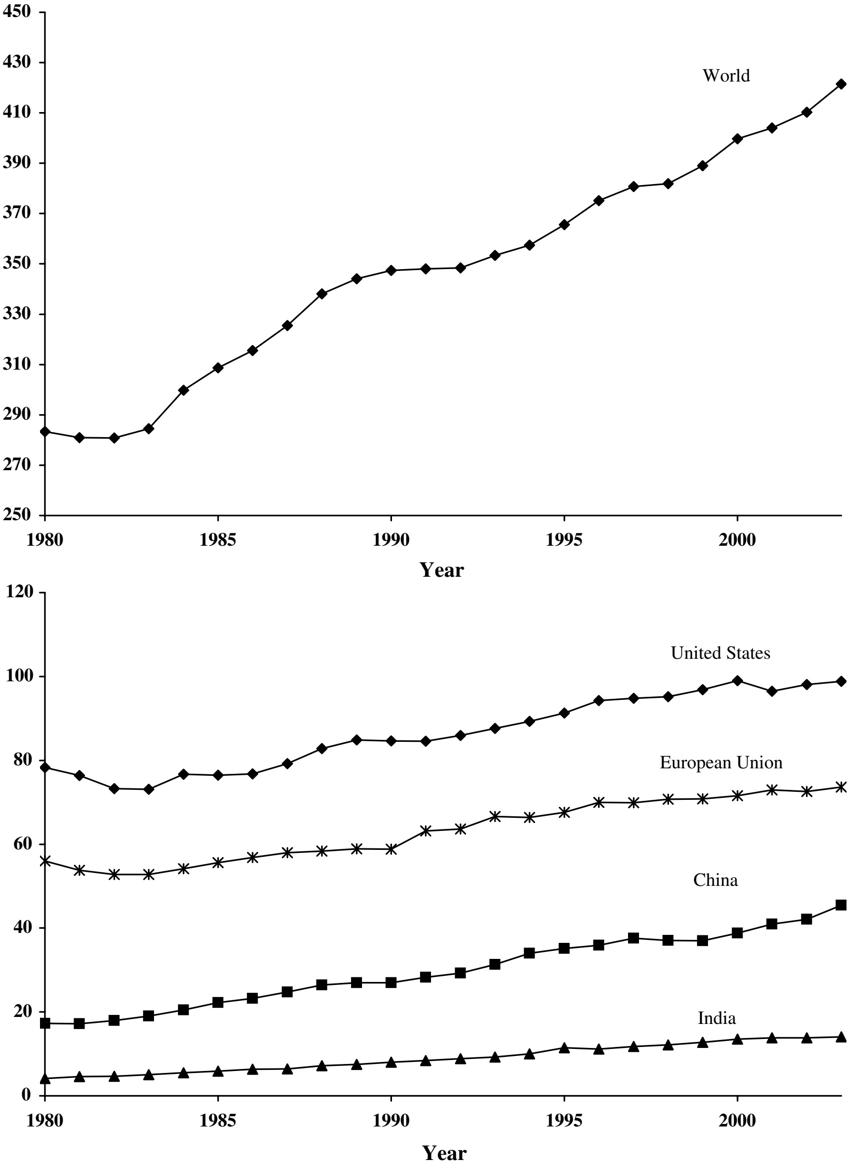

Fig. 1. Global energy use. The units in Q can be converted to EJ by multiplying Q by 1.06 [recalculated from EIA (2003)].

Table 1
World energy consumption (EIA, 2004)

Year	Consumption (Q)
1970	207
1975	243
1980	285
1985	309
1990	348
1995	368
2000	400
2001	404
2003	422
2010	471
2015	517
2020	568
2025	623

Units in Q can be converted to EJ by multiplying Q by 1.06.

Table 2
US energy consumption (EIA, 2004)

Year	Total (Q)	Renewable (Q)	Biofuel (Q)	
			Amount	% of Total
1949	32.0	3.0	1.6	5.0
1950	34.6	3.0	1.6	4.6
1955	40.2	2.8	1.4	3.5
1960	45.1	2.9	1.3	2.9
1965	54.0	3.4	1.3	2.4
1970	67.8	4.1	1.4	2.1
1975	72.0	4.7	1.5	2.1
1980	78.3	5.5	2.5	3.2
1985	76.5	6.0	2.9	3.8
1990	84.7	6.1	2.7	3.2
1995	91.3	6.7	3.1	3.4
2000	99.0	6.2	2.9	2.9
2004	99.7	5.9	2.8	2.8

Units in Q can be converted to EJ by multiplying Q by 1.06.

Table 3
Sources of electric power generation in the US in 1997 (Brown, 1999; Weisz, 2004)

Source	Percent
Coal	53
Nuclear	18
Natural and other gas	14
Petroleum	3
Renewable	12
(i) Hydroelectric	10.0
(ii) Biomass	1.56
(iii) Geothermal	0.36
(iv) Wind	0.096
(v) Solar	0.036

Table 4
Sources of US energy supply of 98 Quads in 2003 (EIA, 2004a)

Source	Percent
Petroleum	39
Natural gas	24
Coal	23
Nuclear	8
Renewable	6
(i) Biomass	2.82
(ii) Hydroelectric	2.70
(iii) Geothermal	0.30
(iv) Wind	0.12
(v) Solar	0.06

The estimated biomass consumption to produce 2.9Q of energy was 190 million tons of total biomass comprised mostly of forest products (e.g., wood residues, pulping liquors, urban wood, fuel wood, and by-products).

The US energy consumption, 25% of the world total energy use (Table 2), increased 186% from 36.7 EJ in 1950 to 104.9 EJ in 2000, at an average rate of increase of 1.37 EJ yr^{-1}. Principal sources of energy in the US in 2006 included 42.4 EJ of petroleum, 24.9 EJ of natural gas, 24.3 EJ of coal, 8.3 EJ of nuclear, 3.8 EJ of combined biofuels, solar, wind and geothermal, and 3.1 EJ of hydropower. Projections of energy supply for different sources for 2030 are 55.2 EJ for petroleum, 36.4 EJ from coal, 28.7 EJ from coal, 9.9 EJ from nuclear, 6.5 EJ from combined biofuels, solar, wind and geothermal, and 3.8 EJ from hydropower (Krauss, 2007). Most of the electricity supply in the US (88%) comes from fossil fuel combustion (Table 3). Only 12% of the US electricity demand is met from renewable sources. Of the total energy consumption of 106 EJ yr^{-1} in the US, about 3% is supplied by the biomass (USDA-DOE, 2005) (Table 4). Presently, liquid biofuels play a minor role in supplying the energy demand of the world and the US. It is envisioned that biomass will supply 5% of the US power, 20% of its transportation fuels and 25% of its chemicals by 2030 (DOE, 2003). Worldwide nuclear energy contributed 1% of total consumption in 1973 and 6% in 2004. Similarly, hydro-energy contributed 2% of total consumption in 1973 and 6% in 2004 (Vorholz, 2006). Of the total global consumption of biomass energy of 45 ± 10 EJ yr^{-1}, about 7 EJ yr^{-1} is considered modern biofuel (Turkenberg, 2000). Modern biofuels are projected to contribute future energy needs of 10–50% of the total primary energy demand (Berndes et al., 2003; Fischer and Schrattenholzer, 2001). By 2010, 6% of all fuel consumed in EU countries is envisaged to be grown on farmland (Vorholz, 2006).

The demand for ethanol production is increasing worldwide. The US produced 17.0 billion L of ethanol in 2005. The production is envisaged to increase to 28.4 billion L yr^{-1} by 2012 under the US Energy Policy Act of 2005. In contrast, the US uses 530 billion L yr^{-1} of ground transportation fuel. To substitute 30% of this by ethanol would require 227 billion L of ethanol yr^{-1} (Somerville, 2006). Pacala and Socolow (2004) estimated that global ethanol production of 7.5 billion L day^{-1} by 2054 would off-set fossil fuel emissions by 1 Pg C. This ethanol production rate is about 50 times larger than the ethanol production rate of 2004 (149.3 million L day^{-1}). Such a large production of ethanol would require reliable sources of biofuel feedstock.

3. Biomass as traditional and modern fuel source

Biomass comprises all plant and plant-derived materials including animal manure, not just starch, sugar, oil crops already used for energy (USDA-DOE, 2005). These materials have a vast potential to supply renewable energy. Biofuel feedstocks are plant products containing a high concentration of carbon (C) and hydrogen (H) and a low concentration of oxygen (O), nitrogen (N) and other inorganic constituents (e.g., Ca, Mg), and which directly or indirectly (their conversion products) burn readily to release energy to perform work or regulate temperature in an environment. The energy value of plant-derived feedstock is about 15 GJ Mg^{-1} compared with 50 for methane and natural gas, 40 for butanol and gasoline, and 35 for triglycerides and petroleum (Lipinsky, 1978). Atmospheric CO_2 is fixed into high energy biomass containing high concentration of C and H, by the natural process of photosynthesis. This process has also been the primary source of energy contained in fossil fuels. The energy contents of fuel products are much higher than those of the original simple biomass products (e.g., glucose, starch, lignin). The additional energy arises from loss of CO_2, H_2O and formation of energy-rich carbon–carbon double bonds or ring structures. Ethanol produced from corn grains, sugarbeets, potatoes and or other grains is not as efficient as that from renewable BTL (biomass to liquid). The entire plant biomass (stem, leaves, roots) are gasified and then synthesized into a liquid fuel (Vorholz, 2006). These BTL do not release any additional CO_2 than originally photosynthesized from the atmosphere. Thus, it is a CO_2 neutral fuel, although there are some carbon costs (fertilizer, tillage, herbicides, pesticides) associated with the production of the biomass (Lal, 2004; Cowie et al., 2006). Tilman et al. (2006) proposed C-negative biofuels from the low-input high-diversity (LIHD) grassland biomass. They observed that high-diversity grasslands have 238% more bioenergy yields than monoculture yields. Tilman and colleagues concluded that LIHD biofuels are a C-negative net ecosystem. CO_2 sequestration (4.4 Mg ha^{-1} of CO_2 in soil and roots) exceeds fossil fuel CO_2 released during biofuel production (0.32 Mg ha^{-1}).

Biomass is the only renewable energy source which can supply the liquid transport fuel. Therefore, developing viable alternatives for an annual production of about 1 billion Mg of biomass in the US (USDA-DOE, 2005) and 4–5 billion Mg in the world is a high priority. There are several potential sources of biofuel feedstock. Important among these are crop residues, forestry residues, animal waste, by-products of the food processing industry, saline culture and growing halomorphic plants, and biofuel plantations. It is in this context that the importance of using crop residues (e.g., corn, wheat, rice, barley) as a source of biofuel feedstock has become an important issue. With the focus on crop residue, a strategic question is: Are land resources in the US and the world sufficient to meet the alternate and competitive demands? It is estimated that over 1.3 billion Mg of biomass can be produced annually in the US, comprised of 368 million Mg from the forest land and 998 million Mg from agricultural resources (USDA-DOE, 2005).

4. Crop residue as a source of biofuel feedstock

Agricultural by-products, especially crop residues, are considered as a source of biofuel feedstock, especially in countries with large arable land area. In this context, the extent of agricultural land area in the US is a pertinent example (Table 5). There are a total 184.2 Mha under agricultural use. This comprises 141.3 Mha of actively used cropland, 15.8 Mha of idle cropland including CRP, and 27.1 Mha of cropland used as pastures. Between the 1950s and 2000, primarily due to mechanization, cropland area under oat production decreased form 15.2 to about 1 Mha. There was a strong increase in area under soybean, from less than 2.5 Mha in 1940 to 29.7 Mha in 2000. There has also been an increase in the area under conservation tillage since the 1970s. No-till farming is used on 25.1 Mha, and an additional 20.2 Mha is periodically under other forms of conservation tillage (CTIC, 2004). Globally, no-till farming is practiced on about 95.5 Mha (Table 6). Increase in land area under no-till farming will necessitate use of crop residue as surface mulch.

Estimates of crop residue production in the US and the world are shown in Tables 7 and 8, respectively. In 2001, crop residue production was estimated at 483 million Mg in the US, compared with 3800 million Mg in the world. Of this, residue from cereal crops was 367 million Mg in the US and 2802 million Mg in the world, or about 75% of the total residue produced.

Estimates of total biomass availability, the amount that can be dedicated to biofuel production, from agricultural lands in the US are shown in Table 9. Total biomass availability of 176 million Mg at present is about 15% of the 1.1 billion Mg of plant biomass produced on agricultural lands in the US. By adopting recommended management

Table 5
Agricultural land use in the US in 1997 [calculated from USDA-NRCS (2003)]

Land use	Area (10^6 ha)
1. Actively used cropland	141.3
(i) Corn grain	28.1
(ii) Small grains	26.4
(iii) Soybeans	29.1
(iv) Hay	25.8
(v) Silape	3.1
(vi) Cotton	5.4
(vii) Rice	1.3
(viii) Other crops	7.5
(ix) Fallow and failed	12.1
(x) Unaccounted for	2.5
2. Idle cropland (including CRP land)	15.8
3. Cropland used as pastures	27.1
4. Total	184.2

Table 6
Estimates of the global cropland area under no-till farming

Country	Cropland area under no-till in 2004–2005	
	Total area[a]	% of Cropland[b]
USA	25.3	17.9
Brazil	23.6	40.0
Argentina	18.3	65.6
Canada	12.5	27.4
Australia	9.0	18.9
Paraguay	1.7	55.9
Indo-Gangetic Plains (Rice–Wheat System)	1.9	15.2
Bolivia	0.55	18.0
South Africa	0.3	2.0
Spain	0.3	2.2
Venezuela	0.3	11.5
Uruguay	0.26	19.0
France	0.15	0.8
Chile	0.12	6.1
Colombia	0.10	4.4
China	0.10	0.07
Others	0.10	–
Total	95.48	6.4

[a] From Derpsch (2005).

[b] Cropland area from FAO (2005).

[c] Wheat is seeded by no-till system on 12.5 Mha of rice-wheat system in South Asia.

Table 7
Estimates of crop residue produced in the US [adapted from Lal (2005)]

Crop species	Area (Mha)		Residue production (10^6 Mg)	
	1991	2001	1991	2001
Cereals	62.0	55.3	325.2	366.8
Legumes	25.0	30.8	58.0	81.8
Oil crops	7.5	7.5	17.1	20.2
Sugar crops	0.9	0.9	25.3	13.8
Tubers	0.6	0.5	4.8	5.3
Total	96.0	95.4	430.4	487.9

Table 8
Estimates of crop residue production in the world [adapted from Lal (2005)]

Crop species	Area (Mha)		Residue production (10^6 Mg)	
	1991	2001	1991	2001
Cereals	704	671	2563	2802
Legumes	194	212	238	305
Oil crops	87	70	162	108
Sugar crops	26	25	340	373
Tubers	465	524	145	170
Total	1476	1502	3448	3758

Table 9
Estimates of biomass availability from agricultural sources in the US [calculated from USDA-DOE (2005)]

Source	Current technology[a] (10^6 Mg)	Yield increasing technology[b] (10^6 Mg)		Land use change[c] (10^6 Mg)	
		Moderate	High	Moderate	High
Perennial crops	–	–	–	142	342
Corn stover	68	154	232	144	232
Wheat straw	10	32	52	32	47
Small grain residue	5	14	23	14	23
Soybeans	–	–	–	12	44
Other crop residues	19	34	44	33	43
CRP biomass	0	25	25	16	16
Grains to biofuels	14	51	88	51	79
Manures	32	40	40	40	40
Other residues	28	36	40	36	40
Total	176	386	544	530	906

[a] These estimates are based on residue collection efficiency of 40%.

[b] Increase in crop yield by 25% at moderate level and 50% at high level.

[c] Land use change along with improved crop production technology.

practices (RMPs), which enhance biomass production, it is estimated that the amount of biomass available for biofuel production can be increased to 386 million Mg with moderate increase, and 544 million Mg with high increase in productivity. Assumed rates of yield increase are similar to those recommended by USDA-DOE (2005). It is further assumed that collection efficiency in this scenario is 60% of the residue under moderate, and 75% under high yield increase. Further, no-till is assumed to be practiced on 81 Mha (USDA-DOE, 2005; Dobermann et al., 2002) which in 2005 was practiced on only 25 Mha (Table 6). However, these rates of increase are less than those predicted by FAO (2003). These estimates also include 68 million Mg of manure, 50% of the biomass produced from CRP lands, and widespread adoption of no-till farming. No-till is currently practiced on 25.3 Mha of cropland comprising 11.8 Mha of soybeans, 6.4 Mha of corn, 2.7 Mha of winter wheat, 1.7 Mha of spring grains, 1 Mha of cotton and 0.7 Mha of sorghum (CTIC, 2004). In this scenario (with 542 million Mg with high yield and 384 million Mg with moderate yield), about two-thirds of the biomass comes from crop residues.

Biomass production and availability also depends on the procurement price (Energy Policy Act, 2005; Walsh, 2006; McLaughlin et al., 2002; Ugarte et al., 2003; McLaughlin and Kszos, 2005). Regardless of the price and increase in the profit margin by selling it for ethanol production, residues from cropland must never be removed. Long-term benefits in enhancing soil quality and advancing sustainable use outweigh any short-term economic gains by selling residues for ethanol production. Furthermore, residue retention is essential for successful conversion of plow tillage to no-till farming. At present, no-till farming is adopted only on 95 Mha of cropland (Derpsch, 2005). Extension of no-till farming to all cropland (1500 Mha) worldwide would sequester another 0.5–1 Pg C yr^{-1} (Pacala and Socolow, 2004), for which retention of crop residue is essential. Rather than selling crop residues, it is possible to trade credits on C sequestration in soils managed by no-till farming (Brahic, 2006; Breslau, 2006).

5. Solid waste produced in the US

A large quantity of solid waste is being generated in the world, but especially in developed/industrialized economies. Total solid waste produced in the US is increasing. It was 269 million Mg in 1990, 281 in 1992, 307 in 1994, 327 in 1996, 340 in 1998 and 375 in 1999. The annual rate of growth in the 1990s was 10.6 million Mg yr^{-1} (Glenn, 1999). Of the 375 million Mg produced in 1999, 31.5% was recycled, 7.5% incinerated, and 61.0% landfilled (Glenn, 1999).

Of the total solid waste, the amount of municipal solid waste (MSW) produced in the US is estimated at 215 million Mg yr^{-1} (USEPA, 2006). The quantity of MSW produced in the US increased from 89 million Mg in 1960 to 215 million Mg in 2003, at an average rate of increase of 2.9 Mg yr^{-1} (Table 10). The MSW in the US doubled between 1970 and 2003. The per capita MSW production was 1.2 kg $person^{-1}$ day^{-1} in 1960 and 2.0 kg $person^{-1}$ day^{-1} in 2000. Of the total amount of MSW generated, the recyclable waste is about 65%. Components of MSW which can be used as biofuel feedstock include paper, yard trimmings, food scraps and wood, which together form about 53% of the total.

Sending MSW to landfills leads to emission of GHGs (e.g., CH_4, N_2O and CO_2). In the US, emission of GHGs from MSW in 2003 accounted for 0.1% of the total GHG emissions (Johnson, 2006). It is estimated that the GHG emissions from MSW declined from 60.5 Tg CO_2 equivalent in 1970 to 7.8 Tg of CO_2 equivalent in 2003 (Johnson, 2006). The reduction was attributed to the use of innovative technologies (e.g., bioreactor landfills). Collection of GHGs as a source of energy (CH_4) is a viable option. Therefore, judicious management of MSW is necessary in improving the environment quality.

Food waste, especially vegetables and fruits, are also an important source of biosolids. Food processing and packing companies generate a substantial amount of MSW, which can be used for composting and biofuel production rather than sent to the landfill.

6. Estimates of animal manure produced in the US

The total amount of animal manure produced in the US has remained constant over the 15-yr period between 1982 and 1997 (Table 11). The total quantity of animal manure produced in the US in 1997 was 132.3 million Mg, of which cattle manure was 107.6 million Mg or 81%. If not properly used, animal manure can be a major source of pollution of natural waters and emission of N_2O and other noxious gases (NH_3) into the atmosphere.

Table 10
Trends in municipal solid waste production in the US [calculated from USEPA (2006)]

Year	Total amounts (10^6 Mg)	Biosolids (10^6 Mg)	Total per capita (kg $person^{-1}$ day^{-1})	Total amount recycled (10^6 Mg)
1960	89.0	47.3	1.2	5.1 (6.4%)
1970	110.0	58.4	1.5	7.3 (6.6%)
1980	137.7	73.1	1.7	13.1 (9.64%)
1990	186.3	98.9	2.0	30.0 (16.2%)
2003	214.5	113.9	2.0	65.6 (30.6%)

Biosolids comprise paper, yard trimmings, food scraps, and wood (or 53.1%).

Table 11
Animal manure produced in the US (USEPA, 2006)

Year	Manure (10^6 Mg)					Total
	Feedlot beef	Dairy cows	Poultry	Other cattle	Swine	
1982	11.2	29.2	10.5	73.5	7.0	131.4
1987	11.3	27.2	12.5	68.3	6.9	126.2
1992	10.7	25.6	14.0	69.5	7.6	127.4
1997	11.1	24.5	16.3	72.0	8.4	132.3

7. Energy value of biomass

The approximate energy value of biomass is 18.6×10^9 J or 3×10^6 kcal (Stout, 1990; Weisz, 2004). Assuming all crop residue is used for energy production, the total energy value of crop residue is 8.5 EJ for the US and 63.6 EJ for the world (Lal, 2005). This is equivalent to 8% of the current energy needs of the US, and 15% of that of the world. Total biosolids produced as MSW are estimated at 114 million Mg (Table 10) and animal waste at 132 million Mg (Table 11). Together, 246 million Mg of biosolids and animal waste are equivalent to 42 Q of energy. Production of 1 billion Mg of biofuel feedstock would contribute 17 EJ of energy in the US, and 4–5 billion Mg in the world would contribute 67.8–84.8 EJ of energy. As a substitute for fossil fuel, this amount of energy from biofuels would make a significant impact in reducing the net rate of CO_2 emissions into the atmosphere. Therefore, identifying sustainable sources of biofuel feedstock is a high priority.

8. Crop residues and soil quality

Three scenarios of using crop residues for decreasing CO_2 emissions are: sequestration in the ocean, cofiring with coal, and conversion to ethanol. Metzger et al. (2001, 2002) reported that sequestering of biomass carbon in the ocean is more efficient than burning it for generating energy. They argued that the ratio of C emitted per unit of primary energy released through combustion (C:E) favors oceanic sequestration for reasons of chemistry. For the same amount of thermal energy released by combustion, crop residue burning emits twice as much C as burning of natural gas (Metzger et al., 2002). However, adverse ecological impacts of removing crop residue from soil and burying it under the ocean can be drastic and with double jeopardy: adverse impact on soil quality and on marine ecosystems. Therefore, carbon sequestration in soil, rather than in the ocean, is favored for reasons of improving soil quality and achieving sustainable use of natural resources.

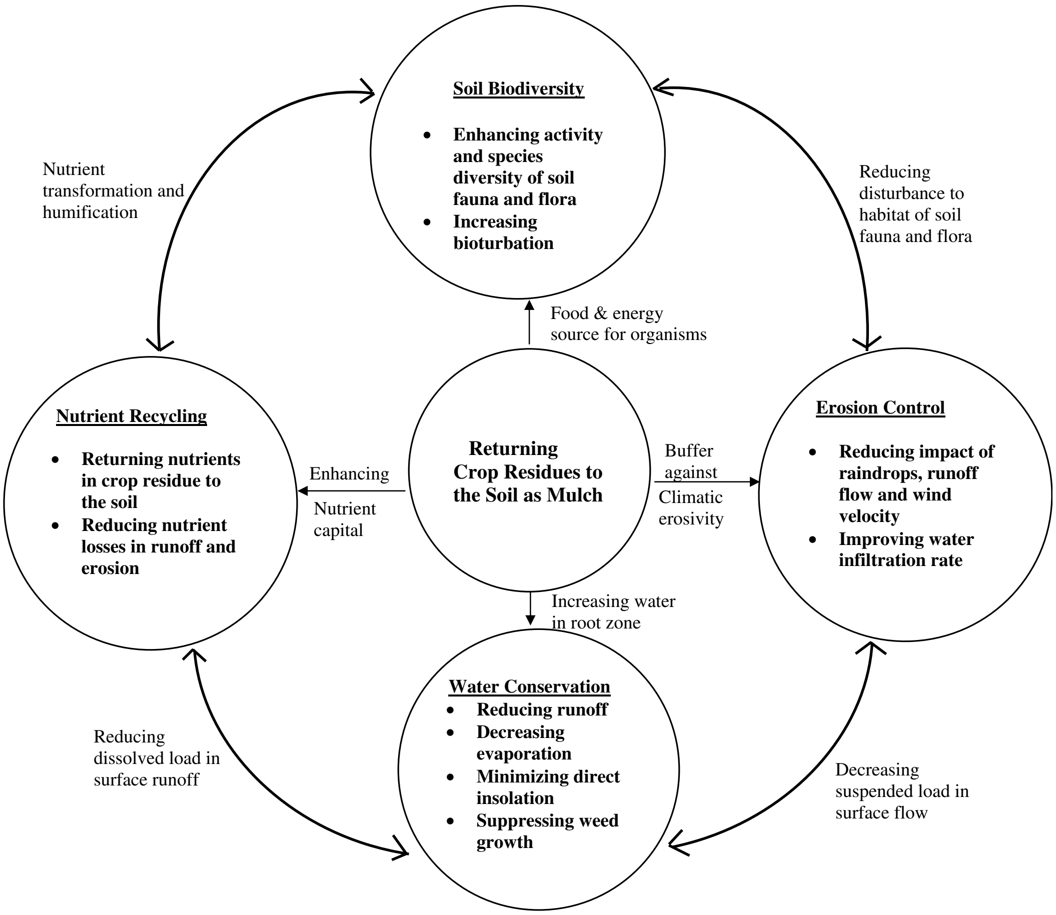

Fig. 2. Returning crop residues as surface mulch has numerous beneficial impacts on soil processes with positive and synergistic impacts.

Rather than burning residues, some argue that cellulosic biomass (e.g., corn stover) should be converted into ethanol. Tally (2002), among others, estimated that about 244 million Mg of corn stover produced annually in the US can be used for ethanol production. Nelson (2002) estimated that 42 million Mg of corn stover and 8 million Mg of wheat straw could be harvested annually from the eastern midwestern US for ethanol production. However, removing crop residues would increase the risks of soil erosion and reduce water storage in the root zone. The economics of stover removal for ethanol must outweigh the direct and ancillary benefits of stover retention.

Returning crop residues to the soil has numerous functions of importance to maintenance of soil quality (Fig. 2). Crop residue retention affects soil structure and water infiltration rate (Carter, 2002; Martens, 2000). Residue removal can exacerbate risks of soil erosion by water and wind. Accelerated soil erosion reduces crop yield and agronomic productivity and decreases use efficiency of inputs (Adams, 1949; Battitson et al., 1987; Fenton et al., 2005). Crop residue mulch, at about 4–6 Mg ha^{-1}, prevents raindrop impact, reduces velocity and shearing strength of flowing runoff and blowing wind and effectively reduces rate and magnitude of accelerated erosion. Several experiments in the US have indicated that removal of residues by more than 20–30% can cause severe erosion by both wind and water (Lindstrom and Holt, 1983; Lindstrom, 1986; McAloon et al., 2000; Nelson, 2002). Decrease in runoff by residue mulching also implies increase in infiltration of water into the soil profile. Further, presence of crop residue mulch on the soil surface decreases soil evaporation. In addition, improvement in soil structure and increase in soil organic carbon (SOC) concentration in the root zone increase plant-available water capacity and decrease intensity and frequency of drought. Residue requirement for erosion control may not be enough for maintaining or enhancing the SOC pool, which is also essential to off-setting CO_2 emission and improving agronomic productivity. If C inputs are limited to unharvestable biomass (e.g., roots and stubbles), the limitation may cause reduction in the SOC pool (Clapp et al., 2000; Wilhelm et al., 2004), with attendant decline in soil quality. Crop residue enhances biodiversity by providing food substrate and habitat for soil organisms (Franzluebbers, 2002). Presence of crop residue mulch has a profoundly positive impact on earthworm activity with an overall increase in bioturbation which improves macro-porosity and increases aggregation. Crop residues contain a large quantity of macro- and micro-nutrients (Burgess et al., 2002; Mubarak et al., 2002). Therefore, retention of crop residue strengthens nutrient recycling and enhances soil fertility (Fig. 2). The severe problems of soil degradation in sub-Saharan Africa and Asia are attributed to systemic removal of crop residue for use as fodder, residential fuel, construction material and other purposes. Indeed, experiments conducted in Ohio (US) have documented strong adverse impacts of removal of crop residue by more than 25% on increase in crusting, decrease in SOC concentration, reduction in soil moisture and infiltration rate, decline in earthworm activity, and decrease in crop growth and yield even 1 yr after removal from plots cultivated by no-till farming for over 40 yr (Blanco-Canqui et al., 2005, 2006a,b, 2007).

Beneficial effects of residue retention on physical, chemical and biological soil quality are not debatable. Rate of improvement in indicators of soil quality (e.g., infiltration rate, SOC concentration, aggregation, nutrient concentration, earthworm activity, microbial biomass C) increases with increase in quantity and quality (C:N, C:P, C:S, C:lignin) of crop residue returned to the soil. The positive effects are especially noteworthy for light-textured soils (clay content <20%) and free internal drainage.

The impact of residue retention on crop yields from season to season is highly variable, and depends on climate, soil properties, management and cropping systems (Wilhelm et al., 2004). In poorly drained soils and sub-optimal springtime temperatures, residue retention can also decrease crop yields by as much as 10–20%. Reduction in crop yields due to residue retention is due to changes in micro-climate, while increase in crop yields with residue retention is due to improvements in soil quality.

In contrast to seasonal variations in crop yields, long-term sustainability of agronomic production depends on soil quality. The latter is strongly influenced by SOC pool and its quality. There is a critical level of SOC concentration in the root zone below which agronomic productivity and use efficiency of input is drastically reduced (Aune and Lal, 1997). The SOC pool of most soils of the tropics and sub-tropics, especially those of sub-Saharan Africa and Asia, is below the critical level and often is as low as 2–5 g kg^{-1}. Thus, restoring the SOC pool of such degraded soils would enhance agronomic production and accentuate use efficiency of fertilizer use, irrigation and other amendments.

The data in Table 12 show that increase in SOC pool in soil of the developing countries by 1 Mg C ha^{-1} yr^{-1}, though residue mulching and/or use of other biosolids, would substantially increase food production even at the same level of input. Estimated annual increase in grain production in developing countries by improvement in soil quality through increase in SOC pool by 1 Mg ha^{-1} yr^{-1} is 24–39 million Mg yr^{-1} (Lal, 2006). In addition, increase in production of roots and tubers is estimated at 7–11 million Mg yr^{-1}. Thus, total increase in food production is estimated at 30–51 million Mg yr^{-1} (Table 12). This increase in food production through restoring the SOC pool is more than enough to meet the food deficit in developing countries, especially of those in sub-Saharan Africa. Thus, crop residue must be used for enhancing soil quality rather than for biofuel or other alternative/competing uses.

Table 12
Estimates of increase in food production in developing countries by increasing SOC pool by 1 Mg C ha^{-1} yr^{-1} [modified from Lal (2006)]

Species	Area (Mha)	Production increase (10^6 Mg yr^{-1})
Cereals	430	21.8–36.3
Legumes	68	2.0–3.2
Tubers	34	6.6–11.3
Total	532	30.4–50.8

Land area for roots and tubers (cassava, yam, sweet potatoes and taro) were taken from FAO (2005). Increase in yield with increase in 1 Mg C ha^{-1} yr^{-1} was assumed at 0.2–0.4 Mg ha^{-1} for cassava, 0.2–0.3 Mg ha^{-1} for sweet potatoes, 0.1–0.2 Mg ha^{-1} for taro and 0.22–0.4 Mg ha^{-1} for yam.

9. Potential grasses as alternative sources of feedstock for biofuel production and soil organic carbon sequestration

Lignocellulosic residues of cereals (e.g., corn, wheat, barley, oats, rice) are needed for enhancing and sustaining soil quality. Excessive (>25%) and continuous (>10 yr) removal can jeopardize soil quality, reduce agronomic productivity, accentuate soil erosion, increase non-point source pollution, and exacerbate the problem of hypoxia in coastal ecosystems. Thus, it is important to identify sources of biomass which can be used as biofuel feedstock without jeopardizing the quality of soil and water resources. The latter include establishing plantations of species with a high biomass productivity established on agriculturally marginal/degraded soils. Such plantations must have low input and maintenance need to be established on land specifically designated for this purpose.

There are numerous plant species with a high biomass productivity (Table 13). Paine et al. (1996) listed a range of environmentally friendly biomass crops which, in addition to producing biomass, have numerous ancillary benefits. Some relevant ancillary benefits are erosion control, water quality improvement, wildlife habitat, and restoration of degraded soils and ecosystems. For the US, Paine et al. (1996) suggested establishment of the following biomass crops on highly erodible land (HEL): switchgrass, big bluestem, and Indian grass. The most desirable plants for drained wetlands are big bluestem, bluejoint grass, and cord grass. Other energy crops for drained wetlands in northern latitudes include bluejoint grass, cord grass, big bluestem, and switchgrass. An important broad leaf for bioenergy production is cup plant (Paine et al., 1996). Some European energy crops are described by Venendaal et al. (1997).

There are several species which can be grown under tropical conditions, and have a high biomass production potential (Table 13). Important among these are guinea grass, elephant grass, molasses grass, andropogan, etc. Some grasses and trees are adapted to salt-affected soils (e.g., *Kallar* grass and mesquite). Identification of such species for specific ecological nitches is a high priority.

Table 13
Common species for biofuel plantations

Type	Name
A. Warm season grasses	Switch grass (*Panicum virgatum* L.)
	Big bluestem (*Andropogan gerardi* Vitman)
	Indian grass (*Sorghastrum nutans*(L) Nas)
	Giant reed (*Arundo donax*)
	Bluejoint grass (*Calamagrostis canadensis* (Michx.) Beau. L.)
	Cord grass (*Spartina pectinata* Link)
	Kallar grass (*Leptochloa fusca*)
	Guinea grass (*Panicum maximum*)
	Setaria (*Setaria sphcelate*)
	Molasses grass (*Melinis minutiflora*)
	Elephant grass (*Pennisetum purpureum*Schm.)
B. Legumes	Alfalfa (*Medicago sativa*)
	Mucana (*Mucuna utilis*)
	Kudzu (*Pueraria phaseoloides*)
	Stylo (*Stylosanthes guianensis*)
C. Broad leaf species	Cup plant (*Silphium perfoliatum* L.)
D. Short rotation woody perennials	Poplar (*Populus* spp.) Willow (*Salix* spp.)
	Black locust (*Robinia pseudoacacia* L.)
	Mesquite (*Prosopis juleflora*)
	Birch (*Onopordum nervosum*)
	Eucalyptus (*Eucalyptus* spp.)
E. Herbaceous spp.	Miscanthus (*Miscanthus* spp.)
	Reed canary grass (*Phalaris arundinacea* L.)
	Cynara (*Cynara cardunculus*)

Global potential of bioenergy, especially with regards to its role in the next few decades, has been described for a range of scenarios by Fischer and Schrattenholzer (2001), Hoogwijk et al. (2005), Pacala and Socolow (2004), and Ericsson and Nilsson (2006). Pacala and Socolow estimated that production of 7.5 million L of ethanol day^{-1} globally would require 250 Mha of land committed to high yield plantations (15 dry Mg ha^{-1} of biomass), such as that of switchgrass. The data in Table 9 also lists some tree species suitable for establishing biofuel plantations. Important among these are mesquite, eucalyptus, poplar, willow, black locust, birch, etc. Similar to establishing biofuel plantations with lingo-cellulosic grasses, identifying land for establishing tree plantations is also important. Pacala and Socolow suggested that the current rate of tropical deforestation should be reduced to zero by 2054. In addition, establishing tree plantations (afforestation) on about 250 Mha in the tropics or on 400 Mha in the temperate zone would be needed to off-set emissions by 1 Pg C yr^{-1}. The current forested land area is estimated at 1500 Mha in the tropics and 700 Mha in the temperate regions (Pacala and Socolow, 2004).

10. Biosaline agriculture and halomorphic

Growing halomorphic plants with irrigation using saline (brackish) water is another important strategy to produce biomass as a potential source of biofuel feedstock. Some halomorphic species can tolerate salt concentrations of 5000–40,000 ppm. Glenn et al. (1993) reported that some halophytes irrigated with sea water can produce a biomass yield of 17–35 Mg ha^{-1} yr^{-1} (Table 14). The biomass returned to the soil in dry environments has a longer residence time because of slow rate of decomposition (Gifford et al., 1992).

Table 14
Some useful halomorphic plants with a high potential to produce biomass by irrigation with brackish/saline water in arid environments [modified from Glenn et al. (1993) and Lal et al. (1999)]

Common name	Scientific name	Salt tolerance (ppm of salts)
Pickle weed	*Salicornia bigelovii*	35,000–40,000
Salt grass (wild wheat)	*Distichlis palmeri*	40,000
Ny Pa forage	*Distichlis* spp.	2000–15,000
Salt brushes	*Atriplex nummularia*	10,000–30,000
	A. halimus	
	A. canescens	
	A. lentiformis	
	A. semibaccata	
	A. glanca	
	A. lineaus	
Other species	*Batis maritime*	10,000–20,000
	Suaeda esteroa	10,000–20,000
	Sesuvium portulacastrum	10,000–30,000
Algae	Spirulina geitleri	High salt conc.

In addition to use as biofuel feedstock, biomass is also useful as high-grade fodder. Some species can produce high-grade oil. Most of these species can also be used to reclaim salt-affected soils. Biosaline agriculture may be a sustainable land use for these harsh ecoregions.

11. Perennial grasses and soil organic carbon pool

Switchgrass is an important crop for producing bioenergy. It is a native warm season grass of the North American tall grass prairie (Sims and Risser, 2000); but can be grown across a wide geographical range. In addition to producing a large quantity of above ground biomass needed as bioenergy feedstock (3–35 Mg ha^{-1} of dry matter), switchgrass also produces a large amount of root biomass (1–12 Mg ha^{-1}) which strongly influences the SOC pool. Above ground biomass yield is in the range of 17–35 Mg ha^{-1} in the southeastern US (Bransby and Sladden, 1991), 8–10 Mg ha^{-1} in Texas (Sanderson et al., 1999), 11–13 Mg ha^{-1} in the western corn belt (Vogel et al., 2002) and 3–10 Mg ha^{-1} in North Dakota (Liebig et al., 2005). McLaughlin and Kszos (2005) reported sustained root mass in the upper 90 cm depth of eight field plots in the mid-Atlantic region to average 16 Mg ha^{-1}, which was comparable to annual above ground biomass production. These researchers observed that soils under switchgrass gained 1.2–1.6 Mg C ha^{-1} yr^{-1} in the upper 30 cm over a 6-yr study interval. A modeling study predicted that the annual SOC sequestration rates ranged from 1.4 Mg C ha^{-1} yr^{-1} over 10 yr in degraded soils in warmer climates, with an average rate of 0.78 Mg C ha^{-1} yr^{-1} across diverse regions in the eastern US. The average sequestration rate was 0.53 Mg C ha^{-1} yr^{-1} over the 30 yr simulation period with a total capacity limit of surface layer at 80 Mg ha^{-1} (McLaughlin et al., 2002). The land area planted to switchgrass is estimated to be 3.1 Mha for the farmgate price (US dollars) of \$30.3 Mg^{-1}, 16.8 Mha for \$44 Mg^{-1}, and 21.3 Mha for \$52.4 ha^{-1}. With a yield of 11.4, 9.4 and 9 Mg ha^{-1}, these farmgate prices would increase farm revenue by \$150 million, \$2272 million and 4437 million, respectively (McLaughlin et al., 2002).

Liebig et al. (2005) assessed the SOC pool under switchgrass and nearby cultivated cropland on 42 paired switchgrass/cropland sites in northern Great plains and northern corn belt in Minnesota, North Dakota and South Dakota (US). They observed the total SOC pool to 120 cm depth was 192 Mg ha^{-1} under switchgrass compared with 174 Mg ha^{-1} under cropland soils. Differences in SOC pool between switchgrass stands and croplands were significant in sub-soil (7.74 Mg ha^{-1} for 30–60 cm and 4.35 Mg ha^{-1} for 60–90 cm depth) due to greater root mass below 30 cm depth in switchgrass (Liebig et al., 2005). Over the 120 cm soil depth, the SOC pool under switchgrass exceeded that under cropland on an average of 15.3 Mg C ha^{-1}). Liebig and colleagues also observed gains in soil inorganic carbon (SIC) under switchgrass. In comparison with cropland, SIC increased under switchgrass in all sampled depths.

12. Impact on the global carbon cycle

Global production of 4–5 billion Mg of biofuel feedstock can strongly influence the global C cycle. However, these targets can only be met through integrating biofuel plantations with food production systems (Fig. 3). When established on degraded soils and ecosystems, biofuel plantations can improve the environment by increasing canopy/ground cover, providing habitat and improving biodiversity, decreasing risks of soil erosion, improving recharge of the aquifer, reducing non-point source pollution, and increasing the terrestrial C storage by enhancing the SOC and biotic pools. In addition to providing 67.8–84.8 EJ energy annually, the biomass thus produced will off-set or decrease anthropogenic emissions by 1.5–2 Pg C yr^{-1} (assuming biomass C concentration of 40%). When combined with other possibilities proposed by Pacala and Socolow (2004) of off-setting 1 Pg C yr^{-1} by no-till farming and another 1 Pg C yr^{-1} by afforestation, total potential of C off-set is 3.5–4 Pg C yr^{-1}. Being a natural process, the strategy of establishing biofuel plantations is a truly win–win option.

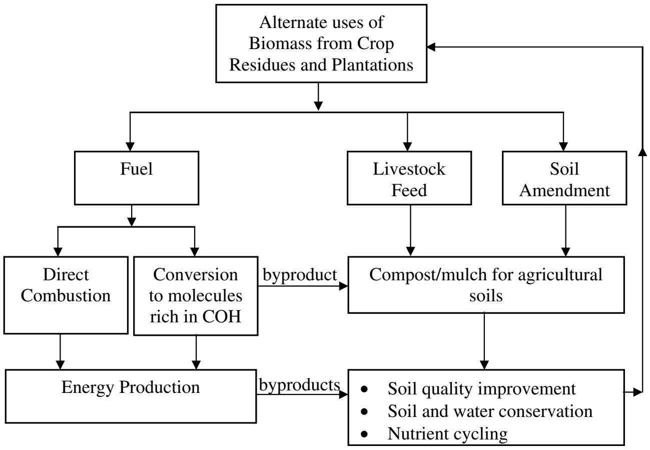

Fig. 3. Integrated biofuel and food production systems.

13. Conclusions

Biofuel production is an important strategy to meet global energy demands while reducing net emissions of CO_2. However, removal of crop residues is not a sustainable option for biofuel production. Retention of crop residues is essential for maintaining soil quality and reducing soil erosion risks. While adverse impacts of residue removal on soil quality are evident even during the first year on coarse-textured soils on sloping lands, it may take 10–20 years for drastic impact on heavy-textured soils on flat terrains. Adverse impacts on crop yields may also not be apparent in poorly drained soils in northern latitudes where soil temperatures are sub-optimal during spring. Additional crop residues (through incorporation of cover crops in the rotation cycle) and biosolids (compost, animal manure, sludge) are often needed to increase the soil carbon pool, enhance soil quality and improve productivity on soils prone to erosion and other degradative processes. Yet, biofuels are an important component of the overall strategy of finding viable alternatives to fossil fuel at national and international levels. Thus, biofuel feedstock must be produced through biofuel plantations and using other biosolids (e.g., animal waste, food industry waste, municipal solid waste). Thus, biofuel feedstock must be produced through establishing biofuel plantations. The latter may include grasses (e.g., switchgrass) and short rotation woody perennials. Such plantations can be established on agriculturally marginal/surplus lands, degraded soils (e.g., eroded, salinized) or disturbed lands (e.g., mined soil). Identification of such lands, selection of species adapted to these lands, and choice of management practices which increase biomass production per unit area, time, and input are priority considerations. Ethanol production plants must be strategically located in the vicinity of the land areas specifically identified for establishing biofuel plantations. Halophytes with high biomass production capacity can be grown in arid climates. Using these diverse sources of biofuel feedstock can strongly impact the global C cycle and reduce net emission of CO_2 into the atmosphere while meeting the global energy demands.

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