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World crop residues production and implications of its use as a biofuel

R. Lal*

Carbon Management and Sequestration Center, The Ohio State University, Columbus, OH 43210, United States

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Abstract

Reducing and off-setting anthropogenic emissions of CO_2 and other greenhouse gases (GHGs) are important strategies of mitigating the greenhouse effect. Thus, the need for developing carbon (C) neutral and renewable sources of energy is more than ever before. Use of crop residue as a possible source of feedstock for bioenergy production must be critically and objectively assessed because of its positive impact on soil C sequestration, soil quality maintenance and ecosystem functions. The amount of crop residue produced in the US is estimated at 367×10^6 Mg/year for 9 cereal crops, 450×10^6 Mg/year for 14 cereals and legumes, and 488×10^6 Mg/year for 21 crops. The amount of crop residue produced in the world is estimated at 2802×10^6 Mg/year for cereal crops, 3107×10^6 Mg/year for 17 cereals and legumes, and 3758×10^6 Mg/year for 27 food crops. The fuel value of the total annual residue produced is estimated at 1.5×10^{15} kcal, about 1 billion barrels (bbl) of diesel equivalent, or about 8 quads for the US; and 11.3×10^{15} kcal, about 7.5 billion bbl of diesel or 60 quads for the world. However, even a partial removal (30–40%) of crop residue from land can exacerbate soil erosion hazard, deplete the SOC pool, accentuate emission of CO_2 and other GHGs from soil to the atmosphere, and exacerbate the risks of global climate change. Therefore, establishing bioenergy plantations of site-specific species with potential of producing 10–15 Mg biomass/year is an option that needs to be considered. This option will require 40–60 million hectares of land in the US and about 250 million hectares worldwide to establish bioenergy plantations.

Keywords: Biofuel; Bioenergy; Residue management; Soil carbon; Global warming

1. Introduction

Progressive increase in atmospheric concentrations of CO_2 and other greenhouse gases (GHGs) since the onset of settled agriculture 10,000 years ago (Ruddiman, 2003) and with the Industrial Revolution since about 1850 has created worldwide interest in identifying strategies of reducing the rate of gaseous emissions (IPCC, 2000). Depending on the land use and management options, agriculture can be a source or sink for atmospheric CO_2. Agricultural practices with impact on atmospheric chemistry include production and management of crop residue, tillage systems, soil fertility and pest management, and supplemental irrigation. With the impending threat of climate change, there is a strong need for a critical appraisal of land use and soil management practices, including crop residue production and management in conjunction with the appropriate tillage methods, nutrient and pest management, water conservation and supplemental irrigation.

An interest in contribution of biomass to the energy supply received considerable attention during the 1970s because of the urgency of achieving energy self-sufficiency (Larson, 1979; Lindstrom et al., 1981; Larson et al., 1982). There has been renewed interest in biomass energy since the mid-1990s because of the quest for mitigating global climate change (Berndes et al., 2003). In 1999, President Clinton called for the USA to increase annual energy production from renewable resources to 6 quads (1 quad=10^{15} BTU) by 2030 (Federal Register, 1999). In 2003, President Bush set a national goal to reduce the greenhouse gas intensity of the US economy by 18% by 2012 (U.S. Dept. of State, 2003). The greenhouse gas

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* Tel.: +1 614 292 9069; fax: +1 614 292 7432.
E-mail address: lal.1@osu.edu.

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intensity is defined as the ratio of greenhouse gases emitted (carbon equivalent) per real gross domestic product. This commitment will achieve about 100 Tg (1 Tg=teragram=1 million Mg) of reduced emissions by 2012, with more than 500 Tg of cumulative savings over the decade (The White House, 2002). The strategy of using biomass as a feedstock for producing biofuel has important implications to realizing these goals. The biomass has the potential to become a major energy source because of its impact on offsetting fossil fuel emissions. Crop residues have a heating value of about 3×10^6 kcal/Mg, about 50% of that of coal and 33% of that of diesel (Larson, 1979). The fuel value of 1 Mg of crop residue is estimated at 18.6×10^9 J, 2 barrels (bbl) of diesel, 3×10^6 kcal or 16×10^6 BTU (Lal, 1995).

Not all the residue produced, however, can be or should be used for bioenergy production. Indiscriminate removal of residue can lead to decline in soil quality with long-lasting adverse impacts on the environment. Returning crop residue improves soil quality through its impact on reducing risks of soil erosion, storing/recycling nutrients, stabilizing soil structure and improving tilth, reducing soil bulk density, improving water retention and transmission properties, providing energy for microbial processes, increasing cation exchange capacity and enhancing agronomic productivity.

Biomass is defined as “all renewable organic matter including plant material, whether grown on land or water; animal products and manure; food processing and forestry by-products; and urban wastes” (Stout, 1984). There are several possible sources of procuring biomass for energy (Fig. 1). It can be procured either by establishing plantations of bioenergy crops including short rotation woody perennials or by removing residue from cropland. Despite numerous sources, there are competing demands on the land resources for biomass production, and for the alternative uses of biomass. For example, the land may be used for agriculture, forestry, recreation, industrial and urban purposes. Similarly, biomass may be used as fodder, fibre, industrial raw material or a soil amendment (Fig. 2). Indeed, biomass is a precious and a limited resource, and has multi-facet uses.

This manuscript provides estimates of crop residue production in the U.S. and the world, assesses the feasibility of using crop residue for bioenergy, evaluates the impact of residue management on soil carbon (C) sequestration to mitigate climate change, and explores the possibility of establishing bioenergy plantations for producing feedstocks for biofuels. The objective is not to collate an exhaustive literature, but to estimate the potential of fossil fuel off-set

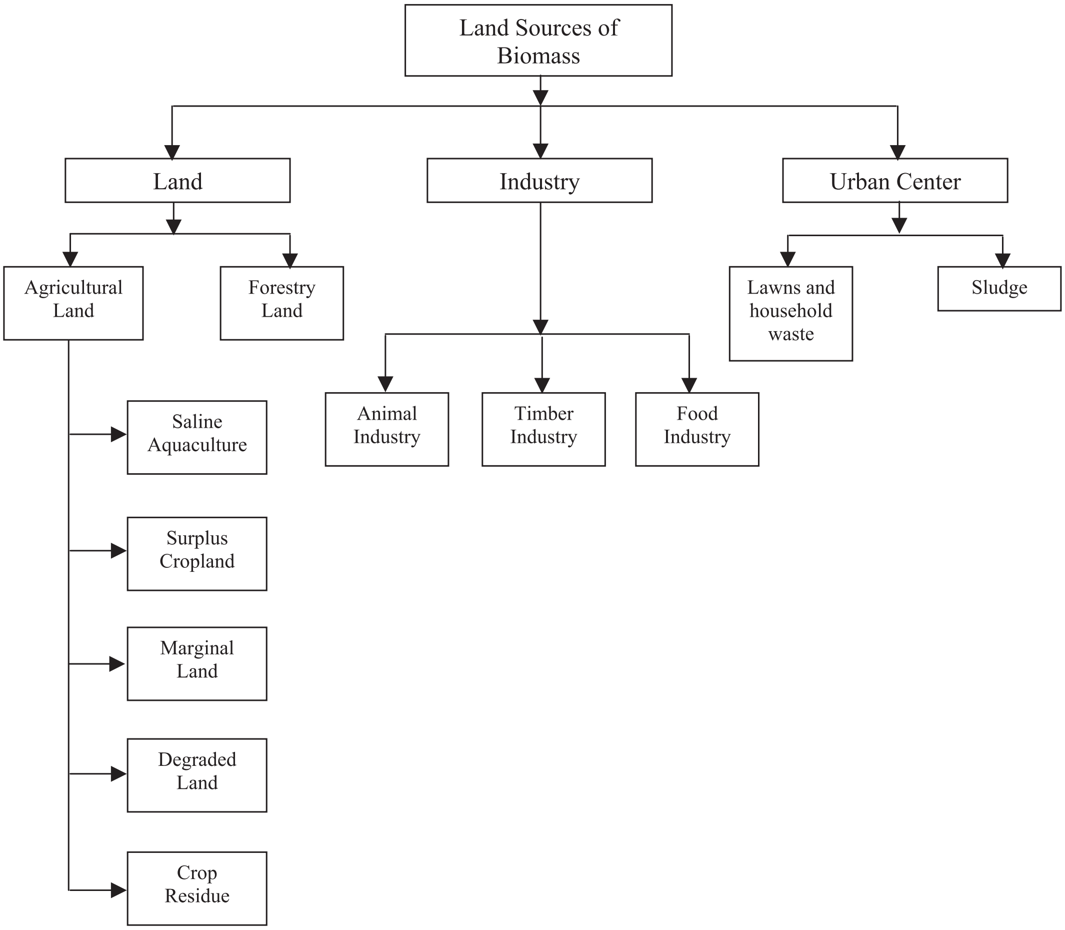

Fig. 1. Land sources of biomass for bioenergy.

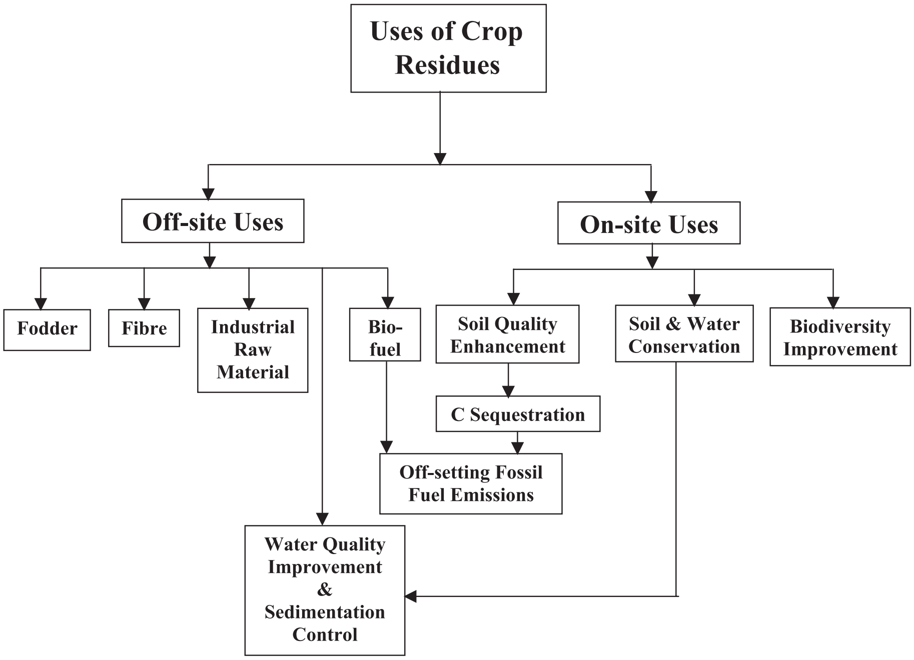

Fig. 2. Alternative and competing uses of crop residues.

by using crop residue for biofuel versus soil C sequestration, and explores an alternative of establishing bioenergy plantations.

2. Crop residue

Crop residue is defined as the non-edible plant parts that are left in the field after harvest. Some researchers also include remains that are generated from crop-packing plants or that are discarded during crop processing into the generic category of crop residue (Ernest and Buffington, 1981). Approximate amount of crop residue produced by different crops differs widely (Table 1). Crop residues also vary widely in properties and decomposition rates. Rather than direct measurement, estimates of crop residue production are made on the basis of data on the area and production of different crops, and research information on the straw/grain ratio (Eq. (1)).

Table 1
Estimate of the amount of crop residue produced by different crops in the US (adapted from Wolf et al., 1980; Wolf and Snyder, 2003)

Crop	Residue amount on dry weight basis (Mg/ha/crop)
Barley (*Hordeum vulgare*)	4.3
Corn (*Zea mays*)	10.1
Cotton (*Gossypium hirsutum*)	6.7
Oats (*Avena sativa*)	5.6
Peanuts (*Arachishypogea*)	5.6
Rice (*Oryza sativa*)	6.7
Sorghum (*Sorghum bicolor*)	8.4
Tobacco (*Nicotiana tabacum*)	4.0
Tomatoes (*Lycopersicon esculentum*)	5.0
Sugarbeet (*Beta vulgaris*)	5.6
Wheat (*Triticum aestivum*)	5.0

$$\text{residue production} = \text{grain production} \times \text{straw/grain ratio} \quad (1)$$

The straw/grain ratios commonly used for different crops are shown in Table 2.

As a renewable resource, a large quantity of residue is produced annually by a wide range of crops grown in the US. Accordingly, there exists a wide range of estimates of crop residue produced in the US (Lipinsky et al., 1983; Miller and Eisenhauer, 1983). Estimates of crop residue produced in 48 contiguous states of USA range from 95×10^6 to 454×10^6 Mg/year (Day, 1989). The major reasons for the variability in estimates are using different combinations of crops and using different grain/straw ratios. Some agronomists/economists argue that relevant crops for estimating residue production include only corn (*Zea mays*), small grains, sorghum (*Sorghum bicolor*), rice (*Oryza sativa*) and sugarcane (*Saccharum officinarum*). It is argued that soybean (*Glycine max*) and cotton (*Gossipium hirsutum*) residues are not collectable because either not enough of these remain in the field (e.g., cotton) or that which remain decompose rapidly (e.g., soybean). Estimates of crop residue production in the US include 363×10^6 Mg/year of nine leading crops by Larson et al. (1978), 390×10^6 Mg/year in the continental US by USDA (1978), 413×10^6 Mg/year by Day (1989) and 422×10^6 Mg/year (including 101×10^6 Mg from legumes and 10×10^6 Mg from other

Table 2
Dry weight ratio of straw to grain for different crops

Crop	Range of straw/grain ratio		
	(Stout, 1990; Larson et al., 1982)	Gupta et al. (1979)	Lal (1995)
Barley (*Hondeum vulgare* L.)	0.82–2.50	1.5	1.5
Corn (*Zea may* L.)	0.55–1.50	1.0	1.0
Cotton (*Gossypium hirsutum* L.)	1.4–3.0	1.0	1.5
Legumes	1.2–1.5	1.0	1.0
Oats (*Avena sativa*)	0.95–1.75	2.0	1.0
Potato (*Solanum tuberosum*)	0.2–0.3	–	0.25
Rapeseed (*Brassica campestris*)	1.25–2.0	–	1.5
Rice (*Oryza sativa* L.)	0.75–2.5	1.5	1.5
Rye (*Secale cereale* L.)	1.20–1.75	1.5	1.5
Sorghum (*Sorghum bicolor* L.)	0.85–2.0	1.0	1.5
Soybeans (*Glycine* max L.)	0.8–2.6	1.5	1.0
Sugarbeet (*Beta vulgaris*)	0.2–0.25	–	0.25
Sugarcane (*Saccharum officinarum*)	0.2–0.25	–	0.25
Wheat (*Triticum aestivum*)	1.10–2.57	1.3–1.7	1.5

crops) by Schomberg et al. (1994) (Table 3). Lal (1995) estimated that 400×10^6 Mg of crop residue was produced annually during the early 1990s by 18 crops comprising of cereals, legumes and oil crops grown on 95 Mha of cropland. Using a 1:1 ratio of dry matter of corn grain to residue, Sokhansanj et al. (2002) estimated that more than 216×10^6 Mg of corn residue (stover) are produced annually in the USA. Corn grain production for 2001 in the USA was estimated at 254×10^6 Mg at 15% moisture content (USDA/NASS, 2001).

Table 3
Estimate of crop residues produced in the US in 1992 (adapted from Schomberg et al., 1994)

Crop	Area harvested (Mha)	Residues produced (10^6 Mg)
I. Cereals		
Barley	3.1	9.5
Corn	23.6	187.8
Oats	2.2	4.7
Rice	1.2	10.9
Rye	0.2	0.6
Sorghum	4.1	23.5
Wheat	21.5	74.0
Total	55.9	311.0
II. Legumes		
Ground nuts	0.7	2.5
Soybeans	23.2	98.4
Total	23.9	100.9
III. Oil crops		
Sunflower	0.8	1.9
IV. Fiber		
Cotton	4.8	5.0
V. Sugar		
Beets	0.5	2.8
Grand total	85.9	421.6

Sunflower (*Helianthus annuus*).

3. Estimates of crop residue production in the US and the world

The data in Table 4 show annual residue production of 367×10^6 Mg of nine cereal crops, 82×10^6 Mg of five legumes, 20×10^6 Mg of five oil seeds and 5×10^6 Mg of two tuberous crops. The total crop residue production in the US are estimated at 488×10^6 Mg/year of which 75% are of cereal crops including 49% of corn and an additional 16% of

Table 4
US grain and crop residue production in 1991 and 2001 (area and grain production are calculated from FAO, 1991, 2001)

Crop	Area (Mha)		Production (10^6 Mg)		Residue production (10^6 Mg)	
	1991	2001	1991	2001	1991	2001
Cereals						
Barley	3.4	1.7	10.0	5.4	15.0	8.1
Corn	28.0	27.8	190.0	241.5	190.0	241.5
Millet	0.1	0.24	0.2	0.44	0.3	0.66
Oats	2.0	0.8	4.0	1.7	4.0	1.7
Rice	1.1	1.3	7.0	9.7	11.0	14.6
Rye	0.2	0.1	0.2	0.2	0.3	0.3
Sorghum	4.0	3.5	15.0	13.1	23.0	19.7
Wheat	23.0	19.7	54.0	53.3	81.0	80.0
Others	0.2	0.2	0.6	0.2	0.6	0.2
Total	62.0	55.3	281.0	325.5	325.2	366.8
Legumes						
Beans	0.8	0.5	1.5	0.9	1.5	0.9
Groundnut	0.8	0.6	2.2	1.9	2.2	1.9
Lentils	0.05	0.08	0.08	0.1	0.1	0.1
Peas	0.08	0.08	0.2	0.2	0.2	0.2
Soybean	23.0	29.5	54.0	78.7	54.0	78.7
Total	25.0	30.8	58.0	81.8	58.0	81.8
Oil crops						
Linseed	0.1	0.2	0.2	0.3	0.2	0.3
Rapeseed	0.06	0.6	0.09	0.9	0.2	1.4
Safflower	0.1	0.07	0.2	0.1	0.2	0.1
Seed cotton	6.1	5.6	10.0	11.2	15.0	16.8
Sunflower	1.1	1.0	1.6	1.6	1.6	1.6
Total	7.5	7.5	12.0	14.1	17.1	20.2
Sugar crop						
Sugarbeet	0.56	0.50	25.6	23.4	6.4	5.9
Sugarcane	0.36	0.4	75.6	31.6	18.9	7.9
Total	0.9	0.9	101.2	55.0	25.3	13.8
Tubers						
Potato	0.56	0.50	18.9	20.2	4.7	5.1
Sweet potato	0.03	0.04	0.5	0.07	0.10	0.16
Total	0.6	0.54	19.4	20.3	4.8	5.3
Grand total	96.0	95.4	471.6	542.0	430.4	487.9

Lentils (*Lens culiniaris*), peas (*Pisum sativum*), rapeseed (*Brassica campestris*), potato (*Solanum tuberosum*), sweet potato (*Ipomea batata*), safflower (*Carthamus tinatorius*).

wheat (Table 4). Four cereals (e.g., corn, wheat, rice and sorghum) produce 356×10^6 Mg or 73% of the total crop residue produced in the US (Table 4).

The data on estimates of residue production in the world are shown in Table 5. The annual residue production is estimated at 2.8 billion Mg of cereals, 305 million Mg of legumes, 108 million Mg of oil crops, 373 million Mg of sugar crops and 170 million Mg of tubers. The total crop residue production in the world is estimated at 3.8 billion Mg, of which 74% are of cereals, 8% of legumes, 3% of oil crops, 10% of sugar crops and 5% of tubers (Table 5). The most useable crop residue, however, is that of cereals. Of the world total residue produced, about 13% is produced in the US.

Table 5
The world grain, tuber and crop residue production in 1991 and 2001 (area and grain production are calculated from FAO, 1991, 2001)

Crop	Area (Mha)		Production (10^6 Mg)		Residue production (10^6 Mg)	
	1991	2001	1991	2001	1991	2001
Cereals						
Barley	76	54	169	141	254	212
Corn	129	138	479	609	479	609
Millet	37	37	29	29	44	44
Oats	21	13	34	27	34	27
Rice	148	152	520	593	780	890
Rye	14	10	27	23	41	35
Sorghum	45	43	58	58	87	87
Wheat	224	214	551	583	826	875
Others	10	10	18	23	18	23
Total	704	671	1885	2086	2563	2802
Legumes						
Beans	26	23	18	17	18	17
Broad beans	3	2	5	4	5	4
Chick peas	8	9	11	6	11	6
Groundnut	20	26	23	35	23	35
Lentils	3	4	2	3	2	3
Peas	9	6	16	11	16	11
Pulses	70	66	60	52	60	52
Soybeans	55	76	103	177	103	177
Total	194	212	238	305	238	305
Oil crops						
Linseed	4	3	3	2	3	2
Rapeseed	20	24	27	36	41	54
Safflower	1	1	1	0.6	1	1
Seed cotton	38	16	60	16	90	24
Sesame	7	8	2	3	4	6
Sunflower	17	18	23	21	23	21
Total	87	70	116	79	162	108
Sugar crop						
Sugarbeet	9	6	303	234	76	59
Sugarcane	17	19	1054	1255	264	314
Total	26	25	1357	1489	340	373
Tubers	279	322	187	234	47	59
Potato	177	193	266	308	67	77
Sweet potato	9	9	124	135	31	34
Total	465	524	577	677	145	170
Grand total	1476	1502	4173	4636	3448	3758

Millet (*Pennisetum americanum*), sesame (*Sesamum indicum*), chick peas (*Cicer arietinum*), broad beans (*Vicia faba*).

Table 6
Energy value of crop residues produced in the US and the world

Parameter	USA	World
Total crop residue (10^6 Mg/year)	488	3758
Oil equivalent (10^6 barrels)	976	7560
Energy equivalent:		
Exajoules (10^{18} J)	9.1	69.9
Quads	8.0	60.0
10^{15} kcal	1.5	11.3

4. Biomass as energy source

Agriculture is a source of energy through its production of biomass, which can be used as biofuel and is a renewable resource. The energy content of residue varies among crop species. For example, the energy content is 3015 kcal/kg for rice straw and 3738 kcal/kg for hay (Stout, 1990). The approximate fuel value per Mg of crop residue is 16×10^6 BTU (Weisz, 2004), or 2 barrels of diesel, 18.6×10^9 J or 3×10^6 kcal. Based on these approximations, estimates of the energy value of total crop residue produced in the world are shown in Table 6. The energy value of crop residue produced in the US is 976×10^6 barrels of diesel or 9.1×10^{18} J of energy. The corresponding values for the world are 7516×10^6 barrels of diesel or 69.9×10^{18} J of energy.

Energy production is among numerous and competing alternative uses of crop residue (Fig. 2). Biomass is widely used as household fuel in developing countries. The share of global biomass energy consumption varies widely, with 47% in Asia, 25% in Africa, 19% in Latin America, 5% in North America, 3% in Europe and 1% in Oceania (Lansink et al., 2002). Goldenberg (2003) estimated that out of the total energy use of 3.9×10^9 toe (total oil equivalent) by developing countries, 22% came from the biomass. In contrast, out of the total energy use of 6.7×10^9 toe worldwide, only 4% came from biomass. In addition to the high cost of conventional energy sources, the Kyoto Protocol and its several clauses (e.g., The Clean Development Mechanism, The Joint Implementation) provide a renewed interest in using biofuel to off-set fossil fuel combustion (Woods and Hall, 1994). Fuel efficiency in terms of the C emission can be calculated as the CO_2 emission factor (Eq. (2)) (European Commission, 1997).

$$\mathrm{EM} = C \times M_{\mathrm{CO_2}} \times \frac{10}{B_{\mathrm{t}} \times M_{\mathrm{c}}} \qquad (2)$$

where EM is the emission factor, C is % carbon in fuel, $M_{\mathrm{CO_2}}$ is molecular weight of CO_2 (44 g/mol), B_{t} is the lower combustion value for fuel and M_{c} is the molecular weight of C (12 g/mol). The CO_2 emission factor is 0 for biofuels, 57 kg $CO_2/10^9$ J for natural gas and synthetic fertilizers, 74 kg $CO_2/10^9$ J diesel oil and concentrates and 95 kg $CO_2/10^9$ J for coal, machinery and electricity.

5. Crop residue in relation to soil and environmental quality

Principal benefits of retaining crop residue include soil erosion control, maintenance of soil structure, moderation of soil moisture and temperature regimes, energy source for soil biota and maintenance of soil organic matter (SOM) content. Several studies have been conducted to assess the amount of crop residue required to control soil erosion. The residue requirement for soil erosion control depends upon soil erodibility (Lindstrom and Holt, 1983; Lindstrom, 1986), rainfall erosivity, terrain characteristics, land use, farming system, tillage methods and other soil/crop management practices. Some studies have reported that 20–40% of the corn residue produced in the US Corn Belt can be removed for biofuel (ethanol) production, if soil erosion control is the only objective of residue retention (Nelson, 2002; McAloon et al., 2000; Kim and Dale, 2004). Sheehan et al. (2004) concluded that in Iowa, USA, 40% of the residue can be collected under continuous corn production and mulch till, compared with 70% under no-till while keeping erosion risks below the tolerable limit.

However, enhancing and maintaining soil quality are among the principal reasons for residue retention on the soil surface. Further, providing adequate ground cover for achieving a satisfactory level of erosion control is not sufficient to enhance or maintain a desirable level of SOM. Removal of crop residue, even that in excess of effective erosion control below the tolerable limit, can lead to decline in SOM content (Buyanovsky and Wagner, 1997; Clapp et al., 2000; Wilhelm et al., 2004). In addition to the C, crop residue is also a source of macronutrients (N, P, K) and micronutrients (S, Cu, B, Zn, Mo) needed for crop growth and humification of residue (Green et al., 1995; Burgess et al., 2002; NREL, 2003; Mubarak et al., 2002). Decline in SOM content is exacerbated by reduction in soil aggregation and the overall decline in soil structure (Tisdall and Oades, 1982; Hudson, 1994; Carter, 2002). Crop residue is also an essential source of energy for all microbial processes in soil (Franzluebbers, 2002), which are essential to both formation and stabilization of aggregates and recycling of nutrients.

Crop residue and SOM are principal components of the global C cycle and directly impact upon atmospheric concentration of CO_2. Conversion of natural to agricultural ecosystems, along with the attendant biomass burning and follow up soil cultivation leading to erosion, causes depletion of the SOM pool. The resultant increase in mineralization leads to emission of CO_2 into the atmosphere. Thus, a large amount of the relic C in SOM has been released into the atmosphere since the dawn of settled agriculture some 10,000 years ago (Ruddiman, 2003). With restoration of degraded soils and ecosystems and adoption of RMPs, a large portion of the depleted SOM pool can be recovered in agricultural and forest soils. The sink capacity of the world soils has a potential to sequester 0.6–1.2 Pg C/year (Lal, 2004). In addition to mitigating atmospheric enrichment of CO_2 and reversing soil degradation trends, there are several important ancillary benefits of C sequestration in SOM including reduction in erosion and sedimentation, decline in non-point source pollution, increase in soil biodiversity, improvement in biomass productivity and sustainability of agricultural systems.

Within limits, which vary with soil type and crop species, there exists a direct relationship between SOM pool and agronomic productivity (Mann et al., 2002; Lal, 2004). Such a positive relationship exists because of the beneficial impact of SOM on soil structure and aggregate stability (Six et al., 1999), soil tilth (Carter, 2002), soil moisture retention (Wilhelm et al., 1986) and microbial processes (Franzluebbers, 2002). Improvement in plant available water capacity with increase in SOM content is an important factor affecting crop yields (Hudson, 1994; Haynes and Beare, 1996; Emerson, 1995) and sustainability (Lal, 2004). All other factors remaining the same, the SOM content is directly related to the amount of crop residue returned to the soil (Barber, 1979; Larson et al., 1972; Parton and Rasmusseu, 1994; Follett, 2001; Carter, 2002). Therefore, removal of the crop residue may lead to decline in soil quality and reduction in agronomic productivity.

Several studies have documented the magnitude of yield decline with continuous removal of crop residue. In Nebraska, USA, Wilhelm et al. (1986) reported that for each Mg of corn residue removed, grain yield of the following crop was reduced by 0.13 Mg/ha/year. Effects of variable rates of residue return on crop yields were also reported by Maskina et al. (1983), Power et al. (1998) and Linden et al. (2000). The magnitude of the effect, however, may vary among tillage methods.

6. Crop residue and energy needs

The debate on exhaustion of global oil reserves was intensified by yet another surge in gas prices in the US during 2004. Even if the proven reserves of fossil fuel are abundant (Maugeri, 2004), the need to find alternatives to fossil fuel is more than amply justified. While crop residue and animal wastes have been used as a source of fuel ever since the use of fire by humans some 800,000 years ago (Goren-Inbar et al., 2004), the residue must be used judiciously to enhance ecosystem functions. Biomass burning can be environmentally hazardous as has been the case for its use as direct fuel for household cooking in South Asia (Ramanathan et al., 2001). Nonetheless, the use of crop residue for production of ethanol and other clean biofuel must be assessed objectively.

Modern agriculture, as practiced in the US Corn Belt, can produce 10 Mg/ha of crop residue per annum. The biofuel energy of residue is 16×10^6 BTU/Mg. Total amount of usable residue of cereal produced in the US is about 300 million Mg (Table 3). Therefore, the maximum biofuel energy that can be produced from the residue of cereals in the US is 5×10^{15} BTU or 5 quads/year. The net energy produced, assuming 60% efficiency, is 3 quads. If 30% of the residue is removed (Nelson, 2002), a maximum of 1 quad/year can be generated from crop residue. Biomass energy comprised 13% of the 12% of the renewable energy produced in the US during 1997 (Brown, 1999). This is about 1% of the total energy use of 100 quads/year in the US. For a maximum of 1% contribution to off-set the fossil fuel emissions, the economics and environmental consequences of ethanol production from crop residue need to be carefully addressed. Pimentel (2003) argued that about 29% more energy is used to produce a gallon of ethanol than the energy in the gallon of ethanol. In contrast, enhancing energy use efficiency can save about 32 quads of energy (Pimentel et al., 2004) compared to 1 quad of saving by using crop residue.

Removal of residue from agricultural lands can set-in-motion soil and environmental degradation trends with adverse impacts on quality and sustainable use of natural resources (Fig. 3). The adverse impacts of removing crop residue can be short-term and long-term, and both direct and indirect. The long-term impact on SOC pool and soil quality cannot be ignored. Removal of crop residue can reduce SOC pool (Balesdent and Balabane, 1992; Allmaras et al., 2004; Wilts et al., 2004) and make soil as a major source rather than a sink of atmospheric CO_2. The depletion of SOC pool can be exacerbated by soil erosion. Even if residue removal by 40% from conventional till and 70% from no-till can reduce soil erosion to tolerance level (Sheehan et al., 2004), soil erosion at the rate of 11.2 Mg/ha/year is too serious to ignore in terms of the off-site and on-site effects. A critical level of

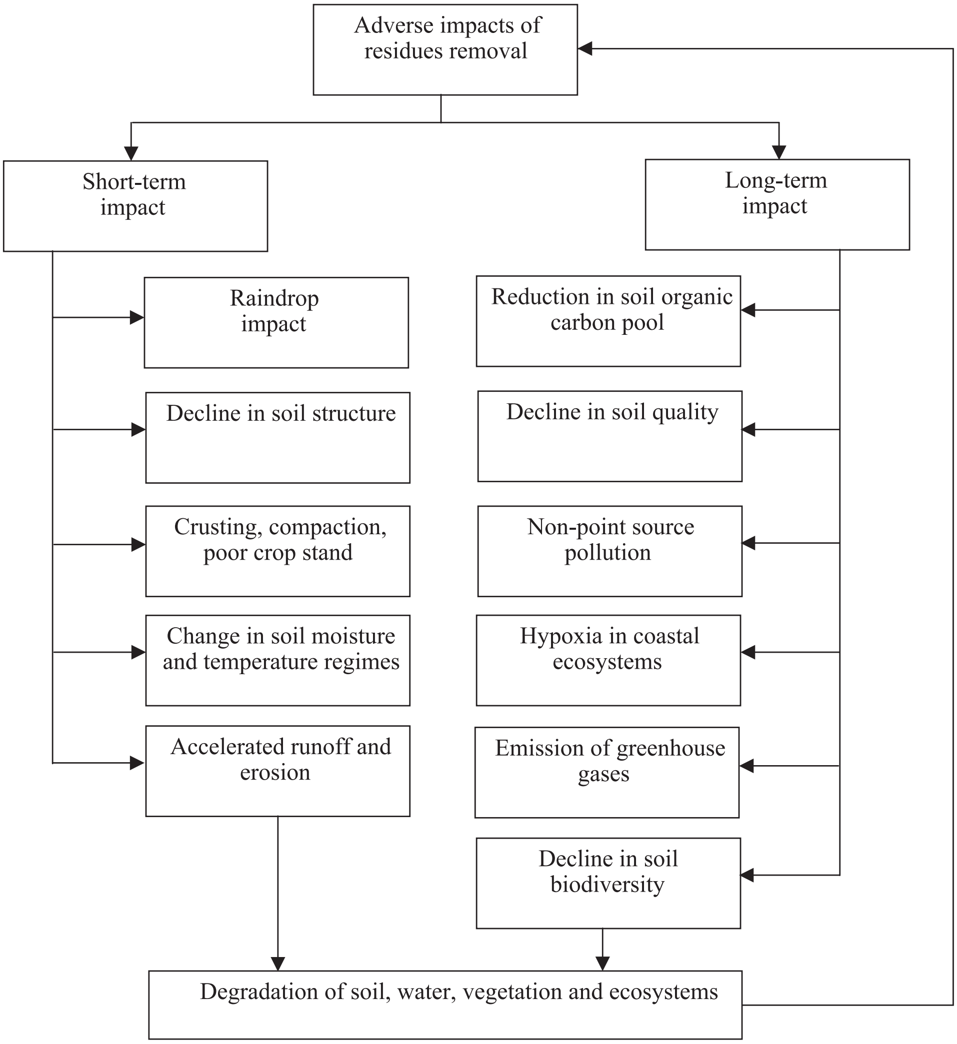

Fig. 3. Short-term and long-term adverse effects of removal of crop residues for biofuel and other purposes.

SOC concentration (Loveland and Webb, 2003) must be maintained to sustain soil's productivity and environmental moderating capacity. The magnitude and severity of adverse impacts of removing crop residue for ethanol production may be lessened to some extent through using the by-products of corn stover fermentation as a soil amendment (Johnson et al., 2004).

7. Bioenergy plantations

Biofuel is undoubtedly an important strategy to reduce dependence on fossil fuel. Rather than removing crop residue, it is important to grow energy crops (e.g., switch grass, willow, poplar) on specifically identified lands. While producing biomass for bioenergy, these lands can also be managed to minimize risks of soil and environmental degradation. Establishing bioenergy plantations on degraded soils enhances soil quality, sequesters C in soil and biomass, and improves quality of aquatic ecosystems (Garten and Wullschleger, 2000; Garten and Wullschleger, 1999; Grigal and Berguson, 1998; Joslin and Schoenholtz, 1998; Graham and Downing, 1995; Hohenstein and Wright, 1994; Makeschin, 1994; Hansen, 1993).

Where surplus land is available, dedicated bioenergy crops can be grown on surplus cropland, agriculturally marginal lands and degraded or drastically disturbed lands. Hoogwijk et al. (2003) estimated that, out of the global potential of biomass energy production of 33–1135 EJ/year, that of growing energy crops on surplus agricultural land is 0–988 EJ/year. Kort et al. (1998) estimated that up to 60 million hectares (Mha) of land could be devoted to bioenergy crop production in the US by conversion of agriculturally marginal soils to production of biomass crops. Most bioenergy crops produce 10–15 Mg biomass/ha/year. With about 16×10^6 BTU/Mg of biomass, production of 10 quads of energy (10% of the total energy need for the US) would require 40 to 60 million hectares (Mha) of land diverted to establishment of bioenergy plantations. Pacala and Socolow (2004) reported that production of ethanol can be one of the 15 viable options to mitigate the climate change by off-setting 1 Pg C/year by 2054. This would require production of about 34 million barrels/day of ethanol by 2054, or 50 times the rate of ethanol production in 2004. The biomass required as a feedstock for ethanol production would require 250 Mha of land worldwide to establish high yielding (10–15 Mg/ha/year) bioenergy plantations.

Closely related to the strategy of establishing bioenergy plantations are those of adopting no-till farming and expanding forest plantations. With full residue retention and incorporation of cover crops in the rotation cycle, expansion of no-till farming from 75 Mha of cropland in 2004 to 1500 Mha of cropland by 2054 would sequester an additional 1 Pg C/year. This important strategy can be jeopardized by residue removal. Pacala and Socolow (2004) also suggested that an additional 1 Pg C/year can be sequestered within the world forest ecosystems by avoiding tropical deforestation, reforestation of 250 Mha in the tropics or 400 Mha in temperate regions, and afforestation of 300 Mha of non-forested lands.

Thus, the urgent and important need of enhancing biofuel production will have to be met through establishment of biomass plantations rather than from removal of crop residues.

8. Conclusions

Crop residues are an important resource, with numerous competing uses. However, the most appropriate use of crop residue is to enhance, maintain and sustain soil quality by increasing the soil organic carbon pool, enhancing activity and species diversity of soil fauna, minimizing soil erosion and non-point source pollution, mitigating climate change by sequestering C in the pedosphere and advancing global food security through enhancement of soil quality. There exists a direct relation between the amount of residue retained and soil organic matter content on the one hand, and between soil organic matter content and crop yields on the other. Production of biomass for biofuel, an important strategy for off-setting fossil fuel emissions, must be undertaken on specifically dedicated land to grow species with a potential to produce high biomass. The economics and environmental consequences of competing uses of crop residue must be assessed objectively with a holistic approach and long-term perspective.

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