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ODYSSEY REQUEST

Soil and environmental implications of using crop residues as biofuel feedstock

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Abstract

Production of biofuels is an important strategy in reducing the net rate of increase of atmospheric CO_2 concentration. Bioethanol can be produced from lignocellulosic biomass such as residues of cereal crops (e.g. rice, wheat, corn, millet). The amount of crop resides produced in the world is estimated at about 4 Pg (1 Pg = petagram = 10^{15}g = 1 billion metric tonnes), of which 2.8 Pg is from cereals. The ethanol yield of crop residues is 0.25 to 0.30 L Kg^{-1}. However, removal of crop residues can adversely impact soil quality with regards to agronomic productivity and numerous ecosystem services. Therefore, feedstock for biofuel production must be produced on specifically identified land (e.g. surplus/marginal croplands, degraded soils, wastelands) by establishing biofuel plantations of switch grass, poplar, willow, mesquite etc. Use of crop residue as mulch/amendment can restore degraded soils and ecosystems. In addition to sequestering carbon in soil and mitigating the climate change, restoration of SOC pool in degraded soils by 1 tonne C ha^{-1} can increase food grain production in developing countries by 24 to 40 million tonnes yr^{-1}. Thus, biofuel feedstock must be produced through establishment of biofuel plantations rather than by removing crop residues.

Las consecuencias del uso de residuos de cosecha como materia prima para biocombustible, sobre los suelos y el ambiente

La producción de biocombustibles constituye una estrategia importante en la reducción del índice neto de aumento en la concentración de CO2 atmosférico. Es posible producir etanol a partir de biomasa lignocelulósica tal como los deshechos de la cosecha de cereales (por ejemplo arroz, trigo, maíz, mijo). Se estima que la cantidad de residuos de cosecha producidos en el mundo es de aproximadamente 4 Pg (1 Pg = petagram = 1015g = 1 billón de toneladas métricas, de las cuales 2.8 Pg proviene de cosechas de cereales. La producción de etanol a partir de residuos de cosecha es de 0.25 a 0.30 L Kg-1. No obstante, la remoción de los residuos de cosecha puede afectar la calidad de los suelos adversamente en cuanto a la productividad agrícola y los ecosistemas. Es por esto que la materia prima para la producción de biocombustible debe ser producida en tierras específicamente identificadas (como por ejemplo, tierras de cultivo excedentes o marginales, suelos degradados y tierras baldías) y la instalación de plantaciones de biocombustibles como pasto para heno (Panicum virgatum) álamo, sauce, mesquite, etc. El uso de residuos de cultivo para aporcar / mejorar puede restaurar suelos degradados y ecosistemas. Además de secuestrar el carbono de los suelos y mitigar los cambios climáticos, la restauración de una fuente de SOC (Soluble Organic Carbon = Carbono Orgánico Soluble) en suelos degradados por un valor de 1 tonelada C ha-1 puede incrementar la producción de cereales para alimento en países en vías de desarrollo de 24 a 40 millones de toneladas por año-1. En consecuencia, la materia prima para biocombustibles debería ser obtenida a partir del establecimiento de plantaciones destinadas para biocombustibles en lugar de utilizar la remoción de residuos de cosechas.

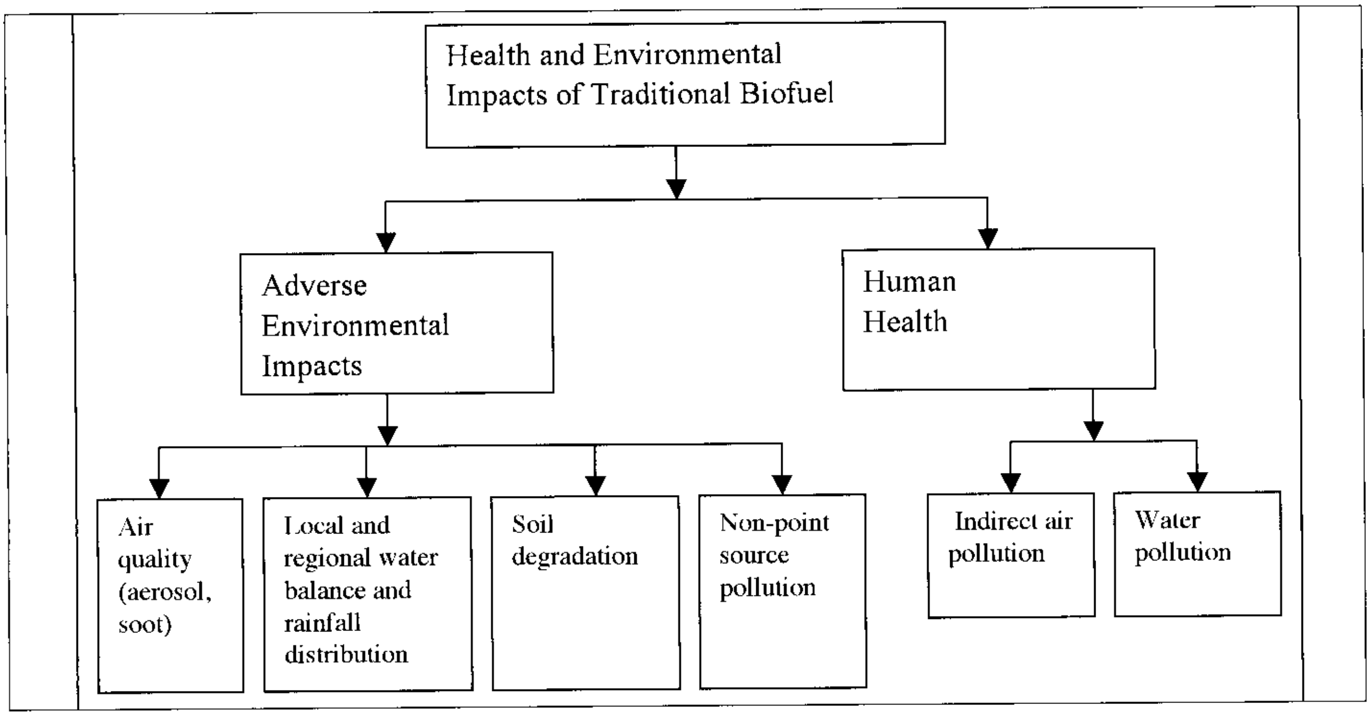
Boden- und Umweltimplikationen der Nutzung von Ernterückständen als Ausgangsmaterial für Biokraftstoff

Die Produktion von Biokraftstoffen ist eine wichtige Strategie zur Reduzierung der Nettozuwachsrate atmosphärischer Kohlendioxid-konzentrationen. Bioethanol kann aus lignocellulosischer Biomasse wie beispielsweise Rückständen von Getreideernten (z.B. Reis, Weizen, Mais, Hirse) gewonnen werden. Das Volumen der in aller Welt produzierten Ernterückstände wird auf zirka 4 Pg (1 Pg = Petagramm = 1015g = 1 Milliarde Tonnen) geschätzt, wovon 2,8 Pg von Getreide stammt. Der Ethanolertrag von Ernterückständen liegt bei 0,25 bis 0,30 L Kg-1. Doch die Entfernung von Ernterückständen kann nachträgliche Auswirkungen auf die Bodenqualität und ihre agronomische Produktivität sowie zahlreiche Ecosystemleistungen haben. Ernterückstände für die Biokraftstoffproduktion sollten daher auf speziell hierfür vorgesehenem Land (z.B. überschüssige Randflächen, degenerierte Böden, Ödland) produziert werden, wozu Biokraftstoff-Plantagen von Rutenhirse, Pappeln, Süßhülsen usw.) anzulegen sind. Durch Verwendung von Ernterückständen als Mulch/Bodenzugabe können degenerierte Böden und Ecosysteme wiederhergestellt werden. Neben der Bindung von Eisen im Boden und der Abschwächung von Klimaveränderungen kann die Wiederherstellung des SOC-Pools in degenerierten Böden durch eine Tonne C ha-1 die Nahrungsmittelgetreideproduktion in Entwicklungsländern um 24 bis 40 Millionen Tonnen yr-1 erhöhen. Das Biokraftstoff-Ausgangsmaterial sollte daher durch Anbau von Biokraftstoff-Plantagen und nicht durch die Entfernung von Ernterückständen gewonnen werden.

Introduction

Using crop residue as a source of fuel for household and other energy needs is as old as settled agriculture, which began about 10,000 years ago. Traditional fuels have been used for cooking, water heating, and space heating since the dawn of human civilization. These

Figure 1. Traditional fuels have numerous human health problems and adverse impacts



age-old traditional fuels are still widely used throughout the developing world. Globally, about 2.5 billion people use traditional biofuels for household energy use (Saldiva and Miraglia, 2004). Traditional biofuels include a wide range of biomass including crop residue, animal dung, fuel wood and wood products, charcoal and agricultural by-products. Traditional biofuels used in unventilated kitchen and traditional stoves have numerous adverse health and environmental impacts (Saldiva and Miraglia, 2004; Venkatarman et al., 2005) (Fig. 1). Adverse effects on human health cause millions of pre-mature deaths in developing countries. Adverse effects on environments are due to changes in the energy balance caused by the haze cloud. On a regional scale, the haze cloud can impact rainfall amount and distribution (Ramanathan et al., 2001).

Recent interest in biofuels in industrialized countries is not in traditional but modern (e.g., liquid, gas) biofuels. This interest originates from the rising cost of energy and projected global climate change due to increasing dependence on fossil fuel combustion. The objective of this manuscript is to describe potential sources of feedstock for biofuel production and deliberate pros and cons of using crop residue for production of liquid biofuels (e.g.,

Figure 2. Potential sources of biofuel feedstock

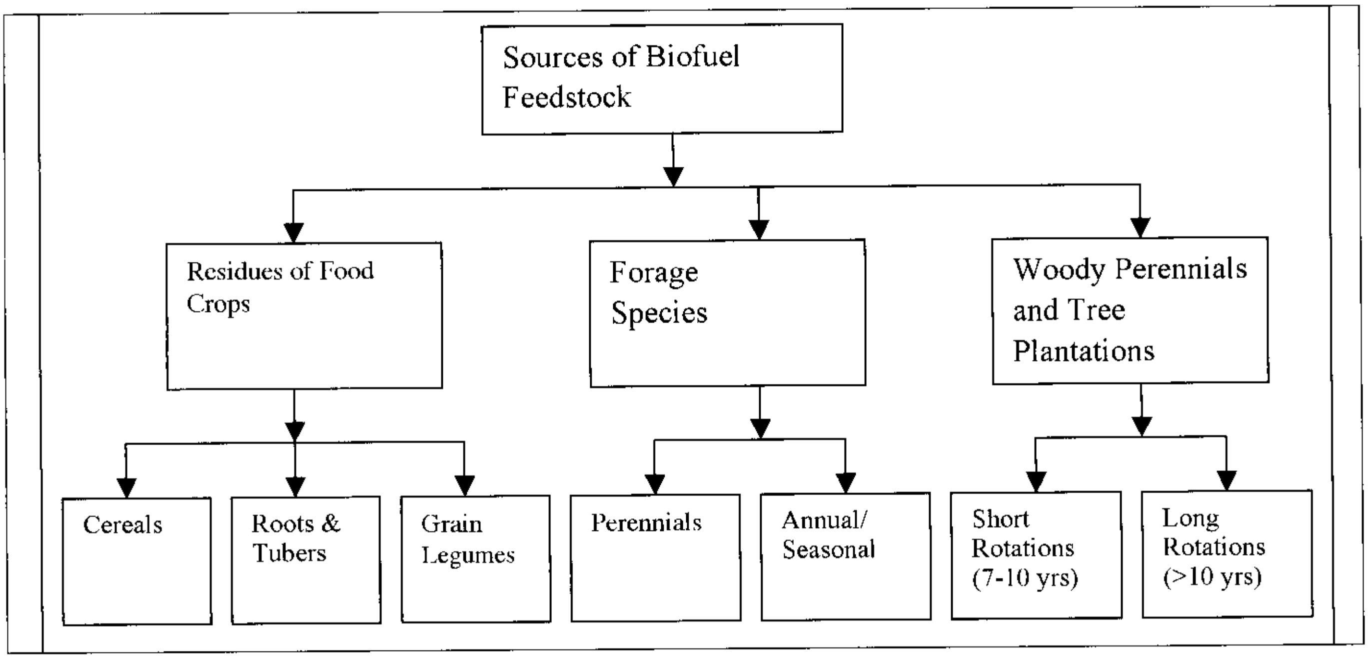


Table 1. Crop residue production in India, U.S. and the World in 2001

Crop	India	U.S.	World
	---- 10^6 tonnes ----		
Cereals	396	367	2802
Legumes	24	82	305
Oil crops	22	20	108
Sugar crops	-	14	170
Tubers	-	5	-
Total	442	488	3385

Source: adapted from Lal, 2004a, b; 2005a, b.

ethanol).

Sources of Biofuel Feedstocks

There is a wide range of potential sources of producing biofuel feedstock (Fig. 2). Important among these are warm season grasses and other forage species (e.g., switch grass, elephant grass, guinea grass). Forage species may be seasonal or annuals. There are also woody perennials and tree plantations with capacity of vigorous growth, adaptability to a wide range of soils and climates especially ability to grow on agriculturally marginal soils (e.g., steep terrain, low soil fertility and other soil-related constraints). There is a wide

Figure 3. Strategies of managing crop residues to reduce the net rate of increase of atmospheric concentration of CO_2

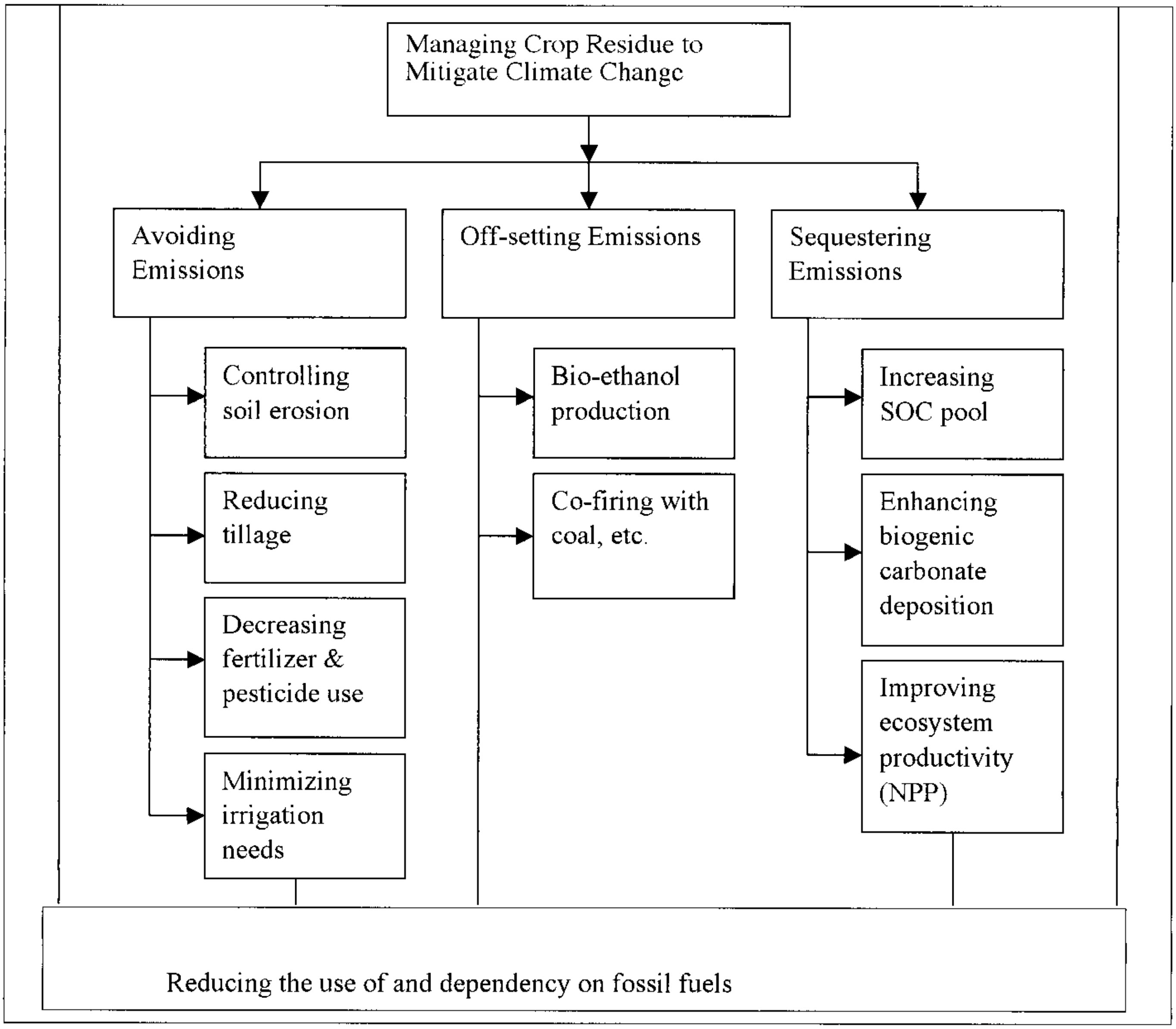


Table 2. Carbon equivalents of some agricutural input based on the use of fossil fuel

Farm Operation	Carbon equivalent (kg C ha^{-1})
Plowing	15
Discing	8
Irrigation	100
Nitrogenous fertilizer	1.3
Pesticides	5

Source: adopted from Lal, 2004c

Table 3. Ethanol production from residues of some crops

Crop	Ethanol yield (L kg^{-1})
Barley straw	0.31
Corn stover	0.29
Oat straw	0.26
Rice straw	0.28
Sorghum straw	0.27
Wheat straw	0.29
Sugarcane bagasse	0.28

Source: adapted from Kim and Dale, 2004

range of species appropriate for both short and long rotations (e.g. poplar, willow, jatropha, mesquite, dalbergia, cassia, acacia, eucalyptus)(Lemus and Lal, 2005). Crop residues constitute an obvious source of feedstock for modern (liquid) biofuels, just as it has been for traditional biofuels for millennias. Annual crop residue production is estimated at about 4 billion tonnes, of which about one billion tonnes is produced in the U.S. and India (Table 1). Lignocellulosic residues of cereal crops (e.g., corn, rice, wheat, sorghum, millet) are appropriately suited for ethanol production, estimated at about 3 billion tonnes per year in the world, and 0.4 billion tonnes per year each in the U.S. and India (Table 1). These are large quantities of residues, and some of it may be used for biofuel production.

Similar to plant species, there are also a wide range of lands (other than cropland) where appropriate biofuel plantations can be established. It is important that land dedicated for biofuel plantations does not compete with that for food production (Wolf et al., 2003). Land for biofuel plantations may include: agriculturally marginal lands, degraded lands, mined lands, and salt-affected land with brackish water (Lal, 2006b). Soil degradation has been a serious issue with many ancient civilizations, some of which vanished because they did not take care of the soil that supported them (Diamond, 2005). It is in this context that establishing biofuel plantations on degraded/marginal lands and drastically disturbed soils (mine lands) would be a truly win-win or no-regrets strategy. There is a strong need to restore these degraded soils and ecosystems to enhance environment quality. Therefore, preparing these degraded soils and ecosystems and establishing biofuel plantations would decrease erosion and non-point source pollution caused by dissolved and suspended loads, improve water quality, increase biodiversity, sequester carbon in soils, and produce biofuel feedstock to off-set fossil fuel emissions.

Biomass feedstock as energy source

The energy demand is estimated at about 400 Quads yr^{-1} for the world and 100 Quads yr^{-1} for the U.S. (1 Quad = 10^{15} BTU, 2.5 x 10^{14} Kcal, or 1.06 x 10^{18} joule)(Weisz, 2004). Overall, the renewable energy (bio, hydro, wind, solar) supplies about 6.6 Quads of primary energy in the U.S., of which biofuel accounts for about 3.5 Quads yr^{-1}. The U.S. ethanol industry is growing rapidly. The U.S. ethanol consumption increased from 660 million litters in 1980 to 2.9 billion liters in 1990, and 5.6 billion liters in 2000 (Kapell,2003;U.S.GAO,2002;Baldwin,2002). In 2004, the U.S. Ethanol Industry set an annual production record of 12.9 billion liters, more than double that produced in 2002. In 2005, ethanol production exceeded 15 billion liters with production of 269,000 barrels per day (RFA, 2005 a). Eleven percent of the U.S. maize and more than eleven percent of sorghum were processed into ethanol in 2004 (RFA, 2005 b).

Therefore, biofuel can be potentially an important source of renewable energy supply. Pacala and Socolow (2004) suggested that bioethanol is one of the 15 technological options to stabilize atmospheric CO2 concentration by 2050. They argued that 1 Pg C yr^{-1} could be off-set by using bioethanol production of 36 million barrels per day by 2054. This much production of ethanol would require 250 million hectacres (Mha) committed to high yield (15 tonnes ha^{-1} yr^{-1}

Table 4. Alternate uses of crop residues

Agricultural	Industrial	Farm household
1 Mulch	1 Construction material	1 Fuel
2 Animal fodder	2 Ethanol feedstock	2 Construction material
3 Composting	3 Source of cellulose, lignin etc	3 Aesthetic value
4 Energy for grain drying	4 Paper manufacture	
5 Animal bedding		

Table 5. Beneficial impacts of crop residue retention as mulch on soil quality

Physical quality	Chemical quality	Biological quality
• Soil aggregation enhancement	• High CEC and AEC	• High SOC concentration
• Low susceptibility to crusting and compaction	• High buffering capacity	• High biomass carbon
• Low soil erosion hazard	• Low leaching losses of nutrients	• High activity and species diversity of soil fauna
• High water infiltration rate	• High use efficiency of fertilizer	• High ability to denature pollutants
• High available water capacity	• High surface area for absorption of pollutants	
• Good internal drainage	• High nutrient recycling	
• Low soil evaporation		
• Favorable soil temperature		

biomass) biomass plantations (e.g. switch grass, poplar) by 2054. Additional area may be required to account for the inputs needed to grow biofuel feedstock. The data in Table 2 lists the carbon equivalent of fertilizers and pesticides. Such inputs can be minimized through adoption of recommended management practices.

Kim and Dale (2004) estimated the potential of bio-ethanol production from wasted crops and crop residues. Wasted crops were defined as crops lost in distribution. They also considered lignocellulosic biomass of the residues of crops such as sugarcane bagass. Kim and Dale estimated that there are 74 Tg (Tg = Teragram = 10^{12}g = 1 million metric tonnes) of dry wasted crops in the world that could potentially produce 49 GL (giga liter or 1 billion liters) of bioethanol per year. They estimated that converting 1.5 Pg of lignocellulosic residues of seven crops (corn, barley, oat, rice, wheat, sorghum, and sugarcane) would produce additional 442 GL of bioethanol per year. In contrast, the global ethanol production in 2001 was only 31 GL. This potential bioethanol production could replace 353 GL of gasoline or one-third of the global gasoline consumption. The ethanol production capacity of residues from lignocellulosic crops ranges from 0.26 to 0.31 L Kg^{-1} (Table 3).

Crop residue and soil quality

Removal of crop residues, for numerous alternative uses including ethanol production (Table 4), can adversely impact soil quality. Retention of crop residues on the soil surface as mulch has numerous beneficial impacts on soil quality, especially with regards to enhancement of soil physical properties, and processes (Table 5). There is a threshold value of crop residue mulch, the specific rate of which depends on soil type and topography, below which soil is prone to accelerated erosion (Wilhelm et al., 1986; 2004). Over and above the need for erosion control and water conservation, crop residues are also needed for enhancing soil organic carbon (SOC) pool, nutrient cycling, enhancing biomass C, and activity and species diversity of soil fauna (Table 5). The importance of crop residue mulch in nutrient cycling and managing soil fertility cannot be over-emphasized. Considering a wide range of the direct and ancillary benefits, most of the crop residues produced on agricultural soils are needed *in situ* to enhance and sustain soil functions and ecosystem services. Therefore, removal of crop residues for ethanol/biofuel production may adversely impact soil quality and ecosystem functions.

Yet, *in situ* retention of crop residues on agricultural soils has numerous functions that contribute to mitigating the climate change by the accelerated greenhouse effect. The schematics in Fig. 3 show three specific functions of crop residue retention with positive impact on mitigation of the climate change. Crop residue mulch avoids emission by minimizing soil erosion risks, and protecting SOC against microbial processes through encapsulation of organic matter within stable micro-aggregates. Use of crop residue mulch also suppresses weed growth and decreases the need for mechanical tillage and use of herbicides. By reducing evaporation and conserving water, residue mulch reduces the need for irrigation. By strengthening nutrient cycling and reducing losses, residue mulching decreases the rate of application of chemical fertilizers. The C equivalent of these input (e.g. tillage, fertilizer, irrigation) shown in Table 3 is equivalent to the avoided emissions.

Using crop residue as mulch or compost also leads to SOC sequestration, which reduces the net rate of emissions of CO_2 through agricultural activities. The rate of SOC sequestration through conversion of plow tillage to no-till farming is about 300 to 500 Kg C ha^{-1} yr^{-1}, with total global potential of 0.6 to 1.2 Pg C yr^{-1} (Lal, 2004d). Pacala and Socolow (2004) estimated that global conversion from plow tillage to no-till farming with crop residue retention as mulch on 1600 million hectacres of cropland could sequester 0.5 to 1 Pg C yr^{-1} by 2050.

Biofuel plantations

Biofuel plantations have an important role in meeting the future ener-

Table 6. Plant species suited for biofuel plantations

English name	Botanical name
Herbaceous crops	
Bana grass	*(P. Purpureum* x *P. typhoides)*
Big blue stem	*Andropogon gerardii*
Buffalo/Klein grass	*Buchloe dactyloides Nutt.*
Eastern gamegrass	*Tripsacum dactyloides*
Elephant grass	*Pennisetum Purpureum Schum.*
Guatamala grass	*Tripsacum laxum*
Guinea grass	*Panicum maximum*
Karnal/Kallar grass	*Leptochloa fusca*
Nandi setaria	*Setaria anceps*
Reed canary grass	*Phalaris arundeneacea*
Sudan grass	*Sorghum sudanese*
Sugarcane (bagass)	*Saccharum officinalis*
Switch grass	*Panicum virgatum*
Tall fescue	*Fetusca arundinacea*
Weeping lovegrass	*Eragrostis curvula*
2. Woody Perennials	
Alders	*Alnus spp.*
Black locust	*Robinia pseudoacacia*
Chinese tallow	*Sapium sebiferum*
Cottonwood	*Populus fremonti*
Mesquite	*Prosopis juliflora*
Poplar	*Populus spp.*
Silver maple	*Acer saccharinum*
Sweet gum	*Liquidambar styraciflua*
Sycamore	*Platanus occidentalis*
Willow	*Salix spp.*

Source: adapted from Lemus and Lal, 2005; Lal, 2001

gy demands without aggravating the greenhouse effect or jeopardizing soil quality. Such plantations can restore degraded sils and ecosystems, provide employment opportunities in rural sector, and establish small-scale industry to produce bioethanol and biodiesel. The choice of appropriate species, depending on soil type and climate, is important. In addition to vigorous growth and high biomass productivity, the species chosen must be adaptable to site-specific conditions and require minimal input for stand establishment, and use of fertilizers and pesticides.

Table 6 lists some herbaceous and woody plants as possible choice for biofuel plantations. There may be other native species which can be used under site-specific conditions. Several holophytes can be grown in arid climates through irrigation with brackish water. These species can produce 15 to 35 tonnes ha^{-1} yr^{-1} of biomass under harsh climate. Some of these species include *Batis maritima, Atriplex linearis, Salicornia bigelovii, Suaeda esteroa, Sesuvium partulacastrum* (Glenn et al., 1993).

While bioethanol is produced from plants that produce lignocellulosic biomass, biodiesel is produced from plants that produce oil seeds. Ideally, biodiesel should be produced from plants that produce non-edible oil. In contrast to seasonal crops which produce edible oil, biodiesel is produced from perennials. Important tree borne oil seed species for biodiesel include neem (*Azadirachta indica*), karanj (*Pongamia pinnata*), mahua (*Madhuca spp*), undi (*Calophyllum inophyllum*) and jatropha (*Jatrophe curcas*) (Hegde et al., 2003). India is planning to establish large areas under jatropha (*rattan jyote*) plantations.

Salt tolerant halophytic plants can be grown on saline/alkaline soils. Woody perennials suitable for salt affected soils are *Prosopis juliflora, Sesbania sesban, Tamarix dioca, Acacia nilotic, Casuarina equiretifolia, Tamarix articulata* (Singh et al., 1994). Among grasses, Karnal grass (*Leptochloa fusca*) is highly adapted to saline soils.

There are some multipurpose woody perennials, which can also be used for fiber/paper production. Important among these are Poplar (*Populus deltoids, P. nigra, P. maximowiczii, P. termula, and P. tremuloides*), European larch (*Larix decidua*) (Miller, 2004). Where appropriate, establishing plantations with multipurpose species is always advantageous.

Crop residue and global food security

An important cause of the widespread problem of soil degradation in developing countries of the tropics and sub-tropics is the perpetual removal of crop residues for fodder, fuel and other uses. While the short-term effects of crop residue removal by 30 to 40% may not be drastic, the long-term effects of the residue removal at higher rates on soil quality and agronomic productivity can be severe. Reduction in crop yield is a serious issue if nutrients (e.g., N, P, K, Ca, Mg) removed in the crop residues are not replaced by the input of additional fertilizer. Further, depletion of the SOC pool in the plow layer also impacts crop yield (Wilhelm et al., 1986; 2004). The decline in crop yield by perpetual removal of crop residues is attributed to a range of factors including water runoff and soil erosion, decline in soil structure, unfavorable soil temperature regime and depletion of the SOC pool.

A severe depletion of SOC pool, as is the case in most resource-poor farms of sub-Saharan Africa and South Asia, decreases crop yields through nutrient/elemental imbalance, compaction and hard setting, and low use efficiency of fertilizers and irrigation. Lal (2006a) synthesized the available data on crop yield in relation to the SOC pool. Increase in SOC pool in the root zone, through use of crop residue mulch and application of manure and other biosolids, by 1 tonne C ha^{-1} can increase grain yields of crops by 20-70 Kg ha^{-1} yr^{-1}

for wheat, 10-50 Kg ha^{-1} $yr^{-1}$for rice, 10-30 ha^{-1} yr^{-1} Kg for soybeans and other pulses, and 30-300 Kg ha^{-1} yr^{-1} for maize. Extrapolating these results to soils of the tropics, Lal (2006a) estimated that food grain production could be enhanced by 24 to 40 million tonnes yr^{-1} (or 24 to 40 Tg yr^{-1}). Of this, increase in food production in sub-Saharan Africa can be 4 to 6 million tonnes yr^{-1} (4 to 6 Tg yr^{-1}). Additional increase in production can occur due to the overall improvement in soil quality and increase in use efficiency of other essential input.

Conclusion

Retention of crop residues as surface mulch or an amendment as compost has multifaceted uses of enhancing soil quality with regards to numerous ecosystem services (e.g. erosion control, water filtration, denaturing pollutants and maintaining/sustaining biomass/agronomic productivity). Removal of crop residues for ethanol or other uses would exacerbate risks of soil degradation by erosion and other processes (e.g. nutrient depletion, structural decline, composition). In some soil specific situations (e.g. clayey soils on gentle slopes), 20 to 30% of crop residues may be removed for ethanol production. However, excessive removal can severely degrade soil quality.

Using biofuel/bioethanol is an important strategy for stabilizing the atmospheric concentration of CO_2. However, the lignocellulosic feedstock for ethanol production must be produced from dedicated biofuel plantations established on specifically identified lands. These lands may include surplus cropland, degraded/wastelands, and agriculturally marginal lands.

Producing liquid biofuels in rural areas in developing countries offer numerous opportunities of providing clean fuel for household cooking, improving the environment, and creating employment opportunities for rural population. Establishing biofuel plantations on wastelands/degraded lands and creating small-scale industry to produce biodiesel or bioethanol provides a unique opportunity for improving the standard of living of the rural poor in developing countries.

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