Land area for establishing biofuel plantations[1]

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Traditional household fuels involving crop residue and animal dung have severe adverse impacts on soil quality, air quality, water quality, climate and human health. The use of crop residues for fuel and non-use of animal dung for manure have exacerbated the problem of soil and environmental degradation. The attendant decline in soil quality, reduction in agronomic productivity and environment moderation capacity are biophysical processes driven by socio-economic and political forces. The problem is widespread in developing countries where extractive farming practices of mining soil fertility are widely used by resource-poor farmers. Biomass productivity of these degraded soils/wasteland is too low and uneconomic. With rapid increase in population in Asia and Africa, the per capita arable land area is decreasing and is already 0.1 ha in several densely populated countries, and arable land cannot be converted to biofuel plantations. Establishing biofuel plantations (e.g., **Jatropha, Pongamia*****) on degraded soils can be a win-win strategy provided that these soils are adequately restored and specific problems (e.g., nutrient and water imbalance, loss of topsoil, shallow rooting depth, drought stress, salinization, compaction, crusting) are alleviated. Another strategy is to adopt practices of land-saving technologies, such as agricultural intensification on prime agricultural lands to improve crop yields, so that surplus land can be converted to biofuel plantations. Production of biofuels can reduce net emissions of greenhouse gases into the atmosphere and advance food security, while achieving energy security, improving environment quality and sequestering carbon in biota and soil. The global potential for soil carbon sequestration is 0.7 to 1.5 Pg C/yr, which can offset 20 to 40 % of the annual increase in atmospheric concentration of*** CO_2***. Trading carbon credits under the CDM or World Bank funds can provide another source of income for resource-poor farmers. The sustainability of a biofuel production system must be assessed through evaluation of the ecosystem carbon budget, accounting for carbon-based inputs in all on-farm operations and industrial processes.***

1. Introduction

Avoiding an oil crunch is a global issue [Abelson, 1999]. Therefore, identifying viable alternatives to fossil fuel, especially for emerging economies such as India and China, is a high priority for achieving energy security and improving environmental quality. In this regard, the importance of establishing biofuel plantations for production of bioethanol and biodiesel cannot be overemphasized. While achieving energy security, ancillary environmental benefits of establishing biofuel plantations are reduction in net emissions of greenhouse gases (GHGs), especially CO_2 and N_2O, and increase in uptake/oxidation of CH_4, restoration of soil quality for enhancement of biomass productivity and environment moderation/buffering capacity, improvement in water quality by decrease in dissolved and suspended loads and reduction in risks of non-point source pollution, and increase in biodiversity by improvement in habitat of flora and fauna (Figure 1). These benefits have positive feedback and synergistic effects because the use of traditional fuels has numerous adverse ecological, environmental and human health effects (Figure 2). Traditional sources of fuel for household cooking in developing countries of Asia and Africa are crop residues, animal dung, and wood products. The widespread practices of removal of crop residues from farmland for fuel or fodder and not using animal dung as a manure generally disrupt nutrient cycling, deplete soil fertility and create elemental imbalance in the root zone, although under certain conditions in temperate climatic regions the damage may be negligible. Lack of crop residue mulch on the soil surface increases erosive forces of impacting raindrops, flowing run-off water and blowing wind, thereby exacerbating the risks of soil erosion by water and wind, increasing dissolved and suspended loads in surface flow, and accentuating non-point source pollution of surface water and contamination of groundwater. Drastic reduction in input of biosolids to agricultural land through non-return of crop residue as mulch and non-use of dung as manure decreases food sources for soil animals (micro, meso, and macro fauna) and reduces population and species diversity of earthworms and termites. Reduction in soil biodiversity has strong adverse effects on soil structure, especially on the total volume and continuity of macropores, formation and stabilization of structural aggregates, and on the soil's resilience against anthropogenic perturbations including vehicular traffic, tillage, and other farm operations.

Traditional fuels are widely used in Asia and Africa. The total amount of traditional fuels used in household cooking in 1995 was 379 Tg (1 Tg or teragram = 10^{12} g

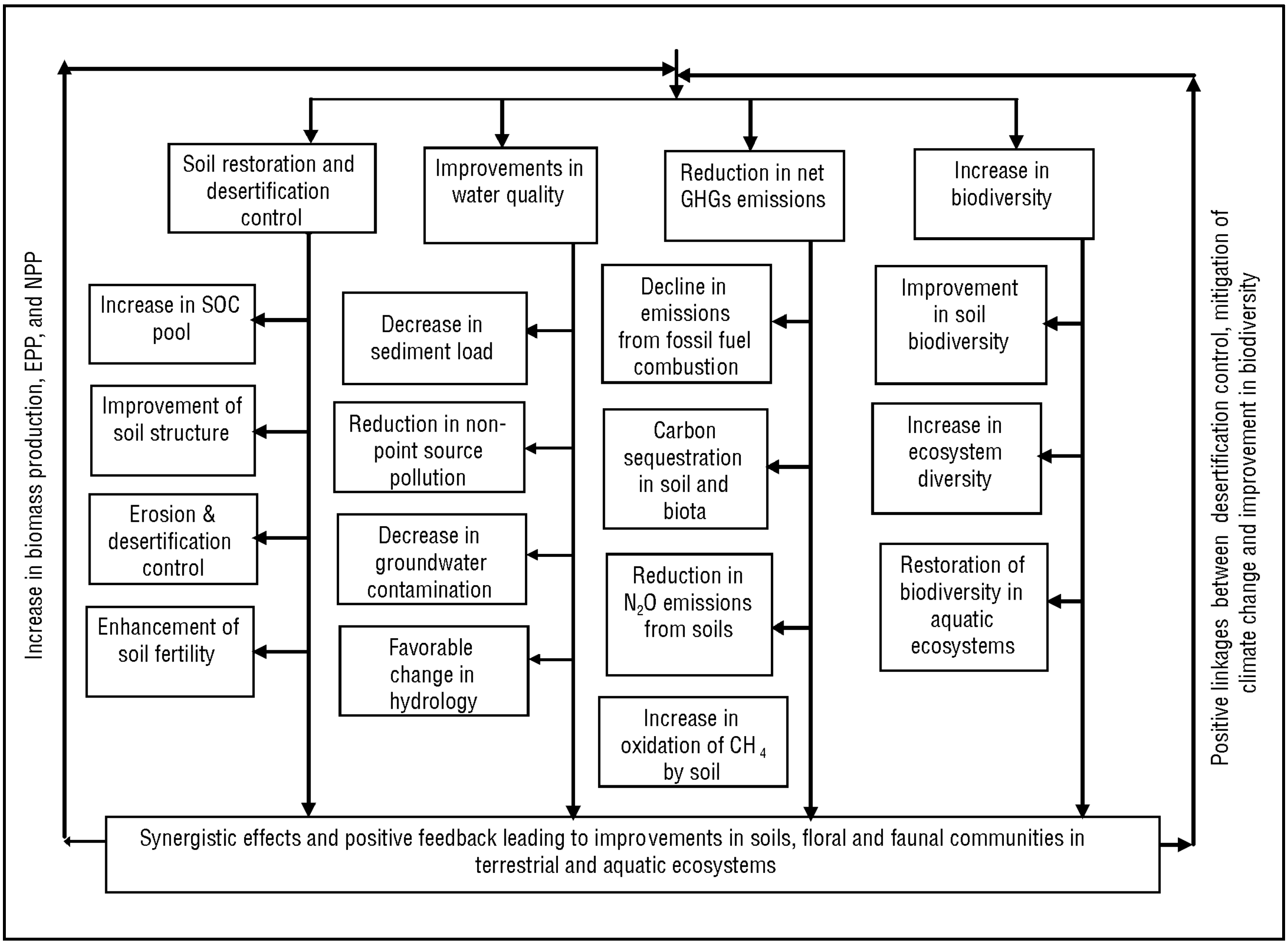

Figure 1. Beneficial impacts of establishing biofuel plantations

= 1 million tonnes) in India, 1518 Tg in Asia and 2325 Tg (2.325 petagrams, Pg) in the world (Table 1). Incomplete combustion of the biomass, often in a traditional stove under unventilated conditions, leads to emission of black carbon (soot). The amount of black carbon emitted in 1995 was estimated at 172 Gg (1 Gg = 10^9g = 1000 tonnes) in India, 705 Gg in Asia and 1075 Gg in the world. In addition to black carbon, there are numerous obnoxious gases (e.g., CO, SO_2, NO_x) emitted which cause severe health hazards. Bailis et al. [2005] estimated that household indoor pollution due to biomass combustion in Africa will cause 9.8 million premature deaths by the year 2030.The large amount of black carbon and aerosols emitted into the atmosphere affects the energy balance through increase in scattering and absorption of solar radiation [Ramanathan et al., 2001]. The aerosols also produce brighter clouds which are less efficient in causing precipitation, and, thus, reduce rainfall. Ramanathan et al. have reported the existence of a brownish haze in the regions of tropics and sub-tropics where heavy biomass-burning occurs. A well-known example is the existence of the Indo-Asian haze which has adversely affected the amount and distribution of monsoons in the Indian subcontinent [Venkataraman et al., 2005].

Because of these strong and long-lasting adverse impacts of using traditional fuels, there is a strong need to identify and develop improved sources and types of clean biofuels. Three issues to be addressed in this regard are: (1) is crop residue a viable source of biofuel feedstock such as bioethanol; (2) can biofuel plantations be established on degraded soils; and (3) how can some of the world's prime agricultural land be converted to biofuel plantations? Thus, the objectives of this paper are to discuss the pros and cons of using crop residue for biofuel production, identify land resources that can be diverted to the establishment of biofuel plantations in developing countries, describe the potential of using degraded soils for growing energy crops, and outline ancillary benefits of soil carbon sequestration and improvement in environmental quality.

2. Can crop residues be used as biofuel feedstock?

Crop residue is defined as the non-edible plant parts that are left in the field after harvest. The amount and quality of crop residues produced vary widely among crops. Crop residue, a renewable resource, is produced annually by a wide range of crops grown in the world. In general, cereals (e.g., corn, wheat, rice, sorghum, millet) produce more residues than legumes (e.g., soybeans, cowpeas, lentils, chickpeas). The amount of crop residue produced annually is estimated at 440 Tg in India, 490 Tg in the US, and 3.8 Pg in the world (Table 2). Of this, the residue produced by cereals is estimated at 335 Tg in India, 367 Tg in the US, and 2.8 Pg in the world (Table 2). Ethanol

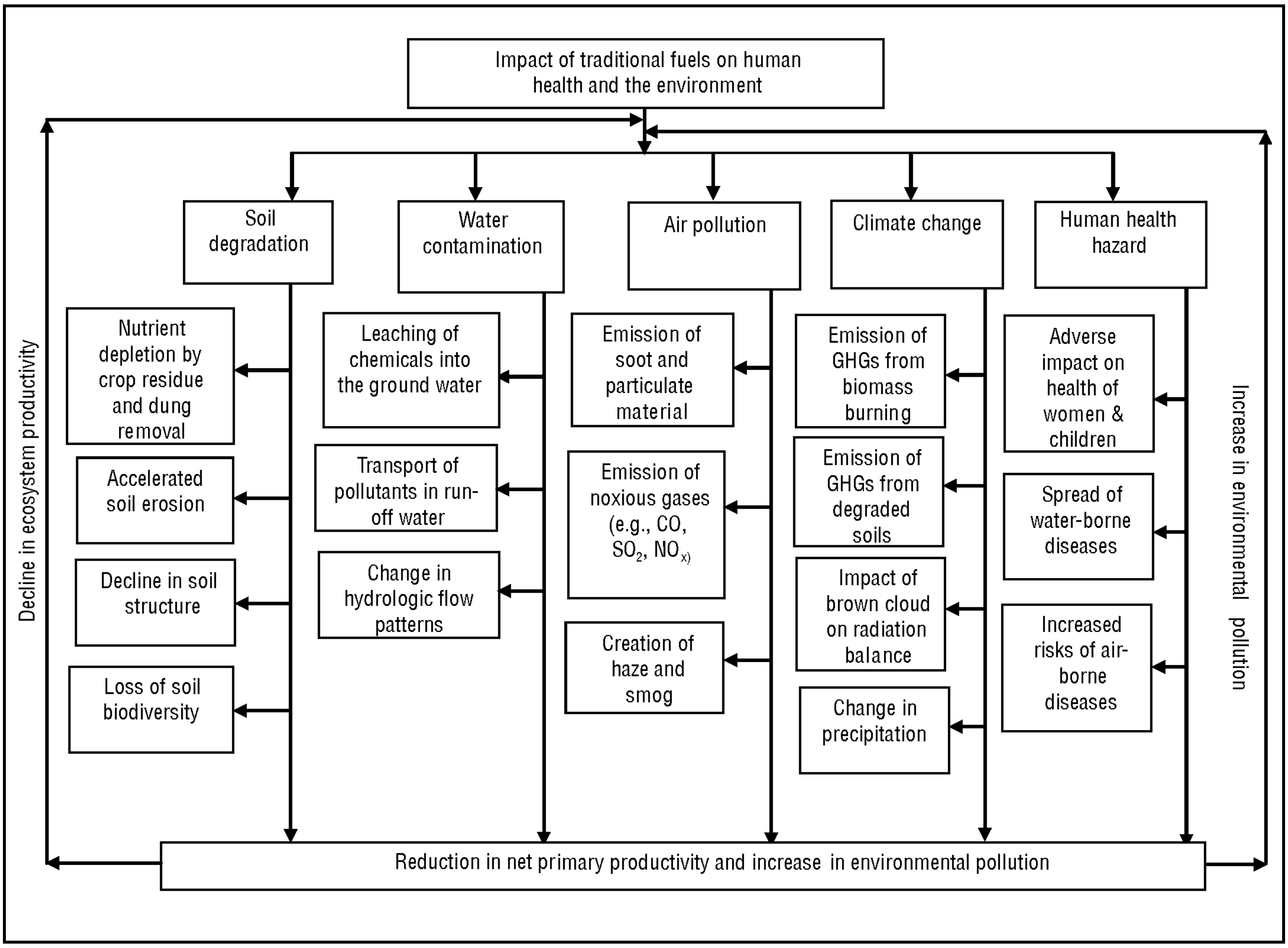

Figure 2. Adverse effects of using crop residues and cattle dung on soil, water, atmosphere and human health

Table 1. Emission of black soot from traditional bio-fuel combustion in India and Asia in 1995 [adapted from Venkataraman et al., 2005]

Region	Fuel-wood		Animal dung		Crop residue	
	Amount of biomass (Tg/yr)	Black C emission (Gg/yr)	Amount of biomass (Tg/yr)	Black C emission (Gg/yr)	Amount of biomass (Tg/yr)	Black C emission (Gg/yr)
India	281	143	62	8	36	21
Asia	800-930	400-470	130-200	15-25	430-545	220-280
World	1324-1615	670-820	159-410	20-50	442-707	230-360

plants are being established at several locations in the US Corn Belt region. In contrast to coal, which comes from mines, crop residues as biofuel feedstock are a widely dispersed source of energy. Transporting bulk quantities of crop residues over long distances can be logistically and economically prohibitive. While 60 to 70 % of the cereal residues may be removed for biofuel production in the vicinity of an ethanol plant, most of the residue will remain inaccessible from locations at a distance where the cost of transport is prohibitive. Thus, establishing a site where the adjacent land is used mainly for biomass production is a better strategy than harvesting crop residue from arable lands.

In addition to a large number of nutrients (e.g., potassium, calcium, magnesium, nitrogen, phosphorus), these residues can also be a source of energy, as has been true of traditional fuels used in the developing countries for millennia. The energy value of crop residues is estimated at 12.6 MJ/kg for rice straw and 15.8 MJ/kg for hay [Stout, 1990]. The approximate fuel value per Mg (1 Mg = 10^6 g = 1 tonne) of crop residue is estimated variously as 16.9 GJ [Weisz, 2004] and 12.6 GJ [Lal, 2004a]. By the latter estiamte, 1 Mg of crop residue would replace 2 barrels of diesel (1 barrel = 136.4 kg). Therefore, an annual equivalent diesel value of the total amount of crop residue produced is 120 Tg in India, 133 Tg in the US, and 1.04 Pg in the world.

Indeed, crop residue can be a major source of energy, and it is being widely considered as a source of feedstock for production of liquid biofuels (e.g., bioethanol). However, because of its important beneficial impact on soil quality and ecosystem functions (e.g., nutrient and carbon cycling, erosion control, hydrologic and energy balance, biodiversity; Figure 3), removal of crop residue for energy production (either as traditional household fuel or as improved liquid fuel) can be counterproductive, with severe adverse effects on the environment in general and soil and water resources in particular, except possibly under high crop yield conditions and specific soil management regimes in temperate climates. In addition to its role in buffering the environment, returning crop residue to the farmland is essential, in most situations, to maintaining/enhancing the soil organic carbon (SOC) pool, sustaining crop yields and achieving global food security.

Table 2. Estimates of the amount of crop residues produced in India, USA and the world in 2001 (in Pg) [adapted from Lal, 2004a; 2005a]

Type	India	USA	World
Cereals	335	367	2802
Legumes	24	82	305
Oil crops	22	20	108
Sugar crops	61	14	373
Tubers	-	5	170
Total	442	488	3758

The use of corn residue for ethanol production is being considered in industry in the US. The June 28, 2004 issue of *Newsweek* had a one-page advertisement (inside back cover) showing a pickup truck loaded with crop residue and reading, “The waste on the truck can be used to fuel it”. This ad raises numerous questions: (1) is crop residue really a waste; (2) can the energy produced by using crop residue really make a difference either now or on long-term basis; (3) what are the environmental and agronomic costs of removing crop residue; and (4) what are other viable sources of feedstock for producing biofuel?

Crop residue is a not a “waste”. It is a precious commodity, has multi-faceted uses, and influences numerous interactive processes necessary for performing ecosystem services and functions. Returning crop residue to soil has numerous short-term and long-term benefits essential to sustainable use of soil and water resources (Figure 3). Indiscriminate and long-term removal of crop residues from farmlands of Asia and Africa has caused the widespread and serious problem of soil and environmental degradation [Oldeman, 1994]. Indeed, a very heavy price has been paid in terms of the severe degradation of soil, pollution of water, and extinction of macro and micro-fauna and flora. The agrarian malaise, perpetual food deficit, and recurring famines in Africa are consequences of the widespread problem of soil degradation exacerbated by residue removal from croplands. This vicious cycle of soil degradation - poverty - malnutrition and hunger - further soil degradation cannot be reversed without returning crop residues and adding additional biosolids to the soil depleted of its life-giving entity, the soil organic matter pool.

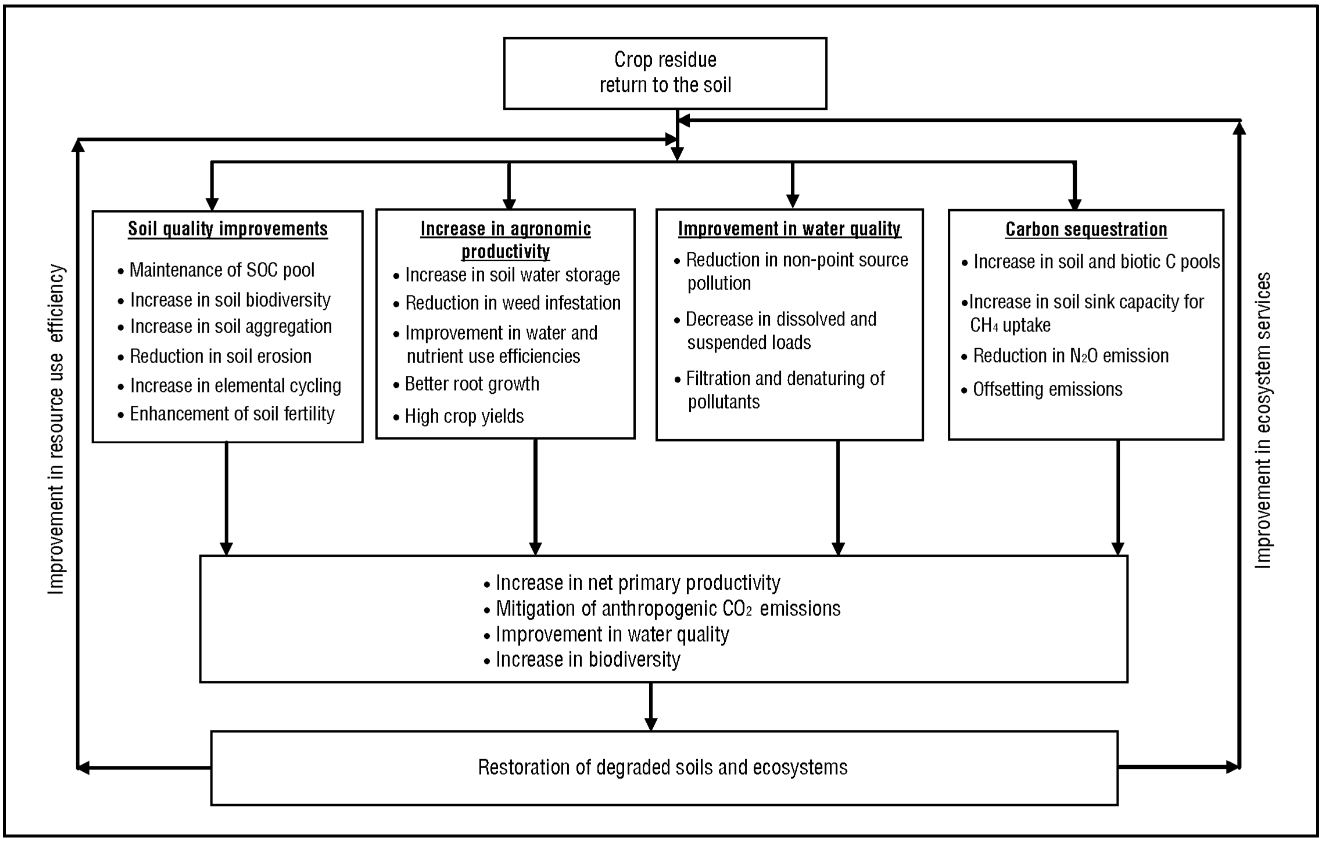

Figure 3. Impact of crop residues on sustainable use of natural resources and ecosystem functions

Reduction in crop yield by inappropriate residue removal and the attendant decline in soil quality poses serious threats to global food security. Depletion of the SOC pool in the plow layer to below the threshold level adversely affects crop yields even if chemical fertilizers are applied. In Nebraska, USA, for example, Wilhelm et al. [1986; 2004] reported that removal of each Mg of residue caused reduction in the yield of the following crop by 0.13 Mg/ha/yr in corn and 0.09 Mg/ha/yr in soybeans. However, not all trials of residue removal have shown such clear-cut yield reduction results [Wilhelm et al., 2004]. In countries and regions where the adverse effects are not so severe, the removal of crop residues for use in producing bioenergy could have value in the short term, especially because of the impetus it would give to a nascent industry whose technological feasibility it would help establish. In such cases, this short-term value would not negate the broad thesis of this paper, which argues for the establishment of biofuel plantations, but would in fact advance it. The pattern of yield reduction is fairly consistent where soil moisture is also reduced by residue removal. The adverse effects of SOC depletion on crop yields are extremely severe in traditional low-input agriculture practiced by resource-poor farmers of Africa, Asia, Central/South America and the Caribbean. Lal [2005b] collated globally available research data on the rate of increase in crop yields with increase in SOC pool in the root zone. On the basis of the literature review, he reported that increase in SOC pool by 1 Mg/ha can increase crop grain yield by 30-300 kg/ha for corn, 20-25 kg/ha for beans, 20-70 kg/ha for wheat, 10-50 kg/ha for rice, 20-30 kg/ha for soybeans, and 5-10 kg/ha for cowpeas. Table 3 shows the worldwide increase in food production that would be achieved by increase in the SOC pool through application of crop residues and other biosolids to farmland. This would be enough to meet the present level of food deficit in Africa and Asia. It is important to realize, however, that the data in Table 3 are based on numerous assumptions with regard to the soil quality impacts of crop residue management. The principal assumption is that crop yield is not limited by other biophysical constraints such as incidence of pests and pathogens, lack of essential plant nutrients or extreme drought. The wide range of increase in crop yields (e.g., 10-50 kg/ha for rice and 30 to 300 kg/mg for corn) is attributed to site-specific conditions especially with regard to the effective rooting depth, length of the growing season, ecoregional characteristics including day and night temperatures, and agronomic practices of soil and crop management. The term "food security" is often used rhetorically. It has as much to do with access to food through purchasing power and household income as with agronomic production. It is in this context that improvement in soil quality through crop residue management is a truly win-win strategy because trading carbon credits would also provide additional income to resource-poor farmers.

Table 3. Increase in world food production through increase in soil organic carbon pool in the root zone (in Pg) [adapted from Lal, 2005b]

Region	+ SOC pool @ 0.5 Mg/ha/yr	+ SOC pool @ 1.0 Mg/ha/yr
Africa	1.8-2.9	3.6-5.7
Latin America	3.3-5.1	6.6-10.2
Asia	6.8-11.9	13.6-23.8
Total	12.0-19.9	24.0-39.8

Note

Crops included in food production are wheat, corn, rice, sorghum, millet, beans and soybeans.

Enhancing the SOC pool and improving soil quality through crop residue management and application of biosolids (e.g., farmyard manure, compost, sludge) are important and environmentally friendly strategies of achieving global food security. Increasing the SOC pool by 1 Mg C/ha/yr in the root zone can increase food production in developing countries by 24 to 40 Tg/yr (Table 3). Such an increase is adequate to bridge the food deficits in Africa and Asia. With about 730 million food-insecure people, mostly in south Asia and sub-Saharan Africa, and 3.7 billion people prone to hidden hunger caused by malnutrition, food security of the ever-growing world population must not be jeopardized by using unsustainable practices of not returning crop residue and animal manure as soil improvers. If not carefully considered and judiciously implemented, "technology without wisdom" may be the 8th deadly sin of humanity, in the words of M.K. (Mahatma) Gandhi. Such wisdom is needed before embarking on a technology for the production of biofuel that would degrade soil quality.

3. Availability of land for biofuel production

3.1. Restoring degraded soils

There are two potential sources of land for establishing biofuel plantations: restoring degraded soils, and saving prime land through intensification of agriculture for increasing crop yields per unit area (Figure 4). The issue of soil degradation, a serious problem worldwide (Table 4) and in South Asia (Table 5), can be addressed through identifying land for establishing biofuel plantations. Soil degradation has been a serious problem throughout human history. Many ancient civilizations vanished because they either ignored their soil resources or did not manage them in a sustainable manner [Diamond, 2004]. Presently, the global hot spots of soil degradation, poverty and hunger, and political instability occur in the same geographic regions. Soil degradation is caused by numerous processes of different kinds, including physical (e.g., erosion, compaction, crusting, drought stress), chemical (e.g., leaching, acidification, salinization, alkalization, nutrient depletion, elemental imbalance) and biological (e.g., depletion in SOC pool, reduction in microbial biomass carbon, buildup of soil pathogens, decrease in activity of soil macrofauna such as earthworms). Processes of soil degradation are influenced by numerous factors such as soil type, climate, vegetation, terrain, hydrology and other biophysical

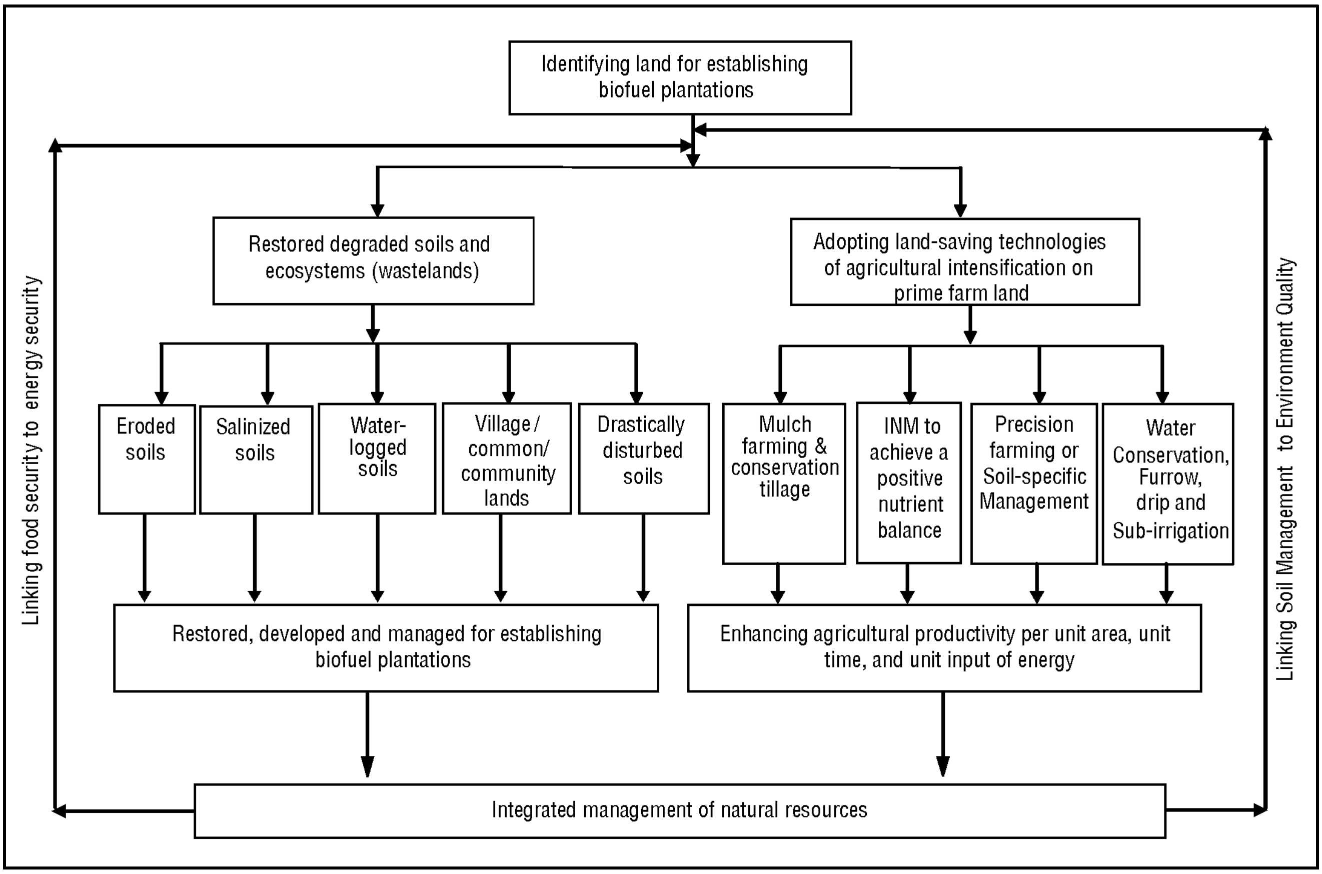

Figure 4. Strategies of identifying land resources for biofuel production

Table 4. Global extent of soil degradation by different processes[1] (in Mha) [adapted from Oldeman, 1994]

Region	Water erosion	Wind erosion	Chemical degradation	Physical degradation	Total
Africa	169	98	62	19	348
Asia	317	90	74	12	493
South America	77	16	70	8	171
Central America	45	5	7	5	62
North America	46	32	-	1	79
Europe	93	39	26	36	194
Oceanic	4	16	1	2	23
World	751	295	240[2]	83[2]	1370

Notes

1. Moderate plus level of degradation
2. All levels of soil degradation included in 240 Mha for chemical degradation and 83 Mha for physical degradation.

and physiographical parameters. Before human intervention, the rates of soil degradation by natural processes were low, and influenced primarily by landscape and physiographic factors. With increase in population, the predominant causes of soil degradation are anthropogenic activities including change in land use and land cover by deforestation, biomass-burning, residue removal, excessive tillage and cultivation of steep lands, uncontrolled grazing at high stocking rates, extractive farming practices based on low external input and extensive farming, and little or no investment in soil restoration for alleviation of soil-related constraints. In simple terms, when people are poor, hungry and desperate they pass their miseries on to the land. However, poverty and lack of resources are not the only causes of soil degradation. It can also happen under conditions of high external input and commercial farming. Poor planning, short-sightedness and cutting corners for quick economic returns over a short

Table 5. Estimates of area affected by different soil degradation processes[1] in South Asia (in Mha) [adapted from FAO, 1994]

Country	Water erosion	Wind erosion	Salinization	Fertility depletion	Waterlogging	Total
Afghanistan	2.6	0.2	0	0	0	2.8
Bangladesh	1.5	0	0	0	0	1.5
Bhutan	0	0	0	0	0	0
India	29.8	10.8	4.1	3.2	3.1	51.0
Iran	11.9	28.8	22.5	0	0	63.2
Nepal	1.1	0	0	0	0	1.1
Pakistan	1.1	6.7	0.4	5.2	1.0	14.4
Sri Lanka	0.2	0.0	0.0	0.7	0	0.9
Total	48.2	46.5	27.0	9.1	0	134.9

Note

1. Moderate plus level of degradation

period of time are also causes of soil degradation. The mechanized groundnut (peanut) scheme in Tanzania, implemented after World War II, was a classic example of soil degradation caused by the use of inappropriate technology in a harsh tropical climate and on fragile soils.

Whatever the cause, biofuel plantations established on degraded soil can be productive and profitable only if soil-related constraints on biomass production are removed through adoption of appropriate soil restorative measures. Biofuel plantations established on unrestored marginal soils cultivated with marginal inputs will produce marginal yields and perpetuate poverty and misery without realizing the goals of achieving energy security. Appropriate restorative measures may include installing terraces and waterways on erosion-prone steep lands, stabilizing sand dunes on lands susceptible to wind erosion, leaching salts with good quality irrigation water and applying gypsum and compost on saline/alkaline soils, using integrated nutrient management (INM) strategies for improving soil fertility, and applying biosolids (e.g., compost, sludge) to enhance the SOC pool for increasing aggregation and aggregate stability and biotic activity. In arid and semi-arid regions, constructing micro-terraces for individual trees to facilitate water-harvesting can enhance plant growth and increase agronomic productivity. The ecological principle "There is no such thing as a free lunch" applies also to the use of degraded soils and ecosystems.

Land along roads, railway lines and irrigation canals is not only degraded but also drastically disturbed. Topsoil in these areas has generally been removed to about 1 m depth for use in raising the road/railbed and constructing dykes for irrigation canals. Thus, these lands are prone to inundation and anaerobiosis during the rainy season, and plants established on scalped soils suffer from nutrient deficiency and elemental imbalance. Similar problems exist on village common lands (known as *Shamlat* in India) which are heavily grazed, compacted, eroded and severely depleted of essential plant nutrients. These common lands are classic examples of the "tragedy of the commons". These lands can be profitably used only if adequately restored, so it will be important to find the economic incentives or subsidies that will facilitate their restoration. Wasteland, if restored, offers a strong possibility of establishing biofuel plantations.

Assuming that 25 % of the restored degraded land can be diverted to biofuel plantations, the available land area is estimated at 87 Mha (megahectares or million hectares) in Africa, 124 Mha in Asia, 43 Mha in South America, 15 Mha in Central America, 20 Mha in North America, 48 Mha in Europe and 5 Mha in Oceania (Table 4). Similarly, if 25 % of degraded soils can be restored, the data in Table 5 show that the land area that can be diverted to establishing biofuel plantations can be 12 Mha in India and 33 Mha in South Asia. If degraded soils under all land-use systems could be restored and if even 10 % of them are diverted to biofuel plantations, land area available for this purpose would be 834 Mha worldwide, comprising 166 Mha in Africa, 279 Mha in Asia, 152 Mha in South America, 20 Mha in Central America, 113 Mha in North America, 80 Mha in Europe and 64 Mha in Oceania (Table 6). While these statistics provide some guidelines about the extent of degraded soils on a regional/continental scale, these lands are used by the community for obtaining several goods and services. For example, village common lands are used for grazing cattle, fuelwood-gathering, harvesting minor forest produce, etc. Thus, these degraded soils are not entirely unused resources but their productivity and usefulness can be drastically enhanced by restoring them and converting some to biofuel plantations.

3.2. Saving prime agricultural lands

Adopting techniques of agricultural intensification on prime agricultural land can enhance crop yields by as much as 50 % to 100 %. Agricultural intensification implies cultivating the best soils with the best management practices to produce the optimum sustainable yield so that land can be saved for other purposes such as establishing biofuel plantations and nature conservancy. The optimum sustainable

Table 6. Global estimates of soil degradation by land use (in Mha) [adapted from Oldeman, 1994].

Region	Agricultural land		Permanent pasture		Forest and woodland		Total degraded land
	Area (Mha)	% degraded	Area (Mha)	% degraded	Area (Mha)	% degraded	
Africa	187	65	793	31	683	19	1,663
Asia	537	38	978	20	1273	27	2,788
South America	142	45	478	14	896	13	1,516
Central America	38	74	94	11	66	38	198
North America	236	26	274	11	621	1	1,131
Europe	287	25	156	35	353	26	796
Oceania	49	8	439	19	156	8	644
World	1475	38	3212	21	4048	18	8,736

Table 7. National average wheat yields for 1996-2000 for 22 countries accounting for 90 % of world wheat production [adapted from Bruinsma, 2003]

Country	Wheat yield (Mg/ha)	Country	Wheat yield (Mg/ha)
UK	7.8	India	2.6
Germany	7.3	Romania	2.6
Denmark	7.1	Ukraine	2.5
France	7.0	Argentina	2.4
Egypt	6.0	Canada	2.4
Hungary	3.9	Pakistan	2.2
Poland	3.4	Turkey	2.1
Italy	3.2	Australia	2.0
China	3.1	Iran	1.6
USA	2.7	Russia	1.4
Spain	2.6	Kazakhstan	0.8

yield is the largest crop yield that can be obtained without decreasing the ability of agro-ecosystems to sustain that yield in the future. Crop yields in India and elsewhere in the developing countries are one-third to one-half of what is potentially achievable (Tables 7 and 8). While such yield comparisons across regions can be misleading and lead to erroneous conclusions, they provide rough guidelines on the magnitude of the yield gap between regions with similar soils and environments. To be useful and valid, however, yield comparisons must be made across countries and regions with similar total and seasonal rainfall, irrigated vs. rain-fed production systems, tillage methods and cropping sequences. With due consideration to such exogenous factors, it is probable that the average yield of wheat in India can be increased from 2.6 Mg/ha to 4.0 Mg/ha, and that of corn from 1.7 Mg/ha to 3.5 Mg/ha. Adopting recommended management practices (RMPs) on these lands can enhance crop yields and spare prime lands for establishing biofuel plantations. Important RMPs for agricultural intensification include using: conservation tillage with crop residue mulch and direct seeding in no-till soil by the use of special seeding equipment and of herbicides for weed control; using INM practices to establish favorable nutrient balance, sub- or furrow irrigation to save water and enhance irrigation efficiency, and precision farming to increase nutrient/chemical use efficiency. Indeed, there exists a vast potential of saving prime land through agricultural intensification and restoring degraded soils through adoption of soil and ecosystem restorative measures.

Wolf et al. [2003] estimated that only 55 % of the present agricultural land area on the global scale is needed

Table 8. National average corn yields for 1996/2000 for 19 countries accounting for 90 % of world corn output [adapted from Bruinsma, 2003]

Country	Corn yield (Mg/ha)	Country	Corn yield (Mg/ha)
Italy	9.4	Thailand	3.5
Spain	9.1	Romania	3.0
France	8.6	Brazil	2.6
USA	8.2	Indonesia	2.6
Canada	7.4	South Africa	2.5
Egypt	7.3	Mexico	2.3
Hungary	6.0	India	1.7
Argentina	5.0	Philippines	1.6
Yugoslavia	4.0	Nigeria	1.3
China	3.8		

Table 9. Land use in South Asia (in Mha) [FAO, 2004]

Country	Land area	Arable land	Permanent crops	Permanent pasture	Forest and woodland	Irrigated area
Afghanistan	65.2	7.9	0.14	30.0	1.4	2.4
Bangladesh	13.0	8.1	0.40	0.6	1.3	4.4
India	297.3	161.8	8.15	10.9	64.1	54.8
Iran	163.6	14.3	2.28	44.0	7.3	7.5
Nepal	14.3	3.1	0.09	1.8	3.9	1.1
Pakistan	77.1	21.5	0.67	5.0	2.5	17.8
Sri Lanka	6.5	0.9	1.02	0.4	1.9	0.6

for food production in the future (specifically, 2050) if intensive agricultural systems based on high external input are adopted. Thus, Wolf et al. argued that the remaining 45 % of the prime land can be used for other purposes, such as establishment of biofuel plantations. On the contrary, no land area is available for biofuel production if an extensive system or ecological agriculture based on low external input systems are adopted. They estimated that land area for future arable crop production ranges from 0.8-1.4 billion hectares (gigahectares, Gha) for the high external input system with moderate to affluent diet to 1.2-2.3 Gha for the low external input system with vegetarian and moderate diet. The maximum global production of biomass for energy use was estimated at 20 Pg/yr (i.e., 360 EJ/yr; EJ = exajoule or 10^{18} J) and 9 Pg of dry matter/yr (i.e., 162 EJ/yr) if the agricultural production can be intensified on the land presently under agriculture, and any additional land can be used for biomass production and conversion to biofuels. Wolf et al. observed that regions where large areas of land are potentially available for the production of biomass for energy use are South America, North America, Central Africa and Oceania.

The data in Table 9 show that India has 160 Mha of arable land. If RMPs of agricultural intensification are not adopted, India will need additional land to feed its population of 1.1 billion in 2005 and growing at the mean annual rate of 1.8 %/annum. On the contrary, adoption of RMPs can save prime land for establishing biofuel plantations. Temporal changes in land areas under crops for the world, developing countries and emerging economies are depicted in Table 10. The wide variations in the trends show that it is possible for growing populations to be fed with only modest increases in cropland, demonstrating the potential of better agricultural practices. Assuming that 10 % of the cropland area can be converted to biofuel plantations with the adoption of RMPs for agricultural intensification, the available prime land can be 16 Mha in India, 79 Mha in developing countries, and 140 Mha in the world (Table 10).

4. Benefits of establishing biofuel plantations

The most obvious benefit of a biofuel plantation is as a source of renewable energy and hence as a means of reducing net emissions of CO_2. A well-managed biofuel plantation can produce 2-4 Mg/ha of biomass in arid ecosystems, 4-8 Mg/ha in semi-arid ecosystems, and 8-12 Mg/ha in sub-humid and humid ecosystems. Thus, the

Table 10. Temporal changes in land area under cropland in developing countries between 1961 and 2001 (in Mha) [adapted from FAO, 2004]

Year	Developing countries	Latin America	Brazil	Mexico	India	China	World
1961	630.1	97.5	22.1	22.4	155.8	103.4	1276.6
1971	668.1	117.4	37.0	21.8	159,6	99.6	1317.4
1981	694.4	128.5	45.6	23.1	162.9	97.5	1344.2
1991	743.1	135.8	52.0	24.1	162.7	123.7	1389.5
2001	791.6	148.6	58.9	24.8	161.8	143.6	1405.5

Table 11. Potential of soil carbon sequestration under biofuel plantations established on degraded soils [adapted from Lal, 2004a]

Degradation process	SOC sequestration rate (kg C/ha/yr)	
	Semi-arid regions	Sub-humid regions
Water erosion	80-120	120-150
Wind erosion	40-60	-
Soil fertility decline	120-150	150-300
Waterlogging	40-60	50-100
Salinization	120-150	-
Desertification control	40-60	-
Soil physical degradation	40-60	150-300

potential rates of SOC sequestration are also generally lower in semi-arid climates compared with those in humid climates (Table 11). In addition to providing a renewable source of energy, thereby reducing the net anthropogenic emission of CO_2 and other GHGs, there are numerous other ancillary benefits of establishing biofuel plantations. Risks of soil erosion by water and wind and of pollution from dispersed sources are generally less under perennial crop land use (e.g., *Jatropha)*. Biofuel plantations are also beneficial to increasing biodiversity. Moreover, there is a distinct benefit of enhancing the terrestrial (e.g., soil and vegetation) carbon pool. When woody biomass (e.g., mesquite *Jatropha)* is established on cropland or very low productivity degraded soils, then there is an increase in the biotic carbon sequestered above ground, as well as an increase in the SOC. The carbon thus sequestered (and verified) can be traded in international markets such as the Clean Development Mechanism (CDM) of the Kyoto Treaty and the BioCarbon and Prototype Carbon Fund of the World Bank. There is an emerging market in carbon trading [Johnson and Heinen, 2003], which can provide an additional source of income to resource-poor farmers and land managers. Carbon credits are being traded at about US$ 2/Mg of CO_2 in the Chicago Climate Exchange, but at a much higher price in the EU countries. Niles et al. [2002] estimated the monetary value of trading carbon credits in developing countries at about US$ 17 billion/yr even at the low price of 2002 (Table 12). The importance of the monetary value of trading credits of carbon sequestered in soil and biomass of biofuel plantations to resource-poor farmers cannot be over-emphasized, and must be carefully considered in any economic analysis of such undertakings. Creating job opportunities through establishing biofuel plantations is in accord with one of the 8 Millennium Development Goals of “eliminating poverty”. While maximizing the terrestrial (e.g., soil and biota) carbon pool is advantageous and can be traded under the CDM, the market mechanism that values carbon may not necessarily provide an effective incentive for conserving the many resources and utilities that land can provide. In some cases, maximizing the terrestrial carbon pool may conflict with other ways that land supports rural livelihoods (e.g., grazing animals, harvesting fuel-wood). Indeed, this is one of the shortcomings of the CDM in relation to sustainable development, and must be objectively considered.

5. Potential of terrestrial carbon sequestration to mitigate climate change

Terrestrial carbon sequestration, by transfer of atmospheric CO_2 into the biotic carbon pool through photosynthesis and into the SOC pool through humification of the biomass returned to the soil, is a win-win process [Lal, 2004d]. While decreasing the net CO_2 emission into the atmosphere, it improves the quality of soil and water resources, and advances global food security through

Table 12. Carbon mitigation and incomes in developing countries for 2003-2012 [modified from Niles et al., 2002]

Region	Forest restoration (Pg)	Sustainable agriculture (Pg)	Avoided deforestation (Pg)	Total C from all activities (Pg)	Total net present value (US$ million)
Latin America	177.9	93.1	1,097.3	1,368.3	10,237.8
Africa	41.7	69.7	167.8	279.2	2,048.9
Asia	96.2	227.3	300.5	624.0	4,528.5
Total	315.8	390.1	1,565.6	2,271.5	16,815.2

increasing agronomic/biomass productivity. Lal [2003; 2004d] estimated the global potential of soil carbon sequestration. The data in Table 13 show the annual potential of soil carbon sequestration through restoration of degraded soils and ecosystems and adoption of RMPs on agricultural (crop and grazing) and forestry lands. The annual potential is estimated at 0.53 to 1.15 Pg C/yr for adoption of RMPs on agricultural and forestry lands, 0.11 to 0.22 Pg C/yr for restoration of degraded soils and adoption of biofuel plantations on these lands, and 0.06 to 0.12 Pg C/yr for sequestration of inorganic carbon as secondary carbonates and leaching of bicarbonates in groundwater and irrigated lands (Table 13). The data in Table 13 provide the average rates over a 20- or 30-year period. In reality, the carbon sequestration rates follow a sigmoid curve: low in the beginning and near saturation at the sink capacity and very high rate between 5 and 15 years after land-use conversion. Thus, the data in Table 13 represent average rates over the entire duration until the saturation capacity is filled. Accordingly, the total potential of soil carbon sequestration in terrestrial ecosystems of the world is 0.7 to 1.5 Pg C/yr, equivalent to 20 to 40 % of the annual increase in atmospheric concentration of carbon as CO_2 estimated at about 3.5 Pg C/yr during 2000-2010. If comparisons are made with annual emissions from fossil fuel combustion, estimated at about 7.0 Pg C/yr, the potential of terrestrial carbon sequestration is equivalent to 10 to 20 % of the annual emissions. These are gross estimates and do not take into consideration the hidden carbon cost of inputs involved in farm operations, discussed in the following sections and presented in Table 14. Even if the net carbon sequestration is only 50 % of the gross sequestration, the importance of soil (and biotic) carbon sequestration towards mitigating climate change cannot be over-emphasized.

Table 13. Global potential of soil carbon sequestration assuming 70 % of managed ecosystems adopt RMPs and 50 % of all degraded soils are restored and some are converted to biofuel plantations [adapted from Lal, 2003]

Land use	Area under RMPs (Mha)	Potential of C sequestration (Pg C/yr)
I. Soil organic carbon		
A. Managed ecosystems		
1. Cropland	1,000	0.10-0.30
2. Grazing land	2,500	0.13-0.25
3. Forest and woodland	3,000	0.30-0.60
Subtotal		0.53-1.15
B. Restoration of degraded soils		
1. Water and wind erosion	500	0.10-0.20
2. Physical degradation	75	0.01-0.02
3. Chemical degradation	20	0.002-0.004
Subtotal		0.11-0.22
II. Soil inorganic carbon		
A. Dryland	5,883	0.03-0.06
B. Irrigated land	267	0.03-0.06
Subtotal		0.06-0.12
Total		0.70-1.49

6. Ecosystem carbon budgeting

There is a need to standardize a methodological protocol for evaluating the energy efficiency of biofuel production systems. While the energy output-input ratio at the factory level (e.g., ethanol production after sugarcane is delivered at the factory) is a useful index, there is a strong need to develop a comprehensive index based on a system approach including the energy balance at the farm level. Because it is the carbon budgeting that is most relevant to the issue of global warming, it is appropriate to develop a comprehensive carbon-based index. In this regard, the sustainability of a biofuel system can be assessed on the basis of the ecosystem carbon budget using the following index (Equation 1):

$$S_I = \frac{\Sigma\,(C_s + C_a)}{\Sigma\,(C_f + C_i)} \qquad (1)$$

where S_I is the sustainability index, C_s is the carbon sequestered in soil and biota, C_a is the carbon equivalent to the avoided emission through biofuel production, C_f is the carbon input at the farm level and C_i is the carbon input at the industrial plant level. This index may be constrained by the in-built assumption that there exists an energy source which can be displaced by the biofuel. Another useful index may be the one that reflects the net life-cycle carbon intensity of a unit of biofuel (Equation 2):

$$S_I = (C_{FF} + C_{FP} - \Delta\ SOC)/\text{GJ of biofuel} \qquad (2)$$

where C_{FF} is fossil carbon consumed at farm and C_{FP} is

Table 14. Carbon input by different farm operations [adapted from Lal, 2004c]

Operation	Carbon equivalent
I. Tillage (kg C/ha)	
Moldboard plowing	13.4-20.1
Chisel plowing	4.5-11.1
Disking	4.0-11.2
Sub-soiling	8.5-14.1
Rotary hoeing	1.2-3.0
II. Fertilizer (kg C/ha)	
Nitrogen	0.9-1.8
Phosphorus	0.1-0.3
Potassium	0.1-0.2
Lime	0.03-0.2
III. Pesticides (kg C/ha)	
Herbicides	1.7-12.6
Insecticides	1.2-8.1
Fungicides	1.2-8.0
IV. Irrigation (kg C/ha)	
Pumping water	150-200

fossil carbon consumed at plant, and Δ SOC is the increase in soil organic carbon pool. The index described in Eqaution 2 computes the carbon intensity of a biofuel in a manner that is directly comparable to the commonly-used life-cycle carbon intensity of fossil fuels. While the C_i at the plant level are easy to quantify, those at the farm level are diffused and difficult to monitor. Lal [2004c] collated and synthesized the available information on C_f for a range of farm operations (Table 14). Fertilizer use, pesticide application, and tillage operations are carbon-intensive inputs. Their use must be optimized and use-efficiency enhanced through adoption of RMPs outlined in the pervious sections.

7. Conclusions

- Traditional household fuels have strong adverse impacts on the soil, the environment and human health.
- Soil degradation is a serious problem in developing countries of Asia, Africa and Latin America. It is exacerbated by low external input and extractive farming practices. Soil degradation hot spots of the world coincide with the region of perpetual food deficit and poverty, and political instability.
- Because of rapid decrease in per capita land area in regions with high growth rate of population, there is a strong need to restore degraded soils and ecosystems. Depending on the predominant degradative process, restoration of degraded soils will involve off-farm input for leveling land, installing terraces and waterways, stabilizing sand dunes, providing drainage and irrigation, improving soil organic matter pool, enhancing soil fertility and alleviating nutrient imbalance. Restoring degraded soils will also involve managerial inputs.
- Agricultural intensification of prime agricultural land through adoption of recommended management practices is essential to enhancing food production for meeting future food requirements.
- Establishing biofuel plantations on restored lands and surplus agricultural lands is an important strategy for achieving energy security.
- Replacing traditional household fuels (e.g., crop residue, animal dung) with improved cooking fuel is important to reducing environmental pollution, minimizing heath hazards, and improving quality of soil and water sources.
- Assessing sustainability of biofuel production systems must be based on an index that involves the ecosystem carbon budget using a holistic approach. The ratio of carbon output to carbon input must be computed considering all components at the farm and industrial plant levels. Farm-level inputs (e.g., tillage operations, fertilizers, pesticides, irrigation) are extremely carbon-intensive. These inputs must be considered in assessing the ecosystem carbon budget and their use optimized through reducing losses. Another useful index is the one that reflects the net life-cycle carbon intensity of a unit of biofuel. It is defined as the fossil carbon consumed on the farm plus fossil carbon consumed in the plant minus net positive change in SOC pool per energy unit of biofuel.
- Soil carbon sequestration is a win-win strategy. With a global potential of 0.7 to 1.5 Pg C/yr, it can offset 20 to 40 % of the annual industrial emissions. Trading carbon credits under the CDM or the World Bank Program is a viable source of enhancing farm income. ■

Note

1. This paper was presented at the STAP Technical Workshop on "Liquid Biofuel", 29 August-1 September, 2005, TIFAC/UNEP/GEF, New Delhi, India.

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REEEP disburses Euro 2.2 million for 32 new clean energy projects

The Renewable Energy and Energy Efficiency Partnership (REEEP) recently announced 32 new projects for funding. The funding round, REEEP's fourth, represented the largest funding round in REEEP's three year history. "More projects have been funded in the areas of financing models and energy efficiency than in previous rounds," stated Morgan Bazilian, REEEP Programme Board Chair. "REEEP has also expanded its priority countries from six to twenty countries and we are engaging some countries for the first time, such as Guatemala, Kazakhstan, Liberia and Tunisia."

The increased funding was driven by the G8 dialogue last November when the UK government announced that a further £ 2.5 million would be provided in 2006-2007 and 2007-2008. In addition, the UK Foreign Ministry also announced the provision of £ 1 million. REEEP has been able to leverage this funding by a factor of six as REEEP funding is attracting co-financing from other agencies as diverse as USAID, Cordaid Netherlands, the budgets of local municipalities in South Africa and also from other donors such as the Government of Ireland. "REEEP is an ideal mechanism to help secure funding for renewable energy and energy efficiency activities in developing countries," stated Dick Roche, Environment Minister for Ireland.

Ten of the thirty-two projects are in Africa as the continent has been targeted as a key REEEP region in 2006. The majority of projects are focused on identifying business models, whether that be for solar water heating, small hydro in the tea industry or in developing biofuels across the region. "Financial barriers to renewable energy and energy efficiency in Africa are significant," stated Glynn Morris, REEEP Southern Africa Regional Secretariat Director. "By working with financial institutions, the carbon market and local government we're hoping to build the business case from the bottom up."

Across Latin America REEEP is funding seven projects, including both national and regional (Guanajuato) initiatives in Mexico to develop policy frameworks in support of renewable energy. In Guatemala REEEP is collaborating with GVEP and Fundacion Solar to assist the Government of Guatemala with the country's first ever National Energy Policy. In Brazil, finance models will be developed for renewable energy projects in the Amazon as part of Brazil's Universal Access Program (Luz para Todos) and the partnership is also assisting Petrobras with the development of a commercial ESCO.

Innovative finance is another area that REEEP is continuing to support as the partnership is promoting the Gold Standard CDM methodology in Africa, Asia and South America. This funding round also has an interesting Tradable Renewable Electricity Certificates (TREC) project in Tunisia thanks to donor funding from Italy. Corrado Clini, the Director General of the Italian Ministry for the Environment and Territory, stated, "Africa needs to develop and disseminate opportunities for innovative approaches to financing that may be generated through the carbon market – Kyoto mechanisms – and through the implementation of a tradable renewable energy certificates system involving all Mediterranean countries."

"The projects we're backing promise to deliver replicable models for renewable and energy efficient development. Our partnership of governments, NGOs and businesses is helping to establish a stable global marketplace for clean energy," explained Mark Lambrides, Director of REEEP's Latin American and Caribbean Regional Secretariat. ■

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