TABLE 3: CUMULATIVE AVOIDED EMISSIONS FROM LAND-USE CONVERSION

Land-use	Conversion to	Avoided emissions (Mg C /ha /30 yr
Tropical forest	(Mg C /ha /30 y	(Mg C /ha /30 yr
Tropical cropland	(Mg C /ha /30 y	(Mg C /ha /30 yr
Temperate cropland	(Mg C /ha /30 y	(Mg C /ha /30 yr
Temperate cropland	(Mg C /ha /30 y	(Mg C /ha /30 yr

Source: calculated from Righelato and Spracklen, 2007

Challenges of enhancing soil carbon storage

C sequestration in soils, and other terrestrial ecosystems, have both mitigation and adaptation implications. The mitigation impacts of innovative agricultural systems accrue from the net reduction in GHG emissions. The adaptation impacts of adopting improved soils and crop management systems are based on the reduction of the adverse effects of projected climate change. Yet, there are numerous challenges to realizing the mitigation and adaptation benefits of adopting agricultural innovations.

The importance of applying crop residues as an amendment to enhance the SOC pool has long been recognized (Melsted, 1954; Tisdale and Nelson, 1966). However, the nutritional requirement (e.g. N, P and S) for humification of biomass C and conversion into stable humic substances and organo-mineral complexes is not widely understood. Himes (1998) observed that additional amounts of N, P and S are required to convert biomass C into humus. Jacinthe and Lal (2005) also showed that application of N increased the humification efficiency of wheat straw in a long-term mulching experiment conducted in central Ohio.

Using the data from Morrow plots in Illinois, Khan et al. (2007) reported that use of fertilizer N promoted the decomposition of both crop residues and SOM content. These authors observed no convincing evidence of increase in the SOC pool in fertilized subplots, despite an increase in the input of the biomass-C. On the contrary, a noticeable decline in the SOC pool occurred after the application of fertilizer. However, Drinkwater et al. (1998) showed that in organic systems (without use of chemical fertilizers), legume-based cropping systems reduced C and N losses, presumably because of an increase in N availability after biological N fixation (BNF).

This important issue of the elemental requirements for SOC sequestration needs to be resolved for soil type, crop rotations and tillage method. Soil-specific and demand-specific (yield of grains and biomass, and desired rates of SOC sequestration) rates of N application are required to minimize losses, reduce environmental pollution (leaching of nitrates and emission of N_2O) and maximize energy efficiency. Biological controls of terrestrial C sinks (Schulze, 2006) and their management strategies must be identified. Innovative techniques must be developed to deliver water and nutrients directly to plant roots at the right time (and in the right formulation and amount) so that their use efficiency is high.

An increase in the SOC pool is essential to advancing global food security, especially for increasing agronomic yields in the developing countries of sub-Saharan Africa and South Asia (Lal, 2004a; 2006). However, despite the multiple benefits, the total sink capacity of biotic/terrestrial C sequestration is low and estimated at about 50–100 Pg over 50 to 100 year period (by the end of the twenty-first century). The sink capacity is limited by several interactive factors including the magnitude of historic C loss, higher rate of decomposition because of change in climate, and the more severe problems of erosion and leaching (Lal, 2009c).

Further, C sequestered in the terrestrial ecosystems can be re-emitted with a change in land use, conversion to plow-based systems, soil drainage and adoption of extractive farming practices. There is also a concern regarding the temperature-sensitivity of soil C with global warming and the positive feedback to climate change (Davidson and Janssens, 2006). There are associated C costs of farm operations related to fertilizers and pesticide use, tillage, irrigation and other farm operations (Lal, 2004b) in terms of fuel/energy, emission from the manufacture of nitrogenous fertilizers and so forth. This highlights the need for both sound cost/benefit analysis at the farming system level and assessment of the value chain and opportunities in improving C balance for the main commodities.

Significant advances in understanding the processes leading to SOC sequestration can be made using modern innovations in nanotechnology, biotechnology and information technology. A combination of nanotechnology and biotechnology can provide useful tools for restoring degraded soils and ecosystems and enhancing the SOM pool. Some possible innovations include nano-enhanced products (e.g. nanofertilizers and nanopesticides) with a nanobased smart delivery system (use of halloysite) to provide nutrients at the desired site, time and rate to optimize productivity.

Using such nanoscale formulations of agricultural chemicals can enhance the use efficiency of input, and minimize losses into the environment. Nanoporous materials (e.g. hydrogels and zeolites) can store water in the soil during the rainfall season and release it slowly during the dry season; thus minimizing the adverse effects of drought stress. With remote sensing of edaphic conditions, automatic release of targeted input (nanoscale precision farming) can effectively and efficiently alleviate soil-related constraints. However, C input into deep subsoil may lead to priming of old or passive C (Fontaine et al., 2007), which is an important topic needing additional research.

Similar to nanotechnology, biotechnology has numerous applications that assist understanding and management of pedospheric properties and processes. Relevant examples of such applications include:

- enhancing the SOC pool in terrestrial ecosystems (soils, trees and wetlands) by using genetically modified (GM) plants characterized by a favourable root:shoot ratio and harvest index with a large biomass production, and a deep root system containing recalcitrant compounds (e.g. phenolics);

- expanding the land base by bringing new land under production, which was hitherto not been cultivable, by growing specifically improved crops/cultivars, and restoring degraded ecosystems through bioremediation of contaminated soils;

- growing efficient plants with high BNF capacity, built-in resistance to drought (aerobic rice), anaerobiosis, nutrient/elemental imbalance, unfavorable soil pH/reaction, etc.; and

- developing plants that emit chemical stress signals that can be remotely sensed and treated with targeted inputs to alleviate the stress prior to severe adverse effects on production.

Co-benefits of terrestrial sequestration

There are numerous co-benefits related to enhancing the quantity and quality of the soil C pool. There is a critical/threshold level of the SOC pool below which soil ecological processes are adversely affected by associated negative impacts on numerous ecosystem services. The critical level of SOC concentrations in the root zone of some soils of the tropics is 1.1 percent (11 g/kg) (Aune and Lal, 1998). Enhancement of the SOC pool in degraded/desertified soils can lead to improvements in soil quality (structure, aeration, water-holding capacity, CEC, habitat for soil organisms, etc.), with numerous ancillary or co-benefits.

Important among the co-benefits are:

- reduced plant water stress as a result of enhanced available water capacity in the root zone;
- increased nutrient (N, P, S. Zn, etc.) retention and availability through enhancement of both the intensity and capacity factors;
- enriched species diversity of soil biota, and activity of macrofauna with regards to biotillage effects (e.g. missing, aerating) and microbial biomass/activity, i.e. decomposing, BNF (Rhizobium) and enhancing nutrient uptake especially P (mychorrhizal fungi);
- increased germination, good stand establishment and better plant growth;
- increased water infiltration capacity and reduction in surface runoff or overland flow;
- reduced risk of soil erosion, decline in dissolved and suspended soil particles and nutrients in surface runoff, and reduction of non-point source pollution;
- decreased risk to fish and other aquatic life owing to oxygen depletion in rivers, estuaries and coastal waters;
- increased use efficiency of inputs (e.g. fertilizers, irrigation) through reduction in losses of nutrients and water;
- increased NPP and agronomic yields of crops and livestock/land area, and
- mitigation of climate change by off-setting anthropogenic emissions through C sequestration in trees and soils.

Thus, in general, there is an overall increase in ecosystem services, through the restoration of SOM including a notable improvement in aesthetic value (fewer dust storms, less waterlogging, less prone to flooding, more vegetation). The economic value of the soil is improved by its improved productive potential and the ability of the ecosystems to adapt to climatic variability/disruptions is enhanced. Above all, the increase in SOM concentration is also related to the urgent and important issue of global food security.

Achieving global food security

There are more than 1 billion food insecure people in the world, and the global population is expected to increase by another 2.5 billion to 9.2 billion by 2050. In addition to caloric intake, there is the widespread problem of hidden hunger (Lal, 2009b). A healthy human diet must contain seven macro-elements (Na, K, Ca, Mg, S, P, Cl) and 17 micro-elements (Fl, Zn, Cu, Mn, I, F, B, Sc, Mo, Ni, Cr, Si, As, Li, Se, V, Co). Improving soil quality by increasing SOM is essential for the retention and availability of these elements. Advancing food security will require an increase in cereal production of 70 percent between 2010 and 2050, and the doubling