Sustainable Horticulture and Resource Management

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Abstract

The world population of 6.5 billion in 2006 is expected to reach 7 billion in 2010, 8 billion in 2025 and 10 - 12 billion by 2100, with most of the expected increase to occur in developing countries. The world's food insecure population is estimated at 730 million in 2005 and 680 million in 2010, of which 200 million are in Africa, and 3.7 billion are at risk of hidden hunger. Agricultural sustainability is closely linked with availability and quality of water and soil. Water use for urban, industrial and agricultural use, respectively, was 20, 30 and 350 km^3 yr^{-1} in 1900, and 440, 1900 and 3400 km^3 yr^{-1} in 2000. Population affected by water scarcity was 130 million in 1990, 436 million in 1995 and projected to be 800 million in 2025 and 3950 million in 2050. Per capita agricultural land availability in 1990 and 2025, respectively, is estimated at 0.05 and 0.03 ha in Egypt, 0.10 and 0.04 ha in Kenya, 0.33 and 0.05 ha in Tanzania, 0.35 and 0.07 ha in Pakistan, 0.20 and 0.12 ha in India, 0.09 and 0.05 ha in Bangladesh, 0.32 and 0.08 ha in Indonesia, 0.32 and 0.06 ha in China and 0.33 and 0.08 ha in the Philippines. Land scarcity is exacerbated by the severe problem of soil degradation in developing countries. Global land area affected by degradation is estimated by ISRIC at 1094 Mha by water erosion, 548 Mha by wind erosion, 240 Mha by chemical and 83 Mha by physical processes. Of these, percentage of degraded areas occurring in developing countries is 77 for water erosion, 83 for wind erosion, 89 for chemical degradation and 53 for physical degradation. Soil degradation depletes the soil organic carbon (SOC) pool leading to emission of CO_2 into the atmosphere. Compared with 270 ± 30 Pg C emitted into the atmosphere through fossil fuel combustion, 136 ± 55 Pg were contributed through terrestrial ecosystems, of which 78 ± 12 Pg came through depletion of the SOC pool. Sustainable horticultural practices, similar to grain crops, include mulching with crop residues and synthetic materials, growing cover crops, water harvesting, and conservation tillage or even no-till farming. The objective is to enhance soil quality and alleviate soil and environmental constraints to increasing production. Sustainable management of natural resources must be based on enhancing productivity per unit area; time and energy input; maintaining a positive trend in productivity over time; creating SOC sink capacity of natural and managed ecosystems; reducing risks of non-point source pollution and sedimentation; and making managed ecosystems a solution to environmental problems. Relevant indices of sustainable horticulture and resource management include soil quality and resilience and factors affecting them, and temporal changes in productivity, and use efficiency of non-renewable or input of limited resources.

INTRODUCTION

Horticulture is a branch of agriculture which deals with the principles and practices of growing vegetable, fruits and flowers. Thus, basic concepts of sustainable agriculture, especially with regards to soil properties and processes, also apply to sustainable horticulture. Two generic definitions of sustainable agriculture, which are also relevant to sustainable horticulture, are presented herein (Brumfield, 1996; Poincelot, 2004). In the 1990 Farm Bill, the U.S. Congress (1990) defined sustainable agriculture as "*an integrated system of plant and animal production practices having site specific*

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application that will, over the long-term: satisfy human food and fiber needs; enhance environment quality and the natural resource base upon which the agricultural economy depends; make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole." Poincelot (1990) defined the term as follows: "*Sustainable agriculture is a system in which: (1) resources are kept in balance with their use through conservation, recycling and/or renewal, (2) practices preserve agricultural resources and prevent environmental damage to the farm and off-site land, water and air, (3) production, profits and incentives remain at acceptable levels, and (4) the system works in concern with soci-economic realities*".

The objective of this manuscript is to identify and deliberate basic principles governing sustainable soil management practices which enhance and maintain productivity while restoring the natural resources. The focus of the manuscript is more on principles and concepts than on either site-specific practices or on a range of rhetorical definitions. The basic premise is how to increase productivity per unit input of the limited resources (e.g., soil area, water, energy) while restoring degraded/desertified soils and ecosystems (e.g., soil and water conservation, reclamation of salt-affected soils) and improving the environment (e.g., sequestering C in soil and biomass, reducing emissions, improving water quality).

GLOBAL ISSUES OF SUSTAINABLE MANAGEMENT OF NATURAL RESOURCES

The Farm Bill (U.S. Congress, 1990) defines sustainability in terms of the global issues which affect human needs and quality of natural resources. Some important global issues of significance during the first decade of the 21st century are discussed below:

World Population

The world population of 6.5 billion (B) in 2006 is increasing at the rate of 1.3% yr^{-1}, and is projected to be 7 B by 2010, 8 B by 2025, 9.4 B by 2050, and may stabilize around 10 -12 B by 2100 (Cohen, 2003). The world average population density of 45 people km^{-2} in 2000 may increase to 66 people km^{-2} by 2050. There are two important points of interest with regards to future changes in world population. One, most of the future increase in population will occur in developing countries where soil and water resources are already under great stress. Two, in the past 10,000 years, world's population has doubled ten times, from less than 10 m to 6.5 billion. However, it will never double again (Anonymous, 2005) because of the advances in science which have made food security a reality.

Food Security

Global grain production tripled between 1950 and 2000 from 631 million Mg to 1840 million Mg (Kondratyev et al., 2003). The rate of growth of food production exceeded that of the population until 1985, but has lagged behind since the mid 1980s. Consequently, per capita grain consumption increased from 267 kg in 1950 to 339 kg in 1985, and decreased to 303 kg in 2000. The number of chronically food insecure people in 2005 was 730 million, and increasing (Rosegrant and Cline, 2003; Shapouri and Rosen, 2006). Some fear that not only will the U.N. Millennium Goals of cutting hunger in half by 2015 not be met; the number of food insecure people may increase, especially in Africa and Asia.

Energy Need and Fossil Fuel Combustion

The global energy demand is about 400 Quads (1 Quad = Q = 10^{15} BTU), and increasing at the rate of about 2% yr^{-1} (Weisz, 2004). The future energy consumption is projected to increase to 623 Q by 2025 (EIA, 2004). The energy demand is rapidly increasing in emerging economies (e.g., China, India, Brazil, and Mexico). Fossil fuel combustion, the principal source of global energy consumption, emits 7 Gt C yr^{-1} (1 Gt = 1×10^9 metric ton) (WMO, 2006). Identifying renewable and C-neutral energy sources and enhancing energy use efficiency are a high priority (Chow et al., 2003; Parfit, 2005).

Global Warming

Atmospheric concentration of CO_2 and other greenhouse gases (GHGs) has progressively increased since the on-set of the industrial revolution. The concentration of CO_2 increased from 280 ppm since the late 1700s to 377 ppm in 2004 (WMO, 2006) and 380 ppm in 2006 (Long et al., 2006). The CO_2 concentration is increasing at the rate of about 1.8 ppm yr^{-1}. Concentration of CH_4 has increased from 700 ppb in the pre-industrial era to 1783 ppb in 2004, and is increasing at the rate of 5 ppb yr^{-1} (WMO, 2006). Similarly, the concentration of N_2O has increased from 270 ppb to 319 ppb and is increasing at the rate of 0.8 ppb yr^{-1}. Air quality, particulate matter and noxious gases with adverse impact on human health, is also a major issue in rapidly industrializing cities (e.g., Beijing) (Akimoto, 2003). The observed increase in temperature during the 20th century was about 0.6 ± 0.2ºC (IPCC, 2001), and the projected increase in temperature by the end of the 21st century may be as much as 4 to 6ºC (IPCC, 2001; Karl and Trenbath, 2003). World soils have been a source of atmospheric abundance of CO_2. It is important to identify land use and horticulture use technologies which make world soils a major sink for atmospheric CO_2.

Arable Land Area

The per capita cropland availability is decreasing, especially in densely populated countries of Asia and sub-Saharan Africa (SSA). The per capita land area in 1990 was: 0.09 ha in Bangladesh, 0.32 ha in China, 0.05 ha in Egypt, 0.20 ha in India, 0.10 ha in Kenya, 0.35 ha in Pakistan and 0.33 ha in the Philippines. The projected per capita land area in 2025 will be: 0.05 ha in Bangladesh, 0.06 ha in China, 0.11 ha in Colombia, 0.15 ha in Ecuador, 0.03 ha in Egypt, 0.11 ha in Ethiopia, 0.12 ha in India, 0.08 ha in Indonesia, 0.04 ha in Kenya, 0.18 ha in Mexico, 0.14 ha in Nigeria, 0.07 ha in Pakistan, 0.15 ha in Peru, 0.0 ha in the Philippines, and 0.05 ha in Tanzania, (Engelman and LeRoy, 1995). Therefore, the basic necessities of life of food, feed, fiber, fuel and forest must be met on an extremely small land area of as little as 0.03 - 0.04 ha (Egypt and Kenya) and 0.05 - 0.06 ha (Tanzania, Bangladesh, China). Future food demand will have to be met by increasing crop yields on existing lands (Wild, 2003). Similar to food crops, area under permanent horticultural crops is also limited. Global land area under permanent crops was 110 Mha in 1985, 120 Mha in 1990 and stabilized at 130 Mha since 1995 (McCalla and Revoredo, 2001).

Water Scarcity

Similar to land, an adequate availability of renewable fresh water resources is already a serious problem in many densely populated countries with arid and semi-arid climates. Until 1950, agriculture was the principal user of water. Agricultural water use (km^3 yr^{-1}) was 350 in 1900, 860 in 1950, 2100 in 1975 and 3400 in 2000 (Kondratyev et al., 2003). Water use for agriculture increased as land area under irrigation increased. Global irrigated land area was only 8 Mha in 1800 and 24 Mha in 1850 (Postel, 1999). It increased to 40 Mha in 1900, 81 Mha in 1931, 139 Mha in 1961, 168 Mha in 1970, 210 Mha in 1980, 244 Mha in 1990, and 274 Mha in 2000 (Federico, 2005). Expansion of irrigation increased the global water withdrawal to 3900 km^3 yr^{-1} or 10% of the total global renewable resources. Consumptive use of water (not returned to the watershed) is estimated at 1800 to 2300 km^3 yr^{-1}, and agriculture accounts for 85% of global consumptive use (Foley et al., 2005). India uses 200 km^3 yr^{-1} of water for irrigation, which is 3 times the flow of water in China's Yellow river, and the use efficiency is hardly 20 to 30%. With industrialization and urbanization, however, there is also a strong competition for water for municipal and industrial uses. Global water consumption (km^3 yr^{-1}) was 20 in 1900, 60 in 1950, 150 in 1975 and 440 in 2000 for municipal use compared with 30 in 1900, 190 in 1950, 630 in 1975, and 1900 in 2000 for industrial use (Kondratyev et al., 2003). The number of water-scarce countries and affected population (millions), respectively, was 20 and 130 in 1990, 29 and 436 in 1995, and are projected to be 30 and 800 in 2025, and 58 and 3,950 in 2050 (Engelman and LeRoy, 1993). Water scarcity is also a problem in many dry regions of North America (Parfit, 1993). In addition to water scarcity (<1000 m^3 $capita^{-1}$ yr^{-1}), water quality is an ever-increasing concern. As much as one-third of the world's rural population lacks access to safe drinking water. Ground water overdraft and lack of adequate water for expanding or maintaining the irrigated land area are major concerns (Rosegrant et al., 2003). A new approach to water resources management is inevitable (Gleick, 2003).

Soil Degradation and Desertification

Soil degradation has plagued humankind since settled agriculture began about 10,000 to 13,000 years ago. Soil area affected by degradative processes is estimated at about 2 B ha (Oldeman, 1994). However, degradation and desertification are more serious problems in developing countries of the tropics and sub-tropics than in developed economies of the temperate climates. For example, estimates of soil area (Mha) affected by degradation in the world and developing countries, respectively, are 1094 and 837 (77%) by water erosion, 548 and 455 (83%) by wind erosion, 240 and 213 (89%) by chemical degradation, and 83 and 44 (53%) by physical degradation (Oldeman, 1994). The fact that soil degradation was a common factor in many of the extinct civilizations (Diamond, 2005) has not been a learning experience to the present C-based industrial civilization.

Rural Poverty

Rural poverty has plagued agrarian societies since the beginning of time. As much as 56% of the developing world's population lives below the internationally established poverty line of \$2 day^{-1} (Litvin, 1998). Estimates of the absolute poor (millions) in developing countries was 770 in 1975, 1,125 in 1985, and 1,199 in 1998 (McCalla and Revoredo, 2001). There exists a strong link between soil degradation, low crop yields, and rural poverty. It is difficult to establish the cause-effect relationship between unsustainable soil and water management practices on the one hand, and low crop yields on the other. Nonetheless, low yields and unsustainable practices are closely linked. A large population in developing countries is prone to food insecurity because of low purchasing power.

Strategies of sustainable management of natural resources must address these global issues. Yet, site-specific management may differ because of differences in constraints to achieving high productivity. Biophysical, economic and the human-dimensions issue of sustainable development also differ among developed and developing countries.

SUSTAINABILITY ISSUES IN DEVELOPED VS. DEVELOPING COUNTRIES

Resource-poor, small landholders of South Asia, SSA, the Caribbean, Central America and elsewhere in the tropics suffer from food insecurity and poverty, and try to eke out a living from ever-degrading soils without the benefits of essential input (e.g., fertilizers, machinery, etc.). In contrast, the capital-intensive large landholders of North America, Australia and Europe are concerned not so much about hunger and malnutrition, but with low profit margin, high inputs, decreasing biodiversity, increasing reliance on fossil fuel energy and environmental pollutants. Therefore, the planning time horizon for small landholders may be daily, or at the most, seasonal food supply for the farm family, compared with generational sustainability of soil and water resources and environmental quality for the large-scale commercial farms. For resource-poor farmers to whom the off-farm input (e.g., fertilizer, pesticides, machinery for tillage, etc.) are either not available or are available at a prohibitively expensive cost, the concept of sustainable agriculture as it evolved during 1980s in North America is completely irrelevant. To a small landholder in SSA, cultivating 0.5 to 1 ha of land, sustainable agriculture is not synonymous with a range of terms that emerged in North America (Poincelot, 2004), such as: alternative agriculture, biodynamic farming, biological/ecological farming, Kyusei nature farming, low input, etc. Crop yields in case of resource-poor farmers are low and their agricultural practices unsustainable, as is evidenced by perpetual hunger and sub-standard living, because they are unable to use the essential input needed to break the agrarian stagnation. For the resource-poor farmers, in the strong grip of poverty and hunger, the concept of "low input" farming is not only utterly irrelevant, it is the cause of the deplorable conditions in which farmers of SSA and South Asia have existed for generations, and must not be condemned to exist in such conditions for future generations to come. Therefore, the concept of sustainable horticulture for resource-poor farmers of SSA, etc., is different than that of the large landholder and commercial farmers of North America (Table 1; Lal, 2004a). The overall goal for small landholders is to achieve food security, increase farm income, optimize input, and restore degraded soils.

For the large-scale farmers, high input, increasing energy costs, massive capital investment in heavy equipment and high cost of labor are cutting into the profit margin and jeopardizing the cash flow. Indiscriminate use of farm chemicals at high rates is causing pollution and eutrophication of water. High energy consumption for mechanized farm operations (Table 2) is causing emission of CO_2 and other GHGs into the atmosphere. Thus, the goal of large-scale commercial farmers is to reduce input of fertilizers and pesticides, find alternatives via integrated nutrient management (INM) and integrated pest management (IPM) and decrease energy-intensive farm operations by converting plow tillage to no-till farming, etc. For small, resource-poor farmers, on the other hand, application of organic amendments may be useful but not enough to create a positive and balanced nutrient budget needed to increase crop yield; use of crop diversification for pest control may be irrelevant because he/she already grows 6 to 10 crop species on the same land at the same time; substituting energy-efficient equipment for farm operations is inappropriate because the only equipment he/she uses are a hoe, machete and a match box.

Despite the apparent differences and seemingly contradictory approaches to creating the new culture of agriculture/horticulture, regardless of the farm size and resource availability to land managers in the tropics and temperate regions, there are numerous commonalities towards advancing the goals of sustainable resource management (Fig. 1). The common goal of increasing productivity per unit use of soil area, time, and off-farm input can be achieved by two synergistic approaches:

a. Conserving, restoring and enhancing the natural resource base by:
   (i) Increasing soil carbon pool and improving soil quality,
   (ii) Conserving and restoring soil and water resources, and
   (iii) Strengthening the recycling mechanisms and creating a positive nutrient budget.

b. Reducing, decreasing and minimizing losses out of the ecosystem by:
   (i) Minimizing losses of energy and energy-based input,
   (ii) Reducing emissions of CO_2, N_2O, CH_4 through mineralization, decomposition, methanogenesis, volatilization, nitrification and denitrification, and
   (iii) Decreasing losses of soil through erosion, water through runoff and evaporation, and nutrients through leaching and extractive farming practices.

NEED FOR SUSTAINABILITY

Domestication of plants and animals began about 10,000 to 13,000 years ago, when most probably women initiated settled agriculture (Cavalli-Sforza and Cavalli-Sforza, 1995). Anthropologists argue that hunter-gatherer society comprise the men who hunt and women who gather. Naturally, therefore, women of Neolithic age (new Stone Age) knew more about plants and used their knowledge to sow seeds near their dwellings and started to produce their own food. Horticultural plants, especially fruit trees such as fig (Kislev et al., 2006), may have been among the earliest domesticated plants along with cereals. Some studies suggest that fruit rather than grains (e.g., wheat, barley) may have been purposefully planted at the onset of settled farming (Gibbons, 2006). This shift led to a drastic increase in the carrying capacity of the land. Therefore, a population of a few million about 10,000 years ago increased over a thousand-fold to 6 billion by 2000 in four to five hundred generations (Smil, 2000), and is expected to reach 10 billion mark by 2100 (Cohen, 2003). However, the issues of sustainability have changed little over 10,000 years. Yet, the approach, strategies, and soil management options keep changing to suit specific needs and technological skills of every generation.

Adoption of the so-called "Green Revolution" technologies (e.g., growing improved high-yielding cultivars with chemical fertilizers, pesticides, mechanization and irrigation) have doubled global grain harvests and edibles between 1965 and 2005 to 2 billion Mg of grains yr^{-1} (Foley et al., 2005). The doubling of grain production was achieved by increase in fertilizer use by 700% and irrigated land area by 70%, with drastic adverse environmental consequences with regard to water quality, salinization (+1.5 Mha yr^{-1}), accelerated erosion (40% of world cropland affected by erosion, fertility depletion, etc.) and the loss of native habitat of useful insects (Foley et al., 2005). Expansion of agriculture has also affected components of the hydrological cycle - increasing surface runoff over the seepage or plant uptake (Lal, 1998). Water tables are declining in regions intensively irrigated with ground water (e.g., Punjab, India) (Pachauri and Sridharan, 1999).

Expansion of land area sown to grain and horticultural crops has depleted the world's forest resources by 700 to 1100 Mha between 1700 and 2000 (Ramankutty and Foley, 1999). In addition, intensively managed forest plantations cover 190 Mha of land area (Williams, 1994).

Change in land use (conversion of forests and prairies to agriculture), alterations in components of the hydrological cycle (increase in surface runoff and consumptive use), depletion of the terrestrial C pool (136 ± 55 Gt of C emitted into the atmosphere) (IPCC, 2000), have altered global climate as evidenced by increase in mean annual temperature (0.6 ± 0.2ºC) (IPCC, 2001). Deforestation of tropical rainforest may create a warmer and drier micro-climate in the tropics (Lal, 1981, 1997a; Lawson et al., 1981).

Changes in land use and the attendant anthropogenic perturbations have adversely impacted ecosystem services, especially the capacity of world soils to sustain food production, moderate climate, and maintain a clean fresh water supply. Thus, there is a strong need to identify and adopt sustainable land use and soil management systems to support the world population of 10 B inhabitants on shrinking soil, water and other resources.

APPROACHES TO SUSTAINABILITY

Sustainable management of soil implies that losses by erosion must be curtailed, nutrient cycling mechanisms must be strengthened, the SOC pool depleted by mineralization and erosion/leaching must be replenished, nutrient supply must be maintained to achieve the desired yields, soil structure and tilth must be maintained at favorable level to create an optimal air: water balance, and the activity of soil flora and fauna enhanced to an optimal level to create favorable edaphic environments. These basic principles of sustainability must be considered in the context of the scarcity of non-renewable resources and increasing demand of the world's growing population. Thus, there is a strong need to rethink the strategies of land use, water resource management, energy use, and intensive agricultural/horticultural practices. Approaches to sustainable horticulture have been described by many (e.g., Dixon, 1991; Brumfield, 1996; Poincelot, 2004), and are outlined in Table 3. Some specific sustainable horticultural technologies suggested include: (i) intercropping in field vegetables (e.g., white cabbage inter-cropped with white clover; leeks planted in subterranean clover) to reduce dependence on pesticides and to increase the land equivalent ratio (Theunissen, 1997); (ii) improving N and P management to enhance nutrient use efficiency of carrots, cauliflower, Chinese cabbage, etc., in western Australia by reducing leaching losses by moderating irrigation application (Paulin et al., 1995); (iii) enhancing water use efficiency under irrigated horticulture by matching the biophysical efficiency with the economic efficiency (Stirzaker, 1999); (iv) preventing erosion and soil structural decline on sloping lands through soil management practices (Rose, 1997); (v) using minimum tillage and other improved management practices for horticultural crops on peat soils (Frengley, 1983; Cohen, 1984); (vi) using compost as an integrated nutrient management option for vegetable production (Kropisz, 1992); (vii) enhancing soil fertility through soil organic matter management (Kazlowski and Kropisz, 1992); and (viii) managing crop residues and biosolids to improve nutrient cycling and reducing leaching losses (Rahn et al., 2003).

Approaches to sustainable horticulture and resource management options depend on specific questions such as (Brumfield, 1996):

- What management practices affect sustainability?
- What crops can be established using no-till farming?
- How can use efficiency of inputs be enhanced?
- How can degraded soils be restored?

Some technological options for sustainable management of soil and water resources for horticulture crops are outlined in Table 5 and briefly described below:

Mulch Farming

Mulch farming is an important component of improving soil quality, conserving soil and water, moderating temperature and improving yield of horticultural crops. There is a wide range of mulching materials including plastic sheet (e.g., black, clear, translucent (Figs. 2a and 2b), and plant biomass (Fig. 3). Daniello et al. (1999) evaluated the benefits of water harvesting using plastic mulches on yield of musk melon (*Cucumis melo* var. *reticulatus* L.) in Texas. Rainfall capture by plastic mulch resulted in 108% average yield increase over the conventional dry land techniques. In comparison with the convectional furrow irrigation, rainfall irrigation increased marketable yield by 6000 kg ha^{-1}, saved water, and enhanced water use efficiency (Table 4). Using biomass (e.g., crop residue or mulch from a specifically grown cover crop (such as elephant grass or guinea grass) can have ancillary benefit of enhancing soil organic carbon (SOC) concentration and nutrient cycling. A combination of plant biomass with no-till farming has additional benefits of erosion control and SOC sequestration (Lal, 2004b). Runoff from tomatoes can be decreased by biological measures such as mulching (Arnold et al., 2004). The effect of mulching on bunch yield of plantain (*Musa* spp.) was assessed for an Ultisol in eastern Nigeria. There were two types of mulch materials: biomass of elephant grass (*Pennisetum purpureum*) and live mulch of *Flemingia congesta* grown as an inter-crop with plantain. The data in Table 4 show that mulching with biomass induced flowering earlier than the other two treatments. Further, bunch yield of the treatments with biomass mulching was significantly (+25%) more than that of the unmulched control (Table 5). Similar effects of mulching on growth and yield of coffee have been widely reported. Mulch farming is extremely beneficial to the production of summer vegetables, especially with its positive impact on water conservation and temperature moderation.

Cover Crops

A wide range of cover crops are used for vegetable production in North America. A survey conducted by Stivers-Young and Tucker (1998) indicated that vegetable growers in western New York used the following cover crops: oats (*Avena sativa* L.), rye (*Secale cereale*), clover (*Trifolium pratense*), and wheat (*Triticum vulgare*). Some farmers also used sudan grass (*Sorghum sudanese* pipe) and the sorghum-sudan hybrid (*Sorghum biocolor* × *s. sudanese*). Principle benefits of using cover crops included erosion control, weed suppression, improvement in the SOC pool, increase of soil fertility, reduction in soil compaction, improvement of soil tilth, decrease in pest incidence, conservation of soil moisture, reduction in runoff and increase in crop yield. Establishing cover crops is a cultural tradition for soil and water conservation in tree plantations in the tropics (e.g., rubber, oil palm). A commonly grown cover crop is kudzu (*Pueraria phaseoloides*), which also enhances soil fertility through biological nitrogen fixation (BNF). Experiments conducted at the Rubber Research Institute in Malaysia (1974) showed that soil erosion under a cover of Nephrolepis (a fern) was zero compared with 35 $t \cdot ha^{-1} \cdot yr^{-1}$ under grass cover and 82 $t \cdot ha^{-1} \cdot yr^{-1}$ for bare soil in between the rubber trees. Cover crops under oil palm and coconut plantations are also very effective in erosion control (Fig. 4).

Rainfed tree crops (e.g., olives, almonds), are grown on large areas in Mediterranean regions (Faulkner et al., 2003), and these plantations are established on agriculturally marginal steeplands. Orchards are frequently plowed to minimize weed competition for water, which causes severe soil degradation. (Oñate and Peco, 2005). Van Wesemael et al. (2006) reported that tillage erosion in these orchards can be as much as 27 $t \cdot ha^{-1} \cdot yr^{-1}$, making orchard soils progressively thinner and stonier.

Erosion Control

Accelerated soil erosion is a serious problem on sloping lands of the tropics and sub-tropics where fruit trees are grown. Growing cover crops, mulching and use of herbicides for weed control are extremely effective in erosion control under fruit trees established on steep terrains. Lombardi et al. (1975) observed that soil erosion under coffee trees in Brazil decreased from 49 $t \cdot ha^{-1}$ under unmulched control to 0.4 $t \cdot ha^{-1}$ with a low growing cover crop planted in between coffee trees. Soil surface management with crop residue mulch is more effective in erosion control than terracing and other engineering structures (Lombardi et al., 1975). Erosion control on sloping lands is also achieved by constructing terraces for fruit trees (Fig. 5).

Sustainability and Climate Change

Among numerous emerging issues, sustainable horticulture and agriculture have to address the concerns related to the projected climate change. A few aspects of climate change of relevance to sustainable production are: (i) increase in temperature; (ii) increase in frequency of extreme events such as drought and flood; (iii) increase in risks of soil degradation; and (iv) uncertainties about the CO_2 fertilization effect. Any increase in soil temperature and the attendant decline in plant-available soil moisture would enhance the rate of mineralization of soil organic matter (SOM), and increase soil's susceptibility to erosion and other degradative processes. Any increase in crop yield because of the CO_2 fertilization effect may be negated by soil degradation and drought (Long et al., 2006). Furthermore, enhanced productivity due to CO_2 fertilization would require additional plant nutrients (e.g., N, P) and water.

One of the strategies to address the concerns of global climate change is to adopt management practices which enhance SOC pool, improve soil structure, reduce risks of soil erosion, moderate soil moisture and temperature regimes, recycle plant nutrients, increase use efficiency of water and nutrients and suppress weeds. Some of these technological options including use of mulch, cover crops, compost, etc. (Table 6). No-till farming with use of crop residue mulch may be an important option to address the issues of potential climate change.

No-Till Farming

Similar to grain crops, no-till farming is also gaining popularity for vegetable production. Mundy et al. (1999) assessed yields of potato (*Solanum tuberosum* L.) by no-till, sub-surface tillage and conventional tillage at two sites in North Carolina. Potatoes were planted in the residue of sorghum x sudan grass mulch. Potato yield was more in all tillage systems at one site, but was lower under no-till at another site. Yield reduction in no-till may have been caused by soil compaction. Adoption of strip tillage can reduce the impact of soil compaction. Bottenberg et al. (1999) assessed soil quality, crop growth and incidence of pests in snapbean (*Phaseolus vulgaris* L.) planted in rye mulch with and without strip tillage. The average yield loss was 63% in rye mulch without strips and 20% in rye mulch with strips compared to conventional tillage (Table 7). The adoption of no-till farming for vegetable production has been slow because of the need for a new type of equipment, especially for transplanting. Morse (1999) outlined several reasons for slow adoption of no-till farming in horticultural crops. Important among these are: (i) inadequate equipment; (ii) poor, uneven stands; (iii) loss of precocity or earliness; (iv) weed control problems, and others. Adoption of no-till for horticultural crops can be greatly facilitated by establishing appropriate cover crops which produce the desired mulch but also suppress weed growth. Some relevant winter cover corps for temperate climates are black oat (*Avena stregosa* Schreb.), cereal rye (*Secale cereale* L.), fox tail millet (*Setaria italica* L.), buckwheat (*Fagopyrum saggitatum* Grlib.) and crimson clover (*Trifolium incarnatum* L.) Cover crops for tropical environment are kudzu (*Pueraria phoseoloides*), mucuna (*Mucuna utilis),* centrosema (*Centrosema pubescens*) and others. It is easy to transplant vegetables through the killed sod of a cover crop. Effects of mulches and cover crops on tomato yields are shown in Tables 8 and 9. While it is possible to obtain yields equivalent to conventional tillage, reduction in yields of vegetables sown with a no-till system can happen due to soil compaction, weed competition and other factors. Thus, development of a soil guide to tillage requirements is essential (Lal, 1985).

Synthetic Mulches

Use of synthetic mulches (polethylene, paper) (Figs. 2a and 2b), have been useful for moisture conservation, soil temperature management and weed control. Synthetic mulches are more effective in weed control than organic mulches (e.g., crop residue, compost). However, synthetic mulches do not increase the SOC pool or recycle nutrients as organic mulches do. Synthetic mulches are also not easily biodegradable. Beneficial effects of black plastic mulch on the yield of tomato are shown in Table 10.

SUSTAINABILITY INDICES

Economic Indicators of Sustainability

There are several indices to assess sustainability. The relevance or choice of an index depends on the site-specific conditions and specific sustainability question being addressed. Some relevant indices with regard to soil quality and sustainability are briefly described below (Lal, 1991, 1993, 1994, 1998).

1. Productivity. It is related to the biophysical output measured in terms of biomass yield or production per unit area ($t \cdot ha^{-1} \cdot yr^{-1}$). The term productivity refers to production per unit of resources used (Eq. 1).

$$P = p/R \quad \text{. . . . . (Eq. 1)}$$

where P is productivity, p is total biophysical production (tomato yield) and R is the resource input (e.g., fertilizer and water use, land area). In general, productivity P is measured over decadal time scale. A system is sustainable if P has a non-negative trend over a long time horizon.

2. Total Factor Productivity (TFP). While productivity (P) is computed in relation to a single factor (e.g., land area, fertilizer use, irrigation), Total Factor Productivity (TFP) is assessed by considering the cost of all factors of production (Eq. 2).

$$TFP = p/\sum_{i=1}^{n} (R_i / C_i) \quad \text{. . . . . (Eq. 2)}$$

where p is total production, R_i is the resource used, C_i is the cost of specific input and n is the amount of input or resources used. The term TFP is an economic index, and is a measure of total output relative to total managed input (e.g., seed, water, fertilizer, labor, land, pesticides, machinery).

3. Total Natural Resource Productivity (TNRP). While TFP considers only the managed input, TNRP also considers all indirect costs associated with specific output.

Indirect costs may be due to degradation of soil resources such as decline in topsoil depth by accelerated erosion, depletion in the ground water table by irrigation, increase in soil salinity, decrease in SOC pool (Eq. 3).

$$TNRP = (TFP)/\Delta S \quad \text{(Eq. 3)}$$

where ΔS refers to the change in soil properties. The TNRP index is also called the “Total Social Factor Productivity” (Herdt and Steiner, 1995). A sustainable system would maintain a non-negative trend in TNRP over a decadal time scale.

Land Resources Indicator of Sustainability

Productivity per unit of land area is an important indication if soil resources are limited, as is the case in densely populated countries. In a sustainable system, productivity increases with time even though it may be lower than other systems over a short period of time. In contrast, productivity decreases with time in an unsustainable system even through it may be higher than productivity in the sustainable system over a short period of time (Fig. 6). Thus, temporal changes in productivity per unit area in relation to changes in soil properties are a good measure of sustainability. Some relevant indices of sustainability are as follows:

1. Land Use Factor (L). The factor “L” is defined as the ratio of cropping period (C) plus fallow period (F) to the cropping period (Eq. 4).

$$L = (C + F)/C \quad \text{(Eq. 4)}$$

The factor L is generally high for low intensity or extensive land use systems (e.g., shifting cultivation, bush allow rotation (Okigbo, 1978).

2. Land Equivalent Ratio (LER). The LER is a useful index for inter-cropping system, and is calculated as follows (Eq. 5).

$$LER = \sum_{i=1}^{n} Y_i / Y_m \quad \text{(Eq. 5)}$$

where Y_i and Y_m are yield of component crops in the intercrop and monoculture system, respectively, and n is the number of crops involved (Willey and Osiru, 1972).

3. Area Times Equivalent Ratio (ATER). Most horticultural crops involved in an intercrop mixture vary widely in their maturity. Therefore, the ATER index considers the growth duration of different crops, (Hiebsch and McCollum, 1987) (Eq. 6).

$$ATER = \frac{1}{t} \left[\sum_{i=1}^{n} \frac{d.Y_i}{Y_m} \right] \quad \text{(Eq. 6)}$$

where d is the growth period of the crop in days, t is the time in days for which the field remained occupied (i.e., the growth duration of the longest crop). Numerical value of ATER approaches that of LER for a mixture of crops of identical growth or when t = d in Eq. 6.

Soil Sustainability Indices

Several compound parametric indices have been proposed as indices for measuring sustainability (Lal, 1991). Of relevance to horticultural sustainability among these are the following:

1. Coefficient of Sustainability (C_s). It is a measure of change in soil properties in relation to production under specific management system (Eq. 7) (Lal, 1991).

$$C_s = f\,(O_i, O_d, O_m)_t \quad \text{(Eq. 7)}$$

where C_s is coefficient of sustainability, O_i is output per unit input that maximizes per capita productivity or profit, O_d is output per unit decline in the most limiting or non-renewable resource, O_m is the minimum assured output, and t is time.

2. Index of Sustainability (I_s). It is a measure of sustainability relating productivity to change in soil and environmental characteristics (Lal 1993; Lal and Miller, 1993) (Eq. 8).

$$I_s = f\,(P_i * S_i * W_i * C_i) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 8)}$$

where I_s is index of sustainability, P_i is productivity per unit input of the most limited resource, S_i changes in soil properties, W_i is change in water resources and quality, C_i is change in climatic parameters, and t is time. Specific changes in soil properties may include a decrease in the effective rooting depth, reduction in the SOC pool, decline in available water holding capacity, etc.

3. Horticultural Sustainability. It is broad-based index based on several parameters associated with horticultural production (Lal, 1993, Eq. 9):

$$H_s = d\,(P_t * S_p * W_t * C_t)_t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 9)}$$

where H_s is horticulture sustainability, P_t is productivity per unit input of the limited or non-renewable resource, S_p is critical soil property (e.g., SOC pool, rooting depth), W_t is available water capacity including water quality, and C_t is the climatic factor such as gaseous flux from horticultural activity, and t is time.

4. Sustainability Coefficient (S_c). It is a complex and a multi-purpose index based on a range of parameters, and is similar to H_s (Eq. 10 and 11):

$$S_c = f\,(P_t * P_d * P_m)_t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 10)}$$

$$S_c = d\,(P_t * W_d * C_t)\,dt \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 11)}$$

when P_t is productivity per unit input of the limited resource, P_d is productivity per unit decline in soil property, P_m is minimum assured productivity, S_c is critical level of soil property, W_t is soil water regime and quality, C_t is climatic factor, and t is time.

Soil Resilience Based Index

The term "soil resilience" refers to ability of a soil to recover following a perturbation, and it strongly affects sustainable use of soil (Lal, 1997b). There are a number of processes and factors which affect soil resilience. Important processes which affect soil resilience are: soil formation, nutrient cycling, and plant community succession. There are also several factors which affect soil resilience such as soil quality, terrain, climate and biodiversity. In addition, causes of changes in soil resilience include anthropogenic activities such as land use and management, socio-economic and political factors (Lal, 1997b). Soil resilience refers to the rate of change of soil quality (Eq. 12).

$$S_r = dS_q/dt \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 12)}$$

where S_r is soil resilience, S_q is soil quality and t is time. Soil resilience can be modeled as per Eq. 13.

$$S_r = S_a + \int_o^t (S_n - S_d + I_m)\,dt \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 13)}$$

where S_a is the initial or antecedent condition, S_n is the rate of soil renewal, $\acute{I}_d$ is the rate of soil degradation, and I_m is the management input. Eq. 13 is more easily applied to a specific soil property (e.g., SOC pool) than to a combination of several properties or soil system as a whole (Lal, 1993, 1994).

Scale of Assessment of Sustainability

Sustainability can be assessed at different temporal and spatial scales. Temporal scales may range from a season to decadal, human generation (25 years) or longer (centuries or millennia). Sustainability of soil resources must be assessed at long time scale of generations, centuries or millennia. There are also a range of spatial scales which may include: Micro-plot <10^1 m^2), field plot (10^1 - 10^2 m^2), landscape (10^2 - 10^4 m^2), watershed (10^4 - 10^6 m^2), and river basin (10^6 - 10^{12} m^2). The choice of a scale depends on the specific objectives.

CONCLUSIONS

Sustainable management practices include mulch farming, cover cropping, no-till, integrated nutrient management, inter-cropping, etc. The long-term goal is to minimize risks of soil erosion, enhance soil organic carbon pool, improve soil structure, increase soil resilience and maintain a non-negative trend in horticultural productivity per unit input of energy, or other limited or non-renewable resources. Globally, per capita soil resources are decreasing and renewable fresh water declining, while the number of food insecure people is increasing. Thus, it is important to adopt soil and water management practices which enhance productivity per unit land area and sustain the increasing trend in perpetuity. There are several indices of assessing sustainability at different temporal and spatial scales. The choice of index, whether economic (productivity, TFP), ecologic (L, LER, ATER) or soil (C_s, I_s, H_s, S_r) depend on the objectives. Further, the sustainability must be assessed at generational scale temporally and at farm or a small watershed scale spatially. The choice of sustainable practices, both in terms of land use and soil/crop management, must address the critical global issue (e.g., food security, global warming), and these issues may change with time, region, and socio-economic and political situations.

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Tables

Table 1. Conceptual differences in sustainable horticulture for resource-poor small land holders vis-à-vis large scale commercial farms.

Parameters	Resource-poor small land holders of sub-Saharan Africa	Large scale commercial farmer of North America
1. Crop yields	Maximize	Optimize
2. Off-farm input	Optimize	Minimize
3. Time horizon	Short-term	Long-term
4. Societal concerns	Immediate family	Community, nation, global
5. Soil quality	Mining for short-term	Enhancing for long-term sustainability
6. Cash flow	Enhance income	Increase profit
7. Water resource	Increase supply	Improve quality
8. Productivity criterion	Minimum assured yield in a bad year	Maximum stable yields
9. Sustainability	High total production	High production per unit input
10. Knowledge base	Traditional	Science-based

Table 2. Carbon emission from farm operations (Adapted from Lal, 2004c).

Farm operations/input	Equivalent carbon emission
Farm Operations (kg C ha^{-1})	
Moldboard plowing	13.4 - 20.1
Chisel plowing	4.5 - 11.1
Disking	4.0 - 7.1
Sub-soiling	8.5 - 14.1
Cultivation	3.0 - 8.6
Rotary hoeing	1.2 - 2.9
Spraying herbicides	0.7 - 2.2
No-till-planting	3.7 - 3.9
Sowing	2.2 - 3.9
Corn harvesting by a combine	8.5 - 11.5
Input (kg C kg^{-1})	
Nitrogen fertilizer	0.9 - 1.8
Phosphorus	0.1 - 0.3
Potassium	0.1 - 0.2
Herbicides	1.7 - 12.6
Insecticides	1.2 - 8.1
Fungicides	1.2 - 8.0

Table 3. Technological options for sustainable management of soils.

Objectives	Technological options
Soil conservation	No-till farming, residue mulch, cover crops
Water conservation	Mulching, fertigation, drip irrigation, water harvesting and recycling
Positive nutrient budget	Nutrient cycling through use of crop residue mulch, compost, manure and fertilizers, precision farming, inter-cropping with legumes
Energy management	No-till or conservation tillage, precision farming, fertigation

Table 4. Impact of water harvesting by plastic mulch on yield of musk melon in Texas (Modified from Daniello et al., 1999).

Treatment	Yield ($t \cdot ha^{-1}$)	Total water use (cm)	Water use efficiency ($kg \cdot cm^{-1}$)
Drip Irrigation + Plastic Mulch	30.0	33.6	359
Rainfall Capture	23.8	73.7	323
Control (furrow irrigation)	22.7	136.7	166

Table 5. Effect of mulching with plant biomass on yield of plantain (*Musa* spp.) in eastern Nigeria (Adapted from IITA, 1985).

Treatment	Yield of Plantains ($t \cdot ha^{-1}$)	Mean bunch weight (kg)	Plants fruited (%)	Days to flowering
No mulch (control)	1.87 b	9.8 c	75.0 a	381 a
Inter-cropping with *Flemingia congesta*	22.3 a	10.3 b	86.7 a	391 a
Mulch with biomass of *Pennisetum purpureum*	23.3 a	10.6 a	87.5 a	357 b

Values in column followed by the same letter are not different at 5% level.

Table 6. Effect of sustainable management practices on production of horticulture crops.

Crop	Country	Purpose	Reference
		Straw mulch	
Tomatoes	Nigeria	Moisture conservation	Agele et al. (2000)
Coffee	Ghana	Reduce cost	Afrifa et al. (2003)
Cabbage	USA	Nutrient management	Riley et al. (2003)
Tomatoes	USA	Organic matter management	Schonbeck and Evanylo (1998)
Bamboo	China	Early emergence	Jiang et al. (2002)
Potato	Belgium	Seed quality	Momirovic et al. (1997)
Squash	-	Improve yield	Sari et al. (1994)
		Plastic mulch	
Sweet corn	-	Prolonging growing	Kwabiah (2004)
Tomatoes/cucumber	USA	Nutrient use	Mayfield et al. (2002)
Tomatoes	USA	Improve yield	Abdul-Baki et al. (2002)
Tomatoes	USA	Erosion control	Arnold et al. (2004)
Tamatillo	Mexico	Soil temperature	Diaz-Perez et al. (2005)
Tomatoes	USA	Runoff and pesticides	Rice et al. (2001)
Vegetable	USA	Temperature loss management	Purser (1993)
		Paper mulch	
Vegetables	Belgium	Weed control	Runham et al. (2000)
Vegetables	USA	Alternative to plastic	Anderson et al. (1992)
		Cover cropping and Legume Live Mulch Intercropping	
Tomatoes	USA	Improving soil fertility	Yaffa et al. (2000)
Vegetables	Norway	Weed control	Brandsaeter and Netland (1999)
Vegetables	Tropics	Enhance production	Kleinhenz et al. (1997)
Tomatoes	USA	Improve yield	Abdul-Baki et al. (1996)
Tomatoes	Nigeria	Improving yield	Akintoye et al. (2005)
Vegetables	Taiwan	Soil nitrogen management	Kleinhenz et al. (1997)
Vegetable intercropping	USA	Improve yield	Wiles et al. (1989)
		Compost	
Bell pepper, cucumber	USA	Improve yield	Roe et al. (1997)
		No-Till/Reduced Tillage	
Vegetables	USA	Provide mulch cover	Morse (1999)
Vegetables	USA	Minimize soil disturbance	Abdul-Baki and Teasdale (1993)
Cabbage	USA	Improve yield	Wilholt et al. (1990)

Table 7. Effects of tillage systems on snapbean pod yield in 1996 planted through the mulch of rye cover crop in Illinois, USA (Modified from Bottenberg et al., 1999).

Tillage System	Insecticide	Pod Yield ($t{\cdot}ha^{-1}$)	Relative Yield
Conventional tillage	With	7.3 a	100
Conventional tillage	Without	4.5 b	62
Rye mulch with strips	With	3.0 b c	41
Rye mulch without strips	Without	3.4 b c	47
Rye mulch without strips	With	2.1 c d	29
Rye mulch without strips	Without	1.1 d	14

Means followed by the same letter are statistically similar.

Table 8. Effect of tillage and mulching on yield of late season tomatoes in Nigeria (Modified from Agele et al., 2000).

Treatment	Tomato yield ($t \cdot ha^{-1}$)
Tillage methods	
Hand hoeing	4.9
Raised bed	5.5
Ridging	5.3
S.E.	0.7
Mulching	
Unmulched	5.2
Mulched	7.9
S.E.	0.7

Table 9. Effect of cover crop, mulching and no-till on tomato yield in Maryland, USA (Abdul-Baki and Teasdale, 1993).

Treatment	Total yield for optimum planting date ($t \cdot ha^{-1}$)
Unmulched control	51.8
Hairy vetch	137.2
Subterranean clover	95.7
Horto paper	95.7
Black polyethylene	114.8
LSD (.05)	12.5

Table 10. Effects of mulch type on total tomato yield for site (Modified from Schonbeck and Evanylo, 1998).

Treatment	Soil temperature at 9 cm (°C)		Total tomato yield ($t \cdot ha^{-1}$)		
	A. M.	P. M.	Early	Late	Total
Black plastic	18.8	28.4	19.3	8.6	27.9
Paper	16.5	23.4	15.1	14.9	30.0
Oiled Paper	18.7	30.4	15.2	11.2	26.4
Compost	-	-	14.2	24.3	38.5
Oiled paper + hay	-	-	15.4	20.0	35.4
Hay	-	-	12.0	23.7	35.7
Unmulched	-	-	10.8	14.4	25.2
LSD .05	16.8	26.5	N.S	8.9	N.S

Figures

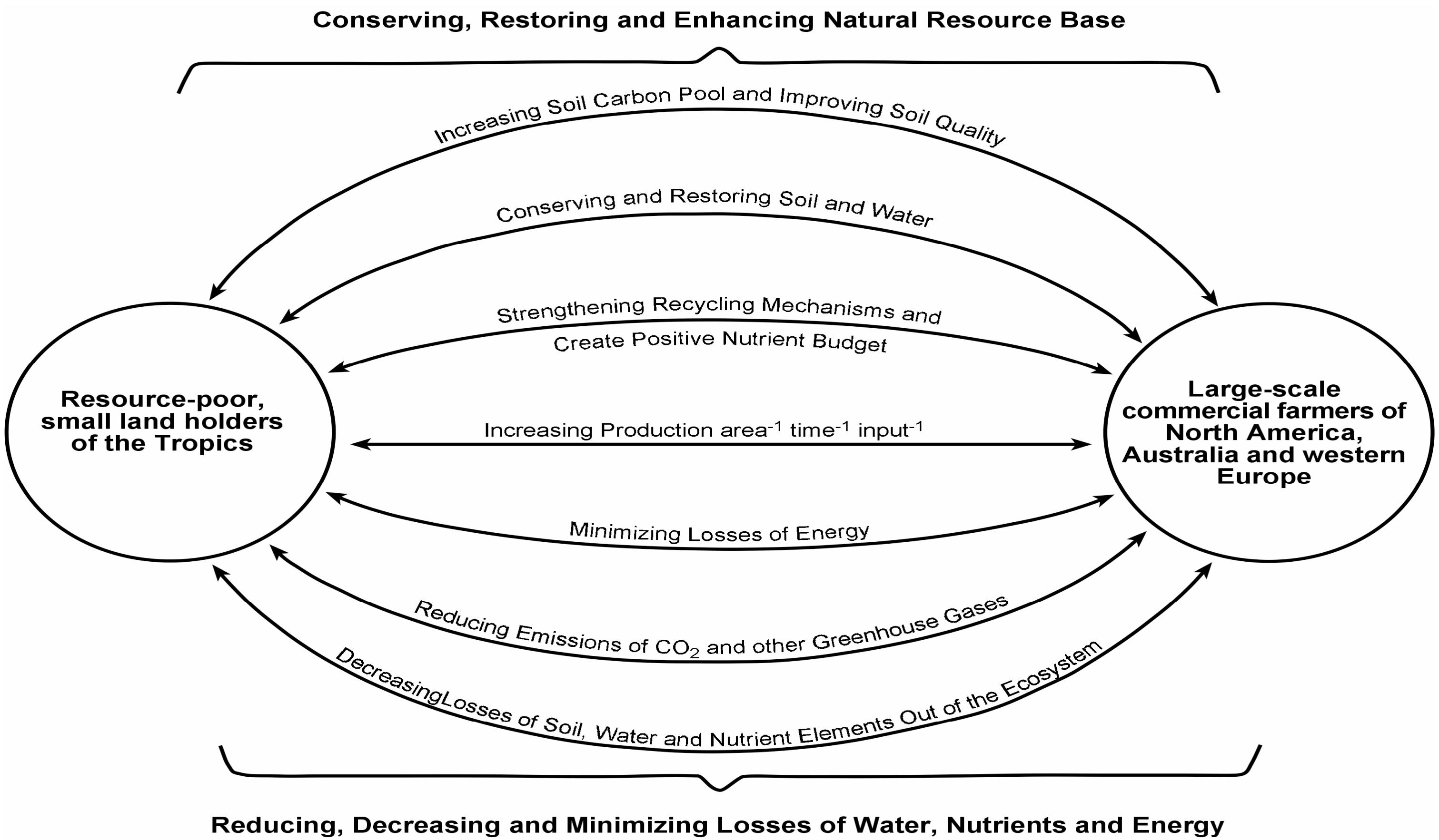

Fig. 1. Principles underlying sustainable management of natural resources common to both resource-poor small landholders and large-scale commercial farmers.

Fig. 2a. Cassava (*Manihoc esculenta*) cultivation with clear plastic mulch for moisture conservation and weed suppression in western Nigeria.

Fig. 2b. Use of black plastic for vegetable production in Willard, Ohio, USA.

Fig. 3. Field experiments on comparison of soil moisture and temperature regimes under straw mulch and clear plastic on Alfisols in western Nigeria.

Fig. 4. Use of kudzu (*Pueraria phaseolides*) in between coconut trees in Java, Indonesia.

Fig. 5. Fruit terraces for citrus plantation in Valencia, Spain.

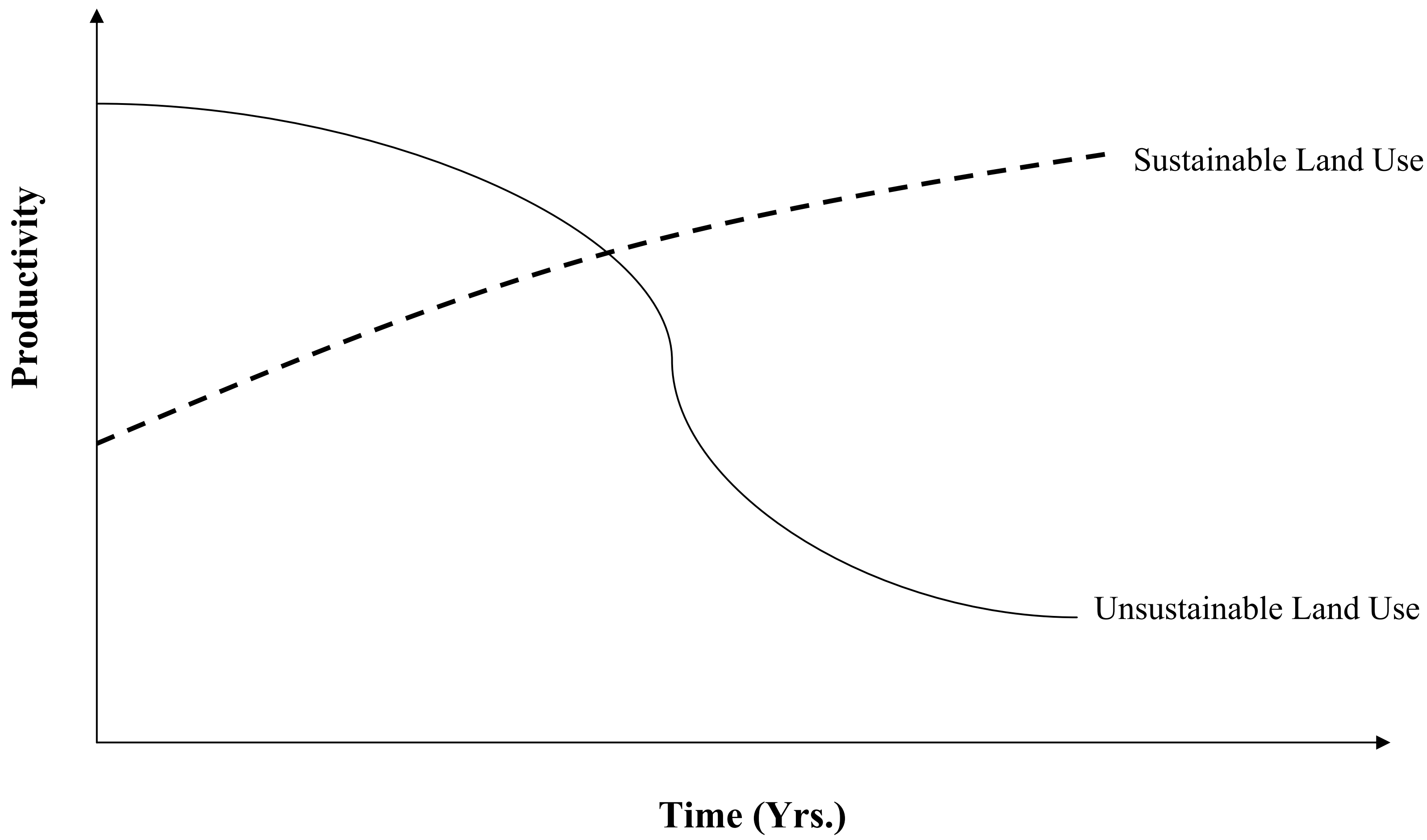

Fig. 6. Temporal changes in productivity in relation to land use and management practices. A non-negative trend in productivity of sustainable land use and management can be assessed through choice of an appropriate index. The productivity response is in accord with temporal changes in soil quality.