Himachal Journal of Agricultural Research 40(1):1-13 (2014)

Improved agricultural practices to mitigate the effect of climate change

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Manuscript Received: 22.02.2014; Accepted: 11.04.2014

Abstract

Agricultural production will manifest large climate change impacts. There is pressing need to improve agricultural productivity for food security while simultaneously protecting the environment as climate is changing. The goal is to produce higher yields with reduced greenhouse gas emissions per unit of production, to conserve and enrich the organic content of soils, to promote efficient water use and ecosystem integrity. This goal can be implemented through advanced agronomic management practices aimed at intensifying and sustaining agricultural production and targeting breeding programs based on improved fundamental understanding of crop genetics and physiology, while preserving natural ecosystems in nonagricultural land. We must take action to reduce the primary root cause; the high rate of CO_2 emissions by burning of fossil fuels, stopping large scale deforestation, preventing reclamation of large wilderness areas for agricultural use. Any delay in action to address the climate change will make future actions more expensive and even more difficult to agree upon.

Key words: Agronomic practices, climate change, mitigation strategies, stages of adaptation.

Introduction

The agricultural sector is facing a significant challenge to provide food security for 9 billion people by the middle of the 21st century, while also protecting the environment and enhancing function of global ecosystems. This challenge is further compounded by factors of climate change. It has been concluded that in many areas of the world where agricultural productivity is already low and the means of coping with adverse events are limited, climate change is expected to reduce productivity to even lower levels and make production more erratic (Cline, 2007; IPCC, 2007). Long term changes in the patterns of temperature and precipitation, are expected to shift production seasons, pest and disease patterns, and modify the set of feasible crops affecting production, income and ultimately livelihoods and lives.

Deforestation, biomass burning and cultivation of soil by ploughing and other tillage methods which enhance mineralization of soil organic carbon (SOC) and releases CO_2 into the atmosphere are among many reasons of climate change (Reicosky *et al.,* 1999). Crop residue and biomass burning (forest fires) are the major sources of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), volatile organic compounds (VOC), nitrogen oxides and halogen compounds (Sharma *et al.,* 2010). Tillage increases soil organic carbon (SOC) mineralization by bringing crop residue closer to microbes where soil moisture conditions favour mineralization (Gregorich *et al.,* 1998), physically disrupts aggregates and exposes encapsulated carbon (C) to decomposition. Thus, a better understanding of tillage effects on SOC dynamics is crucial in developing and identifying sustainable systems of soil management for C sequestration.

There is dire need now for mitigation and reduction of agricultural green house gas (GHG) emissions, sequestration of carbon in soils, and aversion of factors that limit agricultural production. Therefore, agronomic practices must be developed and applied to mitigate climate change and adapt cropping systems to the portending changes, so as to ensure adequate production of food, feed, fiber and bioenergy, as well as protection of natural resources.

Strategies to mitigate the effect of climatic change

Reducing greenhouse gas emission: The emission of GHG from agriculture can be reduced by more efficient management of C and N e.g. practices that deliver added N more efficiently to crops often reduce N_2O emissions (Bouwman, 2001), and managing livestock to make most efficient use of feeds often reduces amounts of CH_4 produced (Clemens and Ahlgrimm, 2001).

Locking up C in soil and vegetation: Practices those increase the photosynthetic input of C and slow the return of stored C to CO_2 via respiration, fire or erosion will increase C reserves, thereby 'sequestering' C or building C 'sinks'. Significant amounts of vegetative C can be stored in agro-forestry systems or other perennial plantings on agricultural lands (Albrecht and Kandji, 2003). Agricultural lands also remove CH_4 from the atmosphere by oxidation {but less than forests (Tate *et al.,* 2006)}.

Replacing fossil fuel with renewable bioenergy sources: Crops and residues from agricultural lands can be used as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel (Schneider and McCarl, 2003; Cannell, 2003). These bio-energy feed-stocks still release CO_2 upon combustion, but now the C is of recent atmospheric origin (via photosynthesis), rather than from fossil C. The net benefit of these bio-energy sources to the atmosphere is equal to the fossil-derived emissions displaced, less any emissions from producing, transporting and processing.

So, affordable novel technologies and energy resources that do not emit greenhouse gases are needed. Diffusion of hydropower (including micro-hydropower), solar energy, biogas, bio-diesel and wind energy are notable examples. Many countries in Asia have experienced forest recovery through policy intervention and the participation of local communities in forest management. Examples include forest conservation in Bhutan, tree plantation in China, community forest user groups in Nepal and joint forest management in India. The forests conserved have contributed significantly to C sequestration (Fang *et al.,* 2001). Further, following best agronomic management practices (BAMPs) can mitigate the adverse effect of climate change.

Agronomic Management Practices to mitigate climate change

Organic farming: According to the Inter-governmental Panel on Climate Change (IPCC, 2007) agriculture currently accounts for 10-12% of global greenhouse gas (GHG) emissions and this figure is expected to rise further. With the right type of agriculture, emissions leading to climate change can be minimized and the capacity of nature to mitigate climate change can be harnessed to sequestrate significant quantities of atmospheric CO_2 – especially in the soil. So, organic agriculture can be a better option for this. According to IFOAM, organic agriculture is a production system that sustains the health of soils, ecosystems and people. It utilizes ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. It combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. Organic agriculture affordably captures carbon from the air and effectively stores it in the soil in high levels for long periods. Global adoption of organic agriculture has the potential to sequester up to the equivalent of 32% of all current man-made GHG emissions (Jordan *et al.,* 2009). The Food and Agriculture Organisation of the United Nations (FAO) regards organic agriculture as an effective strategy for mitigating climate change and building robust soils that are better adapted to extreme weather conditions associated with climate change (Niggli *et al.,* 2009). Organic agriculture optimally combines different practices in a systematic manner and sustains agricultural production in resource-limited regions (Smith *et al.,* 2007).

Conservation agriculture and resource conservation technologies (RCTs): Conservation Agriculture (CA) is a term encompassing farming practices which have three key characteristics: i) minimal mechanical soil disturbance (i.e. no-tillage and direct seeding); ii) maintenance of a mulch of C-rich organic matter covering and feeding the soil (e.g. straw and/or other crop residues); and iii) rotations or sequences and associations of crops which could include nitrogen-fixing legumes. No-till agriculture is widely promoted as a climate friendly farming system, and the IPCC Fourth Assessment Report attributes greenhouse gas mitigation potential to no-till (IPCC, 2007). No tillage is a practice in which seeds are sown by cutting a narrow slot in the soil, and weeds are controlled with herbicides. Since soil disturbance tends to stimulate soil carbon losses through enhanced decomposition and erosion (Madari *et al.,* 2005) reduced or no-till agriculture often results in soil C gain. No-tillage system can also reduce CO_2 emissions from energy use (Marland *et al.,* 2003; Koga *et al.,* 2006). Systems that retain crop residues also tend to increase soil C because these residues are the precursors for soil organic matter, the main C store in soil. Avoiding the burning of residues (eliminating the need for pre-harvest burning; Cerri *et al.,* 2004) also avoids emissions of aerosols and GHGs generated from fire, although CO_2 emissions from fuel use may increase. Conversion from conventional tillage to no-tillage is often considered to be an efficient carbon sequestration strategy with a sequestration rate of 367-3667 kg $CO_2 ha^{-1} year^{-1}$ (Tebrugge and Epperlein, 2011).

Cover crops: The benefits of adopting conservation tillage for SOC sequestration are greatly enhanced by growing cover crops in the rotation cycle. Growing leguminous cover crops enhances biodiversity, the quality of residue input and SOC pool (Singh *et al.,* 1998; Fullen and Auerswald, 1998). It is well established that ecosystems with high biodiversity absorb and sequester more C than those with low or reduced biodiversity. Furthermore, growing vegetative cover between successive agricultural crops, or between rows of tree add C to soils (Barthes *et al.,* 2004; Freibauer *et al.,* 2004) and also extract plant available N unused by the preceding crop, thereby reducing N_2O emissions. The beneficial effect of growing cover crops on enhancing SOC pool has been also reported from Hungary (Berzseny and Gyrffy, 1997), U.K. (Fullen and Auerswald, 1998), Sweden (Nilsson, 1986), Netherlands (Van Dijk, 1982) and Europe (Smith *et al.,* 1997).

Crop rotation: Numerous case studies show that crop rotation with legumes increases SOC content in soil as compared to traditional subsistence farming. Higher SOC content with wheat-grassland and wheat-alfalfa (*Medicago sativa* L.) rotations, especially with conservation tillage system was found by Miglierina *et al.* (1996). Introducing alfalfa in rotation with wheat increased SOC concentration threefold as compared with continuous wheat on a sandy soil of Saudi Arabia (Shahin *et al.,* 1998). Ryan (1998) in Syria reported increased SOC concentration to 1 m depth with incorporation of *M. sativa* in rotation.

Agro-forestry and forest management: Agroforestry is the production of crops on land that also grows trees for timber, firewood, or other tree products. It includes shelter belts and riparian zones/buffer strips with woody species. The standing stock of C above ground is usually higher than the equivalent land use without trees, and planting trees may also increase soil C sequestration (Oelbermann *et al.,* 2004; Mutuo *et al.,* 2005). In the forests, tree species; remain irreversible for decades or even centuries. There is therefore need to include appropriate forest management concepts in countries plans for adaptation of production systems to climate change (FAO, 2013). FAO also systematically advises forestry administrations in member countries about the vulnerability of their forest sector to climate change, on approaches to adaptive management, and possible options in regeneration, tending, harvesting and management planning.

Nutrient management: Judicious nutrient management is also crucial to SOC sequestration. Application of biosolids as soil amendments (e.g. compost, manure) is extremely important in improving productivity (Bejbaruha *et al.,* 2009), and creating a positive C budget and enhancing the ecosystem C pool. The potential of conservation tillage to sequester SOC is greatly enhanced whereby soils are amended with organic manures (Hao *et al.,* 2002). The availability of N and other nutrients is essential to increase yields. N applied through fertilizers, manures, biosolids and other N sources is not always used efficiently by crops (Galloway *et al.,* 2003; Cassman *et al.,* 2003). The surplus N is particularly susceptible to emission of N_2O (McSwiney and Robertson, 2005). Consequently, improving N use efficiency can reduce N_2O emissions and indirectly reduce GHG emissions from N fertilizer (Schlesinger, 1999). Practices that improve N use efficiency include: adjusting application rates (e.g. precision farming); using slow-release fertilizer or nitrification inhibitors; applying N when least susceptible to loss, often just prior to plant uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crop roots; or avoiding N applications in excess than the plant requirements (Robertson, 2004; Paustian *et al.,* 2004; Monteny *et al.,* 2006).

Conserving water resources and water management: Global demand for water has tripled since the 1950s, but the supply of fresh water has been declining (Gleick, 2003). Half a billion people live in water-stressed or water-scarce countries, and by 2025 that number will grow to three billion due to an increase in population. Irrigated agriculture is the dominant user of water, accounting for about 80% of global water use (Molden *et al.,* 2007). As there is no additional water available, the needed increase in food production must come from increasing water productivity through two basic pathways (Molden *et al.,* 2007), namely:

i) Extending the yield frontier in areas where present yields are closer to their potential yield.
ii) Closing the yield gap where considerable yield gains can be achieved with modern technology.

Efficient use of water or using more effective irrigation measures can enhance C storage in soils through enhanced yields and residue returns (Follett, 2001; Lal, 2004). Judicious use of irrigation water in a drought prone soil can enhance biomass production, increase the amount of above-ground and the root biomass returned to the soil and improve SOC concentration. Enhancing water use efficiency holds the key to tackling water scarcity and climate change issues in smallholder agricultural systems. A case study in the Kaithal and Karnal districts of Haryana (India) suggests that varying irrigation and fallowing for rainwater conservation and groundwater recharge would increase productivity of wheat equivalent by 23%, and might stabilize the water table at the desired level (Ambast *et al.,* 2006). Extensive modelling of actual crop water requirements and water supply in major irrigation systems in Australia (Khan and Hanjra, 2008) and the Indus basin of Pakistan (Kahlown *et al.,* 2005) also suggests that the present system of irrigation water supply and water allocation requires adjustments to avoid over irrigation and inefficient use of water, and to address the twin issues of water logging and salinity to maintain crop productivity (Bossio *et al.,* 2010). In addition, enhancing irrigation efficiency can also decrease the hidden C cost (Sauerbeck, 2001). In Texas, Bordovsky *et al.* (1999) observed that surface SOC concentration in plots growing irrigated grain sorghum and wheat increased with time. Furthermore, drainage of croplands in humid regions can promote productivity (and hence soil carbon) and perhaps also suppress N_2O emissions by improving aeration (Monteny *et al.,* 2006). Any N lost through drainage, however, may be susceptible to loss as N_2O (Reay *et al.,* 2003).

Developing and adopting resilient varieties and building resilient farming systems: Widening the array of crop varieties and broadening the range of crops – can be an effective way to moderate the effects of weather variability and extreme events associated with climate change. Modern rice and wheat varieties were developed during the Green Revolution to feed the growing population of the developing world. Their adoption has helped to build food barriers against hunger, protecting millions from malnutrition. However, the adoption rates of modern varieties remain far below universal, particularly in the developing countries. Hardy seeds and wild crops/landraces adapted to aridity, drought, heat, freezing, and salinity stress must be secured from relatively natural ecosystems such as the central Asian states and parts of Africa (Fentahun and Hager, 2009). These landraces have evolved over thousands of years and have survived under harsh climatic conditions and are thus more resilient to climate change.

Farmers living in harsh environments in the regions of Asia, Africa and Latin America have developed/inherited enduring farming systems that offer solutions to many uncertainties facing humanity in an era of climate change (FAO, 2010_a). Multiple cropping farms in Africa are predicted to be more resilient than specialized farms in the future, across the range of climate predictions for 2060 (Seo, 2010).

Resilient ecosystems: Improving ecosystem management and biodiversity can lead to more resilient, productive and sustainable systems that may also contribute to reducing or removing greenhouse gases (FAO, 2010_b). It includes; control of pests and diseases, regulation of microclimate, decomposition of wastes, regulating nutrient cycles and crop pollination. Enabling and enhancing the provision of such services can be achieved through the adoption of different natural resource management and production practices.

Rice production: Flooded rice soils emit significant quantities of methane (Yan *et al.,* 2003). So, replacement of flooded rice by aerobic rice is important for water saving, mitigation of GHGs emission and sustaining crop yields (Bouman *et al.,* 2007; Ladha *et al.,* 2009). System of Rice Intensification (SRI) method also reduces the methane gas emissions as compared to flooded rice cultivation. Alternate Wetting and Drying (AWD) method developed by IRRI can also be a better option for rice production. AWD generates multiple benefits related to methane emission reduction (Khalil and Shearer, 2006), reducing water use (adaptation where water is scarce), increasing productivity and contributing to food security (Bouman *et al.,* 2007). In the off-rice season, methane emissions can be reduced by improved water management, especially by keeping the soil as dry as possible and avoiding water logging (Kang *et al.,* 2002; Xu *et al.,* 2003). Increasing rice production can also enhance soil organic C stocks (Pan *et al.,* 2006). CH_4 emissions can be reduced by adjusting the timing of organic residue additions (e.g. incorporating organic materials in the dry period; Xu *et al.,* 2000; Cai and Xu, 2004) and by composting the residues before incorporation.

Weed Management: Elevated CO_2 due to climate change could provide an even greater competitive advantage to weeds, with concomitant negative effects on crop production due to physiological plasticity of many weeds and their greater genetic diversity relative to crops (Chandrasena, 2009). There is also huge pool of invasive plants available to colonise bare spaces left by climate change (drought, fire and storm damage; Randall, 2007), and wind and flooding waters help spread weeds. Therefore, in future decades, when climate change effects are more consistently felt, weed management requirements in agriculture and non-agricultural situation will change. Aggressive growth of C_3 and C_4 weeds will require more energy and labour intensive management.

For controlling weeds invasion, there will have to be more emphasis on regional cooperation for preventing the spread of certain weeds. So, global and regional co-operation is essential to establish new networks and the capacity to implement early detection and rapid response systems. Increased collection of information, through local and regional surveys of distribution and abundance of potential invaders, sharing of such information and increased border protection of countries through quarantine, are likely to be greater importance in the future (Chandrasena, 2009). More effective integration of on-ground control methods like manual, mechanical, chemical and biological with broader pest control at farm level will be part of future solution.

Restoring degraded soils: A large proportion of agricultural lands have been degraded by unnecessary disturbance, erosion, organic matter loss, salinization, acidification, or other processes that curtail productivity (Batjes, 1999; Foley *et al.,* 2005; Lal, 2004_a). Restoring these degraded soils have a high potential for sequestrating soil C. Most degraded soils have lost a large fraction of the antecedent SOC pool, which can be restored through adopting judicious land use practices including: re-vegetation (e.g. planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids and composts; reducing tillage (zero tillage or minimum tillage) and retaining crop residues; and conserving water (Lal, 2004_b; Olsson and Ardo, 2002; Paustian *et al.,* 2004). Where these practices involve higher N amendments, the benefits of C sequestration may be partly offset by higher N_2O emissions.

Erosion management: Soil C losses can occur both as a result of mineralization as well as through erosion often making it a complex relationship. Where water erosion dominates, a high proportion of soil C may be washed into alluvial deposits close to the erosion site and stored there in the forms which decay more slowly than in the parent soils. Therefore, this kind of erosion may have a positive effect on soil C sequestration. In Western Nigeria, Gabriels and Michiels (1991) observed C losses from bare fallow Alfisol plots with slopes of 1, 5 and 10%, varied from 54 to 3080 kg ha^{-1}. So, management options that increase the amount of live and dead biomass left in agricultural areas decrease erosion in general as well as increase the C input to the soil (Tiessen and Cuevas, 1994). Three main type of erosion preventive techniques are i) those that increase the soils resistance against agents of erosion; ii) soil surface management techniques that help establishment of quick ground cover and; iii) techniques that provide a buffer against rainfall and runoff erosivity (Lal, 1990).

Management of organic/peaty soils: Organic or peaty soils contain high densities of C accumulated over many centuries because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, which aerates the soil, favouring decomposition and therefore, high CO_2 and N_2O fluxes. CH_4 emissions are usually suppressed after draining, but this effect is far outweighed by pronounced increases in N_2O and CO_2 (Kasimir-Klemedtsson *et al.,* 1997). Emissions from drained organic soils can be reduced to some extent by practices such as avoiding row crops and tubers, avoiding deep ploughing and maintaining a shallower water table. But the most important mitigation practice is avoiding the drainage of these soils in the first place or re-establishing a high water table (Freibauer *et al.,* 2004).

Pest and disease management: There are evidences that climate change is altering the distribution, incidence and intensity of animal and plant pests and diseases as well as invasive and alien species. The recent emergence in several regions of multi-virulent, aggressive strains of wheat yellow rust adapted to high temperatures is a good indication of the risks associated with pathogen adaptation to climate change (FAO, 2010_b). These new aggressive strains have spread at unprecedented speed in five continents resulting in epidemics in new cropping areas, previously not favourable for yellow rust and where well-adapted, resistant varieties are not yet available. The wheat disease Spot Blotch, caused by *Cohliobolus sativus*, is another example, causing heavy losses in Southern Brazil, Bolivia, Paraguay and Eastern India, due to a lack of resistance to the disease. As wheat growing areas of Asia become warmer, the pathogen is likely to spread even further and cause further losses. Integrated pest management is a means to help agricultural systems respond to changing pest regimes resulting from climate change.

GM crops: Genetically modified (GM) crops could help in addressing water scarcity through water stress tolerance traits, and through a reduction in pesticide use, thus lowering the risk of soil and water pollution. GM cash crops can also contribute to food security along with maximizing farm profitability by; reducing crop yield losses (Qaim and De Janvry, 2005); protecting against pest and diseases (Thirtle *et al.,* 2003); reducing pesticides and herbicides usage (Rozelle *et al.,* 2004); reducing exposure of farmers to toxic chemicals (Pingali *et al.,* 1994); reducing machinery, labour and fuel costs (Shankar and Thirtle, 2005); and multiplier effects on total production and demand for goods and services and resultant welfare impacts as seen in India (Qaim and Zilberman, 2003) and China (Huang *et al.,* 2004).

Pasture and grazing-land management: On global basis, grassland/grazing lands occupy 3488 Mha or 69% of 5023 Mha agricultural land in 2002 (FAOSTAT, 2006). Excessive and uncontrolled grazing of these lands is a major cause of the acceleration of the desertification process. Adoption of improved grazing practices can improve C sequestration through conservation and better management of surface residue. Restoring degraded grazing lands, improving forage species and converting marginal croplands to pastures is also important in sequestering SOC. Furthermore, similar to cropland, management options for improving pastures include judicious use of fertilizers, controlled grazing, sowing legumes and grasses or other species adapted to the environment, improvement of soil fauna and irrigation (Follett *et al.,* 2001).

i) **Nutrient management:** Practices that alter nutrient additions to plant uptake, such as those described for croplands, can also reduce N_2O emissions (Dalal *et al.,* 2003; Follett *et al.,* 2001). Nutrient management on grazing lands, however, may be complicated by deposition of faeces and urine from livestock, which are not as easily controlled nor as uniformly applied as nutritive amendments in croplands (Oenema *et al.,* 2005).

ii) **Controlled gazing:** The intensity and timing of grazing can influence the removal, growth, C allocation and flora of grasslands; thereby affecting the amount of C accumulation in soils (Conant *et al.,* 2005; Freibauer *et al.,* 2004; Conant and Paustian, 2002; Reeder *et al.,* 2004). It is observed that, C accumulation on optimally grazed lands is often greater than on ungrazed or overgrazed lands (Liebig *et al.,* 2005). The effects are inconsistent, however, owing to the many types of grazing practices employed and the diversity of plant species, soils and climates involved (Schuman *et al.,* 2001; Derner *et al.,* 2006).

iii) **Increased productivity:** As for croplands, C storage in grazing lands can be improved by a variety of measures that promote productivity. For instance, alleviating nutrient deficiencies by fertilizer or other organic amendments increases plant litter returns and hence, soil C storage (Schnabel *et al.,* 2001; Conant *et al.,* 2001). Adding N, however, often stimulates N_2O emissions (Conant *et al.,* 2005) thereby offsetting some of the benefits. Irrigating grasslands, similarly, can also promote soil C gains (Conant *et al.,* 2001).

iv) **Introducing new species:** Introducing grass species with higher productivity, or C allocation to deeper roots, has been shown to increase soil C. For example, establishing deep-rooted grasses in Savannahs has been reported to yield very high rates of C accumulation (Fisher *et al.,* 1994), although the applicability of these results has not been widely confirmed (Conant *et al.,* 2001; Davidson *et al.,* 1995). In the Brazilian Savannah (Cerrado Biome), integrated crop-livestock systems using *Brachiaria* grass and zero tillage are being adopted (Machado and Freitas, 2004). Introducing legumes into grazing lands can promote soil C storage (Soussana *et al.,* 2004), through enhanced productivity from the associated N inputs.

Other practices

- In-*situ* biomass management in shifting cultivation (cover about 1.6 million hectare in North Eastern Region) instead of biomass burning to reduce CO_2 emission and improve hydrology.
- Improve energy use efficiency in agriculture through better designs of machinery and by resource conservation practices.
- Change in planting dates and crop varieties are other adaptive measures to reduce impacts of climate change to some extent. For example, the Indian Agricultural Research Institute study indicates that loss in wheat production in future can be reduced from 4-5 million tonns to 1-2 million tonns if a large percentage of farmers could change to timely planting with better adapted varieties.
- In North-East India with the shift in rainfall pattern and rise in temperature it is important to relook at the present date of sowing and varieties. An example of this is that at mid-altitude of Meghalaya (950 m amsl), where it was not possible to grow a second crop of rice after *kharif* (rainy season) due to early onset of winter, presently double cropping is possible at least at the experimental field with the adjustment of sowing dates and varieties.

Stages of Adaptation

As climate changes proceed in agricultural regions, there are three stages of adaptation related to the level of effort required.

Stage 1: When climate changes are relatively small, many current techniques are available to help farmer's adaptation. These adaptations include; varying sowing dates and cultivars, fertilization and irrigation scheduling; as well as changing to better adapted alternative crops.

Stage 2: As climate change proceeds, more extensive changes may be required, including the genetic improvement of crops to create greater tolerance to elevated temperatures and drought and improved responsiveness to rising CO_2 and the development of new technologies.

Stage 3: In later decades, severe climate changes in agricultural regions may necessitate transformative shifts to entirely different agricultural systems, such as from temperate-zone to sub-tropical or semi-arid zone forms of agriculture.

References

Albrecht A and Kandji ST 2003. Carbon sequestration in tropical agroforestry systems. Agri. Ecosystems Environ. **99:** 15-27.

Ambast SK, Tyagi NK and Raul SK 2006. Management of declining groundwater in the Trans Indo-Gangetic Plain (India): some options. Agric. Water Management **82** (3): 279-96.

Barthes B, Azontonde A, Blanchart E, Girardin C, Villenave C, Lesaint S, Oliver R and Feller C 2004. Effect of a legume cover crop (*Mucuna pruriens* var. *utilis*) on soil carbon in an Ultisol under maize cultivation in southern Benin. Soil Use Management **20:** 231-39.

Batjes NH 1999. Management options for reducing CO_2-concentrations in the atmosphere by increasing carbon sequestration in the soil. In: *Dutch National Research Programme on Global Air Pollution and Climate Change*, Project executed by the International Soil Reference and Information Centre, Wageningen, The Netherlands, pp 114.

Bejbaruha R, Sharma RC and Banik P 2009. Direct and residual effect of organic and inorganic sources of nutrients on rice-based cropping systems in the sub-humid tropics of India. J. Sustainable Agric. **33**: 687-89.

Berzseny Z and Gyrffy B 1997. Effect of crop rotation and fertilization on maize and wheat yield stability in long-term experiments. Agrok mas Talajtan **46**: 377-98.

Bordovsky DG, Choudhary M and Gerard CJ 1999. Effects of tillage, cropping, and residue management on soil properties in the Texas Rolling Plains. Soil Sci. **164** (5): 331-40.

Bossio D, Geheb K and Critchley W 2010. Managing water by managing land: addressing land degradation to improve water productivity and rural livelihoods. Agri. Water Management, Comprehensive Assess. Water Management Agri. **97** (4): 536-42.

Bouman BAM, Lampayan RM and Toung TP 2007. *Water Management in Irrigated Rice: Coping with Water Scarcity*. IRRI, Los Banos, Philippines, pp 54.

Bouwman A 2001. Global Estimates of Gaseous Emissions from Agricultural Land. FAO, Rome, pp 106.

Cai ZC and Xu H 2004. Options for mitigating CH_4 emissions from rice fields in China. In: *Material Circulation through Agro-Ecosystems in East Asia and Assessment of its Environmental Impact (Y* Hayashi eds.), NIAES Series 5, Tsukuba, pp 45-55.

Cannell MGR 2003 Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass Bioenergy **24:** 97-116.

Cassman KG, Dobermann A, Walters DT and Yang H 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Ann. Rev. Environ. Resources **28:** 315-58.

Cerri CC, Bernoux M, Cerri CEP and Feller C 2004. Carbon cycling and sequestration opportunities in South America: the case of Brazil. Soil Use Management **20:** 248-54.

Chandrasena N 2009. How will weed management change under climate change? Some perspectives. J. Crop Weed **5** (2): 95-105.

Clemens J and Ahlgrimm HJ 2001. Greenhouse gases from animal husbandry: mitigation options. Nutrient Cycling Agroeco. **60:** 287-300.

Cline WR 2007. *Global Warming and Agriculture: Impact Estimates by Country*. Center for Global Development, Peterson Institute for International Economics.

Conant RT and Paustian K 2002. Potential soil carbon sequestration in overgrazed grassland ecosystems. Global Biogeochem. Cycles **16** (4): 1143.

Conant RT, Paustian K and Elliott ET 2001. Grassland management and conversion into grassland: Effects on soil carbon. Ecological Applications **11:** 343-55.

Conant RT, Paustian K, Del Grosso SJ and Parton WJ 2005. Nitrogen pools and fluxes in grassland soils sequestering carbon. Nutrient Cycling Agroeco. **71:** 239-48.

Dalal RC, Wang W, Robertson GP and Parton WJ 2003. Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Aust. J. Soil Res. **41:** 165-95.

Davidson EA, Nepstad DC, Klink C and Trumbore SE 1995. Pasture soils as carbon sink. Nature **376:** 472-73.

Derner JD, Boutton TW and Briske DD 2006. Grazing and ecosystem carbon storage in the North American Great Plains. Plant Soil **280:** 77-90.

Fang JY, Chen AP, Peng CH, Zhao SQ and Ci LJ 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Sci. **292**: 2320-22.

FAO 2013. Adapting Agriculture to Climate Change. FAO and the Global Environment.

http://www.fao.org/docrep/011/aj982e/aj982e02.pdf

FAO 2010$_a$. *Climate-Smart Agriculture;* Policies, Practices and Financing for Food Security, Adaptation and Mitigation. FAO, Rome, Italy.

FAO 2010$_b$. Enduring Farms: Climate Change, Smallholders and Traditional Farming Communities. FAO, Rome, Italy.

FAOSTAT 2006. FAOSTAT Agricultural Data. http://faostat.fao.org.

Fentahun MT and Hager H 2009. Exploiting locally available resources for food and nutritional security enhancement: wild fruits diversity, potential and state of exploitation in the Amhara region of Ethiopia. Food Sec. **1**: 207-19.

Fisher MJ, Rao IM, Ayarza MA, Lascano CE, Sanz JI, Thomas RJ and Vera RR 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature **371:** 236-38.

Foley JA, DeFries R, Asner G, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Dailey GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N and Snyder PK 2005. Global Consequences of Landuse. Sci. **309**: 570-74.

Follett RF 2001. Organic carbon pools in grazing land soils. In: *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect (*RF Follett, JM Kimble and R. Lal eds.), Lewis Publishers, Boca Raton, Florida, pp 65-86.

Follett RF, Kimble JM and Lal R 2001. The potential of U.S. grazing lands to sequester soil carbon. In*: The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect (*RF Follett, JM Kimble and R Lal eds.), Lewis Publishers, Boca Raton, Florida, pp 401-30.

Freibauer A, Rounsevell M, Smith P and Verhagen A 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma **122:** 1-23.

Fullen MA and Auerswald K 1998. Effect of grass ley set-aside on runoff, erosion and organic matter levels in sandy soil in east Shropshire, UK. Soil Tillage Res. **46**: 41-49.

Gabriels D and Michiels P 1991. Soil organic matter and water erosion processes. In*: Advances in Soil Organic Matter Research* (WS Wilson eds.). Special Publication No. 90. The Royal Society of Chemistry, Cambridge, pp 141-52.

Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB and Cosby BJ 2003. The nitrogen cascade. Biosci. **53:** 341-56.

Gleick PH 2003. Global freshwater resources: soft-path solutions for the 21st century. Science **302**(28): 1524–28.

Gregorich EG, Greer KJ, Anderson DW and Liang BC 1998. Carbon distribution and losses: erosion and deposition effects. Soil Tillage Res. **47**: 291–302.

Hao Y, Lal R, Owens LB, Izaurralde RC, Post M and Hothem D 2002. Effect of cropland management and slope position on soil organic carbon pools in the North Appalachian Experimental Watersheds. Soil Tillage Res. **68**: 133-42.

Huang J, Hu R, van Meijl H and van Tongeren F 2004. Biotechnology boosts to crop productivity in China: trade and welfare implications. J. Dev. Eco. **75** (1): 27-54.

IPCC (Inter-governmental Panel on Climate Change) 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: *Climate Change 2007, Fourth Assessment Report*, Intergovernmental panel on Climate Change (ML Parry, OF Canziani, JP Palutikof, PJ van der Linden and CE Hanson eds.), Cambridge University Press, Cambridge, United Kingdom and New York, USA. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

Jordan R, Muller A and Oudes A 2009. High Sequestration, Low Emission, Food Secure Farming. Organic Agriculture - a Guide to Climate Change and Food Security, IFOAM.

Kahlown MA, Ashraf M and Zia-ul-Haq 2005. Effect of shallow groundwater table on crop water requirements and crop yields. Agric. Water Management **76** (1): 24-35.

Kang GD, Cai ZC and Feng XZ 2002. Importance of water regime during the non-rice growing period in winter in regional variation of CH_4 emissions from rice fields during following rice growing period in China. Nutrient Cycling Agroeco. **64:** 95-100.

Kasimir-Klemedtsson, A, Klemedtsson L, Berglund K, Martikainen P, Silvola and Oenema O 1997. Greenhouse gas emissions from farmed organic soils: a review. Soil Use Management **13:** 245-50.

Khalil MAK and Shearer MJ 2006. Decreasing emissions of methane from rice agriculture. In: *Greenhouse Gases and Animal Agriculture: An Update* (CR Soliva, J Takahashi and M Kreuzer eds.), International Congress Series No. 1293, Elsevier, The Netherlands, pp 33-41.

Khan S and Hanjra MA 2008. Sustainable land and water management policies and practices: a pathway to environmental sustainability in large irrigation systems. Land Degradation Dev. **19** (3): 469-87.

Koga N, Sawamoto T and Tsuruta H 2006. Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, Northern Japan. Soil Sci. Plant Nutri. **52:** 564-74.

Ladha JK, Yadvinder Singh, Erenstein O and Hardy B 2009. Integrated Crop and Resource Management in the Rice-Wheat System of South Asia. IRRI/ADB/RWC, Los Banos, Philippines, pp 395.

Lal R 1990. *Soil Erosion in the Tropics: Principles and Management*. McGraw-Hill: New York.

Lal R 2004$_a$. Soil carbon sequestration impacts on global climate change and food security. *Sci.* **304:** 1623-27.

Lal R 2004$_b$. Soil carbon sequestration to mitigate climate change. Geoderma **123:** 1-22.

Liebig MA, Morgan JA, Reeder JD, Ellert BH, Gollany HT and Schuman GE 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. Soil Tillage Res. **83:** 25-52.

Machado PLOA and Freitas PL 2004. No-till farming in Brazil and its impact on food security and environmental quality. In: *Sustainable Agriculture and the International Rice-Wheat System (*R Lal, PR Hobbs, N Uphoff and DO Hansen eds.), Marcel Dekker, New York, pp 291-310.

Madari B, Machado PLOA, Torres E, Andrade AG, and Valencia LIO 2005. No tillage and crop rotation effects on soil aggregation and organic carbon in a Fhodic Ferralsol from southern Brazil. Soil Tillage Res. **80:** 185-200.

Marland G, West TO, Schlamadinger B and Canella L 2003. Managing soil organic carbon in agriculture: the net effect on greenhouse gas emissions. Tellus **55:** 613-21.

McSwiney CP and Robertson GP 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. Global Change Biology **11:** 1712-19.

Miglierina M, Galantini JA, Iglesias JO, Rosell RA and Glave A 1996. Crop Rotation and Fertilization in Production Systems of the Semi-Arid Region of Buenos Aires. Revista de la Faculatd de Agronomia, Universidad de Buenos Aires **15**: 9-14.

Molden D, Oweis TY, Steduto P, Kijne JW, Hanjra MA, Bindraban PS, Bouman BAM, Cook S, Erenstein O, Farahani H, Hachum A, Hoogeveen J, Mahoo H, Nangia V, Peden D, Sikka A, Silva P, Turral H, Upadhyaya A and Zwart S 2007. Pathways for increasing agricultural water productivity. In: *Comprehensive Assessment of Water Management in Agriculture, Water for Food, Water for Life*: (D Molden eds.). International Water Management Institute, London: Earthscan, Colombo.

Monteny GJ, Bannink A and Chadwick D 2006. Greenhouse gas abatement strategies for animal husbandry. Agric. Ecosystems Environ. **112:** 163-70.

Mutuo PK, Cadisch G, Albrecht A, Palm CA and Verchot L 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling Agroeco. **71:** 43-54.

Niggli U, Fliessbach A, Hepperly P and Scialabba N 2009. Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. FAO.

Nilsson LG 1986. Data of yield and soil analysis in the long-term soil fertility experiments. J. Royal Swedish Acad. Agric. Forest Supp. **18**: 32–70.

Oelbermann M, Voroney RP and Gordon AM 2004. Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agric. Ecosystems Environ. **104:** 359-77.

Oenema O, Wrage N, Velthof GL, van Groenigen JW, Dolfing J and Kuikman PJ 2005. Trends in global nitrous oxide emissions from animal production systems. Nutrient Cycling Agroeco. **72:** 51-65.

Olsson L and Ardo J 2002. Soil carbon sequestration in degraded semiarid agro-ecosystems-perils and potentials. Ambio **31:** 471-77.

Pan GX, Zhou P, Zhang XH, Li LQ, Zheng JF, Qiu DS and Chu QH 2006. Effect of different fertilization practices on crop C assimilation and soil C sequestration: a case of a paddy under a longterm fertilization trial from the Tai Lake region, China. Acta Ecologica Sinica **26**(11): 3704-10.

Paustian K, Babcock BA, Hatfield J, Lal R, McCarl BA, McLaughlin S, Mosier A, Rice C, Robertson GP, Rosenberg NJ, Rosenzweig C, Schlesinger WH and Zilberman D 2004. Agricultural Mitigation of Greenhouse Gases: Science and Policy Options, CAST (Council on Agricultural Science and Technology) Report, pp 120.

Pingali PL, Marquez CB and Palis FG 1994. Pesticides and Philippine rice farmer health: a medical and economic analysis. American J. Agric. Econ. **76** (3): 587-92.

Qaim M and De Janvry A 2005. Bt cotton and pesticide use in Argentina: economic and environmental effects. Environ. Dev. Econ. **10:** 179–200.

Qaim M and Zilberman D 2003. Yield effects of genetically modified crops in developing countries. Sci. **299**: 900-02.

Randall RP 2007. The introduced flora of Australia and its weed status. Adelaide: CRC for Australian Weed Management and Department of Agriculture and Food, Western Australia.http://www.weeds.crc.org.au/weed_management/intro_flora.html.

Reay DS, Smith KA and Edwards AC 2003. Nitrous oxide emission from agricultural drainage waters. Global Change Biology **9:** 195-203.

Reeder JD, Schuman GE, Morgan JA and Lecain DR 2004. Response of organic and inorganic carbon and nitrogen to long-term grazing of the shortgrass steppe. Environ. Management **33:** 485-95.

Reicosky DC, Reeves DW, Prior SA, Runion GB, Rogers HH and Raper RL 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil Tillage Res. **52**: 153-65.

Robertson GP 2004. Abatement of nitrous oxide, methane and other non-CO_2 greenhouse gases: the need for a systems approach. In: *The global carbon cycle. Integrating Humans, Climate, and the Natural World* (C.B. Field, and M.R. Raupach eds.). SCOPE 62, Island Press, Washington, pp 493-506.

Rozelle S, Huang J and Hu R 2004. Genetically Modified Rice in China: Effects on Farmers in China. Department of Agricultural and Resource Economics at University of California, Davis, USA.

Ryan J 1998. Changes in organic carbon in long-term rotation and tillage trials in northern Syria. Management of carbon sequestration in soils (R Lal, JM Kimble, RF Follett and BA Stewart eds.). CRC/Lewis Publishers, Boca Raton, Florida, pp 285-296.

Sauerbeck DR 2001. CO_2 emissions and C sequestration by agriculture-perspectives and Limitations. Nutrient Cycling Agroeco. **60**: 253-66.

Schlesinger WH 1999. Carbon sequestration in soils. *Sci.* **284:** 295.

Schnabel RR, Franzluebbers AJ, Stout WL, Sanderson MA and Stuedemann JA 2001. The effects of pasture management practices. In: *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect (*RF Follett, JM Kimble and R Lal eds.), Lewis Publishers, Boca Raton, Florida, pp 291-322.

Schneider UA and McCarl BA 2003. Economic potential of biomass based fuels for greenhouse gas emission mitigation. Environ. Resource Econ. **24:** 291-312.

Schuman GE, Herrick JE and Janzen HH 2001. The dynamics of soil carbon in rangelands. In: *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect (*RF Follett, JM Kimble and R Lal eds.), Lewis Publishers, Boca Raton, Florida, pp 267-90.

Seo SN 2010. Is an integrated farm more resilient against climate change? A micro-econometric analysis of portfolio diversification in African Agriculture. Food Policy **35**: 32-40.

Shahin RR, El-Meleigi MA, Al-Rokiba AA and Eisa AM 1998. Effect of wheat stubble management pattern on organic carbon content and fertility of sandy soils under pivot irrigation system. Bull. Faculty Agric. Univ. Cairo **42**: 283-96.

Shankar B and Thirtle C 2005. Pesticide productivity and transgenic cotton technology: the South African smallholder case. J. Agric. Eco. **56** (1): 97-116.

Sharma AR, Kharol SK, Badarinath KVS and Singh D 2010. Impact of agriculture crop residue burning on atmospheric aerosol loading - a study over Punjab State. India Ann. Geophys **28**: 367-79.

Singh BR, Borresen T, Uhlen G and Ekeberg E 1998. Long-term effects of crop rotation, cultivation practices and fertilizers on carbon sequestration in soils in Norway. In: *Management of Carbon Sequestration in Soil* (R Lal, JM Kimble, RF Follett, BA Stewart eds.). CRC Press, Boca Raton, pp 195-208.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B and Sirotenko O 2007. Agriculture. In: *Climate Change 2007: Mitigation.* Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (B Metz, OR Davidson, PR Bosch, R Dave and LA Meyer eds.), Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Smith P, Powlson DS, Glendining MJ and Smith JU 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Global Change

Biology **3**: 67-79.

Soussana JF, Loiseau P, Viuchard N, Ceschia E, Balesdent J, Chevallier T and Arrouays D 2004. Carbon cycling and sequestration opportunities in temperate grasslands. Soil Use Management **20:** 219-30.

Tate KR, Ross DJ, Scott NA, Rodda NJ, Townsend JA and Arnold GC 2006. Post-harvest patterns of carbon dioxide production, methane uptake and nitrous oxide production in a *Pinus radiata* D. Don plantation. Forest Ecology Management **228:** 40-50.

Tebrugge F and Epperlein J 2011. The Importance of Conservation Agriculture within the Framework of the Climate Discussion. In: *ECAF, European Conservation Agriculture Federation.* http://www.ecaf.org/docs/ecaf/positionpaperco2ecaf.pdf.

Thirtle C, Beyers L, Ismael Y and Piesse J 2003. Can GM-technologies help the poor? The impact of Bt cotton in Makhathini Flats, KwaZulu-Natal. World Dev. **31**:717-32.

Tiessen H and Cuevas E 1994. The role of organic matter in sustaining soil fertility. Nature **371**: 783-785.

Van Dijk H 1982. Survey of Dutch soil organic research with regard to humification and degradation rates in arable land. In: *Land Use Seminar on Land Degradation* (DD Boels, B Davis and AE Johnston eds.), Balkema, Rotterdam, pp 133-43.

Xu H, Cai ZC and Tsuruta H 2003. Soil moisture between rice-growing seasons affects methane emission, production, and oxidation. Soil Sci. Soc. America J. **67:** 1147-57.

Xu H, Cai ZC, Jia ZJ and Tsuruta H 2000. Effect of land management in winter crop season on CH_4 emission during the following flooded and rice-growing period. Nutrient Cycling Agroeco. **58:** 327-32.

Yan X, Ohara T and Akimoto H 2003. Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and South Asian countries. Global Change Biology **9:** 237-54.