Range Mgmt. & Agroforestry 34 (1) : 1-11, 2013
ISSN 0971-2070

Carbon and greenhouse gas mitigation through soil carbon sequestration potential of adaptive agriculture and agroforestry systems

S. A. Bangroo[1]*, Tahir Ali[3], S. Sheraz Mahdi[2], G. R. Najar[3] and J. A. Sofi[3]
[1]Irrigation Research Station, Bikramganj, Bihar Agricultural University, Sabour
[2]Bihar Agricultural College, Bihar Agricultural University, Sabour- 813210
[3]Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir Shalimar Campus 191 121
Corresponding author e-mail: shalzsab@gmail.com
Received: 5th August, 2012 Accepted: 3rd January, 2013

Abstract

Agriculture together with agro-forestry systems are perceived as a source of significant greenhouse gas (GHG) emissions, with concomitant potentials for mitigation. It is among the economic sectors having the largest GHG mitigation potential. Conversion to invigorating land uses and implementation of recommended management practices (RMP) can enhance soil organic carbon (SOC). The adoption of these alternatives is likely to have considerable benefits for some cropping systems under moderate climate change. The C sequestration potential in soils of terrestrial ecosystems is $3x10^9$ tonnes C/year or 0.05% reduction of atmospheric CO_2 at the rate of 1 Mg/ha/year by improving C pool by the end of the year 2099. The role of forest and grasslands as a sink for atmospheric CO_2 is the subject of active debate. The carbon stock for the period 2006–2030 is projected to increase from $8.79x10^9$ tonnes C to $9.75x10^9$ tonnes C with forest cover becoming more or less stable, and new forest carbon accretions coming from the current initiatives of afforestation and reforestation programme. With the knowledge and information that is now emerging, the role of agro-forest and plantations in mitigation is becoming more and more important. Over the past decades, national policies of India aimed at conservation and sustainable management of forests have transformed India's forests into a net sink of CO_2. Not all improved management practices are suitable to all soils and ecological conditions. Dealing with many barriers to effective adaptation will require a comprehensive and dynamic policy approach covering a range of scales and issues. A crucial component of this approach is the implementation of adaptation assessment frame works that are relevant, robust and easily operated by all stakeholders, practitioners, policymakers and scientists.

Key words: Carbon sequestration, Greenhouse gases, Soil management, Soil organic carbon

Abbreviations: GHG: Greenhouse gas; **RMP:** Recommended management practices; **SOC:** Soil organic carbon

Introduction

Since the inception of the industrial revolution, concentration of several atmospheric GHGs has been rising alarmingly and is recognized as serious environmental issue of the 21st century (Lal, 2008). Developing strategies to trade off the rate of increase of atmospheric concentration of CO_2 from annual emissions of $8.6x10^9$ tonnes C year^{-1} from various agri and agro-forestry and industrial systems is an important issue (Lal, 2008). According to the 3rd assessment report (TAR) of the Intergovernmental Panel on Climate Change (IPCC, 2001), because of the increase in the concentration of GHGs in the atmosphere in the last 100 years, the mean surface temperature has risen by 0.4-0.8^{0}C globally. The total temperature increase from 1850-1899 to 2001-2005 is 0.76°C ± 0.19°C (IPCC, 2007). The rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) is nearly twice that for the last 100 years (IPCC, 2007). The rate of global temperature has been 0.15^{0}C per decade since 1975. There have been notable shifts in ecosystems (Greene and Pershing, 2007) and frequency and intensity of occurrence of wild fires (Running, 2006; Westerling *et al.*, 2006) over the past decade. The CO_2 concentration has increased by 31% from 0.28% in 1850 to 0.38% in 2005, and is presently increasing at 0.46% year^{-1} and the concentrations of methane (CH_4) and nitrous oxide (N_2O) have also increased steadily over the same period (WMO, 2006; IPCC, 2007).

Agriculture is the biggest land use system across the globe and currently 1.2-1.5 billion hectares are under various crops, with another 3.5 billion hectares being grazed. About 4 billion hectares of forests are used by humans under diverse levels including agro-forestry systems spread over 1 billion ha in diverse eco-regions around the world (Easterling *et al.*, 2007). In recent past, drastic changes have been witnessed in global resource use and between 1900 and 2000, there occurred an increase in world population by a factor of 3.8, industrial output by 35, energy use by 12.5, oil production by 300, water use by 9, irrigated area by 6.8, fertilizer use by 342 and atmospheric CO_2 by 30% (Ponting, 2007) leading to the causes of global warming. Thus there is a key interest in controlling the atmospheric abundance of CO_2 and other GHGs to mitigate the risks of global warming (Kerr, 2007; Kluger, 2007; Walsh, 2007). The role of land use systems in stabilizing the CO_2 levels and increasing the C sink potential has attracted considerable scientific attention in the recent past, especially after the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The Kyoto Protocol and post-Kyoto protocol discussions recognizes the role of afforestation, reforestation, natural regeneration of forests and the adaptive agriculture in increasing the C storage capacity of the terrestrial ecosystems. There is an immense diversity of agricultural practices and forest management due to wide range of climate and other environmental variables; cultural, institutional, and economic factors; and their interactions consequently existence of large array of accessible adaptation options. There are three strategies of lowering CO_2 emissions to mitigate climate change (Schrag, 2007): (i) drawing down the global energy use, (ii) developing low or alternatives to carbon fuel, and (iii) sequestering CO_2 from point sources or atmosphere through natural and engineering techniques. The potential of afforestation together with soils upon adoption of recommended management practices (RMP) can also be major sink of atmospheric CO_2 (Ruddiman, 2003). Thus, the objective of this article is to describe the importance of using eco-efficient / adaptive agriculture and forest management in enhancing agronomic production while restoring degraded soils, their importance as source and sinks of GHGs and encountered.

Global Carbon Cycle

Climate change is expected to determine the potentialities of the land and water ecosystems to act as storehouse for anthropogenic CO_2 and hence allow a feedback to climate change. Comprehending the global C cycle and its intrusion by anthropogenic activities is important for developing viable strategies for mitigating climate change. The principle global C pools include five categories *viz.,* oceanic ($38x10^{12}$ tonnes C), geologic/fossil fuel ($4.1x10^{12}$ tonnes C), pedologic ($2.5x10^{12}$ tonnes C to 1 m depth), atmospheric ($0.8x10^{12}$ tonnes C) and biotic pool ($0.6x10^{12}$ tonnes C). The oceanic pool is increasing at the rate of $2.3x10^9$ tonnes C year ^{1}. The geological/fossil fuel C pool comprises of coal (85%), oil (5.5%) and gas (3.3%). Coal and oil together account for approximately 40% of global CO_2 emissions (Lal, 2008) as a result the geological pool is exhausting via fossil fuel combustion at the rate of $7.0x10^9$ tonnes C year^{-1}. The pedologic pool consists of (i) soil organic carbon (SOC) pool like humus and charcoal ($1.5x10^{12}$ tonnes) in a mixture of partially/fully decomposed plant and animal residues and living organisms and (ii) soil inorganic carbon (SIC) pool like elemental C and carbonate minerals ($0.9x10^{12}$ tonnes). The atmospheric pool is increasing at the rate of $3.5x10^9$ tonnes C year^{-1}.

There is a significant interaction between terrestrial (pedologic and biotic) and atmospheric C pools through photosynthesis. The annual C sequestration rate through photosynthesis by plants is $12x10^{10}$ tonnes C, the significant amount of which is released back into the atmosphere. The emissions and removal of CO_2 resulting from land use change falls within three categories, a) a reduction in forest cover resulting from industrial logging, fuel wood harvesting and shifting cultivation, b) clearing forests for conversion to permanent cropland/ waste lands, and c) clearing land for conversion to forest lands (including plantations). In 1994 India's total GHG emissions were $1.2x10^9$ tonnes, just 3% of the global total. Sixty three percent of India's GHG emissions were CO_2. There is ingress of $0.4–0.8x10^9$ tonnes C year^{-1} to the ocean from the pedologic pool through induced erosion and transportation to aquatic ecosystems. Soil organic carbon (SOC) also plays a very significant role in the global carbon cycle, as it is the largest terrestrial carbon pool. The total SOC pools in Indian forests have been estimated as $4.13x10^9$ tonnes C (top 50 cm) to $6.81x10^9$ tonnes C (top 1 m soil depths) for the period 1980–1982 (Chhabra *et al.*, 2002). Based on different forest types in India, the national average of soil organic carbon per ha in forest soil was estimated at 183 Mg Cha^{-1} (Jha *et al.*, 2003). The terrestrial sink absorbs approximately $2\text{-}4x10^9$ tonnes C year^{-1} and its potential may increase to approximately $5x10^9$ tonnes C year^{-1} by 2050 (Scholes and Noble, 2001). Thus conversion to a judicious land use and adoption of recommended management practices can make these important C sinks.

Carbon sequestration potential in world agriculture and agro-forestry system

There is need for stronger focus on adapting agriculture to future climate change and at the same time meeting the world food security. The diverse nature of agriculture imparts numerous options that are accessible and adaptable at the management level without hindering the production capabilities of soils (Fig. 1). The soil organic carbon (SOC) pool is regarded as the indicator of soil health. Intensification of agriculture and unsustainable land management has lead to the depletion of SOC pool due to higher losses caused by accelerated erosion and leaching (Lal, 2004). Measures of remediation are available by relying on restorative land use and adoption of recommended management practices (RMPs). The purpose of accounting agro adaptation is to effectively manage potential climate risks over the coming decades of climate change. Many management level adaptation options are largely extensions or intensifications of existing climate risk management. For agro systems, there are numerous potential options to alter management to deal with projected climate and atmospheric changes (Butt *et al.*, 2005; Travasso *et al.*, 2006). However, the management levels are region specific and hence are not all adapted in whole agro systems. Mitigation of GHGs through agricultural practices can be broadly divided into three categories (Paustian *et al.*, 2004): (i) Reducing emissions from the agriculture practices by managing more efficiently the flows of carbon and nitrogen in agricultural ecosystems like conservation agriculture with no-till farming, integrated nutrient management, use of organic manures and biochar in conjugation with soil amendments (ii) Enhancing removals that has been lost from the soil organic matter to the atmosphere by enhancing the practice that increases the photosynthetic input of C or slows the return of stored C via respiration or fire will increase stored C, thereby 'sequestering' C or building C 'sinks' (Lal, 2004) like crop residue mulching along with cover cropping and afforestation of degraded soils and (iii) Avoiding emissions by using crops and residues from agricultural lands as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel. When short rotation plantations are used to produce bio-fuels to substitute fossil fuels, they can make an ongoing contribution to reducing net CO_2 emissions. Thus, the net benefit of these bioenergy feed stocks to the atmosphere is equal to the fossil-derived emissions displaced less any emissions from their production, transport and processing. The technical potential of these practices, depending on soil and climate, is in the range of 100 to 1,000 kg C/ha/year, and may be as much as 1.8–4.4Gt C year^{-1} (Gt = 10^9 tonnes) on a global scales.

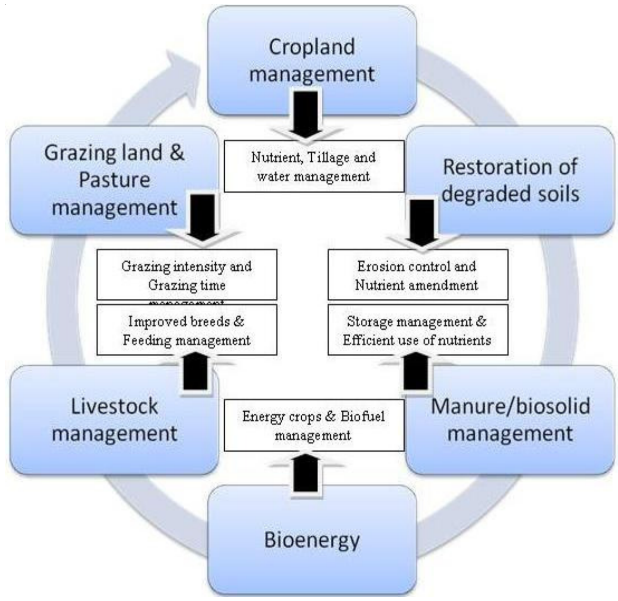


Fig 1. Proposed measures for mitigating GHG emissions from agricultural ecosystems

The principle technical mitigation potential from agriculture by 2030 is estimated to be ~5.5–6x10^9 tonnes CO_2-eq. year^{-1}, with cumulative economic potentials of 1.5–1.6, 2.5–2.7 and 4-4.3x10^9 tonnes CO_2-eq. year^{-1}. Thus agriculture could offset about 20% of total annual CO_2 emissions. Of these principle mitigation potentials, 89% is from reduced soil emissions of CO_2, 9% from mitigation of methane and 2% from mitigation of soil N_2O emissions by 2030. For each region the biophysical potential is defined by the sum of the potential due to improvements in cropland management, grazing land management, reduction of soil GHG emissions under bioenergy cropping, improved rice management, restoration of all degraded lands, livestock management and manure management in 2030.

Agro-forestry is a system that combines trees and/or shrubs (perennial) with agronomic crops (annual or perennial). As a system it offers great opportunity to sequester C both above and below ground. Agro-forestry practices have been recognized as a strategy for the soil C sequestration under afforestration and reforestration programmes and also under the Clean Development Mechanisms of the Kyoto Protocol (Fig 2) (IPCC, 2007). According to IPCC, agro-forestry offers important opportunities of creating synergies between both adaptation and mitigation actions with a technical mitigation potential of 1.1 - 1.2 pg C in terrestrial ecosystems over the next 50 years. Additionally, 630m ha of unproductive croplands and grasslands could be converted to agro-forestry representing a C sequestration potential of 0.586 Tg C/yr by 2040. The total C storage in the above and below ground biomass in an agro-forestry system is generally much higher than that in land use without trees under comparable conditions.

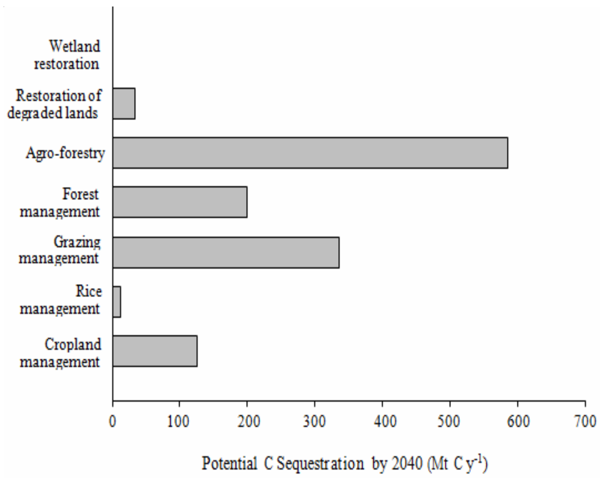
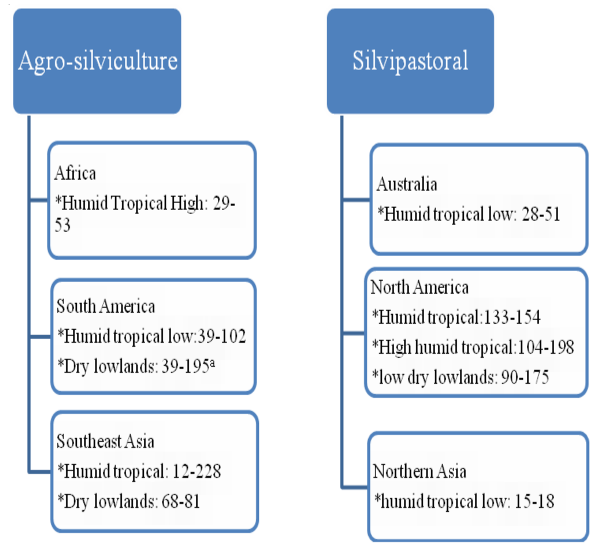


Fig 2. C sequestration potential of different land use and management options (adapted from IPCC, 2000)

Agroforestry practices accumulate more C than forests and pastures (Fig 3) (Schroeder, 1994; Kort and Turnock, 1999; Sharrow and Ismail, 2004). Species in agroforestry systems often have different physiological needs for particular resources in certain amounts, at certain times, and possess different structural or functional means to obtain those (Jose *et al.,* 2004). The utilization of the environment by species includes three main components: space, resources, and time. Any species utilizing the same exact combination of these resources as another will be in direct competition which could lead to a reduction in C sequestration. However, if one species differs in utilization of even one of the components, for example light saturation of C_3 *vs.* C_4 plants, C sequestration will be enhanced.

The total global potential for afforestation and reforestation activities for the period 1995–2050 is estimated to be between 1.1 and 1.6x10^9 tonnes C year^{-1}, of which 70% could occur in the tropics (IPCC, 2001). Afforestation and reforestation are seen as potentially attractive mitigation strategies, as wood production and carbon (C) storage can be combined. Various agro-forestry practices such as alley cropping, silvopasture, riparian buffers, parklands, forest farming, home gardens and woodlots and other similar land use pattern have thus raised considerable expectations as a C sequestration strategy in both industrialized and developing countries. Udawatta and Jose (2011) estimated C sequestration potential for riparian buffers, alley cropping and silvopasture under an area of 1.69, 17.9 and 78m ha as 4.7, 60.9 and 474 Tg C/yr respectively in US. The total potential for the C sequestration under agro-forestry system in the US including the C sequestration potential of wind breaks (8.79 Tg C/yr) is estimated as 548.4 Tg C/yr.



a Carbon storage values were standardized to 50-year rotation.

Fig 3. Potential C storage (Mg C ha^{-1}) for agro-forestry systems in different eco-regions of the world (Winjum *et al*., 1992; Dixon *et al*., 1993; Schroeder, 1993; Krankina and Dixon, 1994; Albrecht and Kandji, 2003)

Management Systems *vis a vis* Carbon Sequestration

Adaptive Agriculture Systems

The IPCC fourth assessment recognizes agriculture as an important sector having the greatest near-term (by 2030) GHG mitigation potential. Moderation in practices at the management unit level will be an important component in adapting agriculture to climate change (Easterling *et al*., 2007). Moderation research undertaken now can help in framing decisions by farmers and policy makers with implications over a range from short-term to long-term strategies. However, it is particularly important to align the spatial, temporal, and sectoral scales and reliability of the information with the nature of the decision. Many options have been devised to mitigate emissions through the mechanisms already discussed. Often a practice will affect more than one GHG, by more than one mechanism, sometimes in opposite ways, so that the net benefit depends on the combined effects on all GHGs. Besides, the temporal influence may vary among practices or among GHGs for a given practice.

The most important strategies for increasing the SOC include (i) restoration of soil degraded by erosion, salinization and alkalization, nutrient depletion, acidification and leaching, competition, crusting and structural decline, pollution and contamination (ii) adoption of recommended management practices on agricultural and forest soils; integrated nutrient management, no-till farming with residue mulch and cover crops, diverse crop rotations, agroforestry and charcoal, precision farming and fertilization. Grainger (1995) estimated that there are approximately 750 Mha of degraded lands in the tropics with potential for afforestation and soil quality enhancement. With a sequestration potential of approximately 0.5 Mg ha^{-1} $year^{-1}$ as SOC and an additional 1.0 Mg ha^{-1} $year^{-1}$ as biomass, a terrestrial C sequestration potential of 750 Mha is approximately $1.1x10^9$ tonnes C $year^{-1}$. Crop yields in eroded soil are highly reduced, even under high fertilizer application (Monreal *et al.*, 1997), which itself increases emission of GHGs (CO_2 and N_2O). The low production is the result of adverse effect of erosion on soil structure, aeration, effective rooting depth, available water-holding capacity, and nutrient reserves which in turn, further reduces the soil carbon pool (Stocking, 2003). Oost *et al.* (2007) estimated that the global contemporary agricultural sediment flux on cropland is about $22x10^9$ tonnes $year^{-1}$ and that an additional approximately $11x10^9$ tonnes $year^{-1}$ is mobilized on pasture- and rangelands. These sediment flux estimates correspond with a cropland SOC erosion rate of $0.32x10^9$ tonnes C $year^{-1}$ and a total agricultural SOC erosion rate of 0.47 to $0.61x10^9$ tonnes C $year^{-1}$. When the rate of SOC replacement on eroded soils and the reduced decomposition in depositional environments found here are applied to the world's agricultural soils, the erosion induced sink strength is ~$0.12x10^9$ tonnes C $year^{-1}$ (range 0.06 to 0.27), of which 67% is accounted for by croplands. Although a part of the C translocated by erosion may be buried and redistributed (Smith and Conan, 2004). Erosion-induced deposition and burial may be 0.4 to 0.6 Gt C $year^{-1}$ (Lal, 2003).

The long term, intensive tillage has caused or contributed to soil degradation in many regions. Reducing erosion and organic matter losses in cultivated soils has been the primary reason for the development of less intensive tillage practices. The intensity of tillage operations largely influences the build-up or depletion of SOC. It determines the soil C balance in two fundamental ways: (i) through the physical disturbance and mixing of soil and the exposure of soil aggregates to disruptive forces and (2) through controlling the incorporation and the distribution of the plant residues in the soil. The IPCC (2007) greenhouse gas inventory guidelines suggested that conversion from conventional tillage to no tillage systems leads to a 10 per cent increase in the estimated sequestration of carbon in the soil. Many workers have estimated that any tillage and related soil disturbance enhances the rate of mineralization of soil organic matter and thus leads to emission of CO_2 into the atmosphere especially high at the depositional site where the labile fraction is concentrated in the top 10 to 20 cm and is tilled frequently (Morris *et al.*, 2004; Duiker and Lal, 1999). West and Post (2002) reported the mean rate of SOC sequestration of 570±140 Kg C ha^{-1} $year^{-1}$, which may lead to the new equilibrium SOC pool in 40–60 years while analyzing 67 long-term experiments round the world. Conversion of plough tillage to no-till farming on 1600 Mha of cropland along with adoption of conservation-effective measures could lead to sequestration of $0.5–1x10^9$ tonnes C $year^{-1}$ by 2050 (Pacala and Socolow, 2004). Adopting reduced or no till may also affect emissions of N_2O, but the net effects are inconsistent and not well-quantified globally (Smith and Conen, 2004; Li *et al.*, 2005). The effect of reduced tillage on N_2O emissions may depend on soil and climatic conditions: in some areas reduced tillage promotes N_2O emissions; elsewhere it may reduce emissions or have no measurable influence (Marland *et al.,* 2001).

For cropping systems, there are many options available that can deal with the projected climate changes (Lal, 2008). The adaptations may be brought at (i) input levels such as varieties/species with more appropriate thermal time and vernalization requirements and increased resistance to heat shock and drought, (ii) management level by widening the technologies to harvest water, conserve soil moisture and nutrients and preventing nutrient mining and erosion and (iii) decision levels by diversifying the income through altering integration with other farming activities. Compared with monoculture cropping practice, multi-crop rotations with two or three crops in a year can result in increased SOC contents (Drinkwater *et al.,* 1998; Buyanoski and Wagner, 1998). These adaptations have substantial potential to mitigate the emissions of GHGs.

It has been estimated that modified rice drainage and straw incorporation practices could reduce global CH_4

emissions from rice cultivation by up to 30% (Yan *et al.*, 2009). Anaerobic decomposition of organic material in flooded rice fields produces methane (CH_4), which escapes to the atmosphere primarily by diffusive transport through the rice plants during the growing season. Of the wide variety of sources of atmospheric CH_4 (Yan *et al.,* 2003) rice paddy fields are considered one of the most important. The Intergovernmental Panel on Climate Change (IPCC*,* 1996) estimated the global emission rate from paddy fields at 60 Tg/year, with a range of 20 to 100 Tg/year. Emissions during the growing season can be reduced by many practices (Aulakh *et al.,* 2001) like draining the wetland rice once or several times during the growing season effectively reduces CH_4 emissions (Smith and Conen, 2004).

Agro-forestry system

The agro-forest practices are promoted as a sustainable land use management system in developed and developing countries. These range from low input system such as alley cropping and short term improved fallow with leguminous shrubs to shade grown coffee (*Coffea arabica* L.) in tropical regions and high input cereal-legume systems and riparian plantings in temperate. The C sequestration potential of agro-forestry system is based on the biotic components growing up within the system including the soil, but should also include activities such as forest fire prevention and other multifunctional outputs from the system (Rodriguez *et al.*, 2009). In agro-forestry systems, C is located in five main pools *viz.,* above ground biomass (tree and understory), plant roots (tree and understory), litter, microbial and soil C. Tree presence would increase C sequestration per unit of land due to the C sequestration by the tree itself, the inputs of residues (leaves and branches) it makes on the soil to build up soil organic matter than herbaceous crops, as they are able to explore soils further from the tree trunk and to a greater depth, assuming small tree density is used (Moreno *et al.*, 2005).

The agro-forest practices like riparian and upland buffers, alley cropping, wind breaks, forest farming, silvopasture and agrosilviculture with site specific adaptive nature offers a great deal of environmental stability and buffer to the climate change. These systems with proper biomass accrual in terms of region, plant composition, soil, climate age and management under adaptive elements can enhance C sequestration potential spatially and temporarily. There has been considerable research to track different functional groups and practices in the agro-forest systems that enhance agricultural production, prevent crop failure and to meet fuel and fodder requirement. A large number of adaptation strategies have been suggested for agro-forests, including changes in management intensity, hardwood/softwood species mix, timber growth, harvesting patterns within and between regions, rotation periods, salvaging dead timber, shifting to species or areas more productive under the new climatic conditions, landscape planning to minimize fire and insect damage, adjusting to altered wood size and quality, and adjusting fire management systems (Weih, 2004). Adaptation measure for controlling pest attack can include prescribed burning for reducing forest vulnerability to increased insect outbreaks, nonchemical insect control and adjusting harvesting schedules. Under moderate climate changes, these adaptation measures may potentially reduce the negative consequences of climate change (Shugart *et al.*, 2003).

System such as hedgerow intercropping and boundary plantings are effective in protecting soils from erosion, restoring fertility in degraded land and enhancing the soil C. Riparian system in the transition zone between upland and aquatic habitats such as wetland, streams, rivers, lakes and bays comprise diverse species mixture of trees and grasses which help to capture both above and below ground resources more effectively than the row crop agriculture. According to Naiman *et al.* (2005) above ground C of a mature riparian forest ranged from 50-100 Mg ha^{-1} in USA. With the age of the riparian system, the above and below ground biomass increases the level of C stock. Giese *et al.* (2003) showed 2.5, 3.7, 5.0 and 5.5 Mg C ha^{-1} below ground in 2, 8, 12 and 60 year old riparian buffers respectively. Alley system includes widely spaced single or multi species tree, grass and/or shrub rows with agronomic crops or pasture grass grown in alleys. The differential composition of vegetative groups depends on landowner, site suitability and management practices. The tree and crop row configuration, C input differences in soil, mineralization rate and soil micro fauna composition of alley system is responsible for spatial heterogeneity in C stocks and sequestration (Udawatta *et al.*, 2008, 2009). In an alley cropping system in southern Ontario, Norway spruce (*Picea abies* L.) sequestered twice as much C as popular in a 13 year study (Peichl *et al.*, 2006). From various studies it is estimated that soil organic carbon differences among alley system and monocropping system were not significant (Bambrick *et al.*, 2010; Peichle *et al.*, 2006; Oelbermann *et al.*, 2006a, b).

However, the spatial variation in soil organic carbon in alley system could result from spatial pattern in above ground biomass, litterfall and root biomass. The significant difference in biomass depends upon the alley system composition. Jose *et al*., (2004) observed significantly greater root biomass in black walnut (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) tree rows compared to maize alleys. Red oak root biomass was 2.1 and 1.8 times greater than the maize root biomass at the tree base and 1.1m from the base. Black walnut had 1.1 and 1.37 times more roots at those distances respectively than maize. Trees had fewer roots at distances greater than 2.3m from the tree row. The adaptive strategies in tree-crop rotation, composition and distance in alley cropping can result in much greater soil C sequestration than agronomic monocropping systems (Oelbermann, 2002; Thevathasan and Gordon, 1997; Peichl *et al*., 2006). The most common agro-forestry system i.e., silvopastoral system involves the integration of trees, forage crops and livestock into a structural and functional system for the optimization of benefit from planned biophysical interactions (Udawatta and Jose, 2011). The system component mainly consists of mixed sparse e.g. most system of trees in pastures with production function of fodder, fuelwood and other wood products ecologically suitable to highland humid tropics. The system has a great C sequestration potential not only due to high biological productivity (as in protein banks), but also to the availability of larger areas under grazing management (Haile *et al*., 2008; Sharrow *et al*., 2009). The C sequestration potential of silvopastoral system is due to its ability to enhance rooting depth and distribution and quality of organic matter input (Haile *et al*., 2008). The system outperforms C sequestration both in comparison to forest and pasture systems. In general, tree store about 50-60% of the C in the above ground biomass where as pasture grasses store only 10% above ground, rest being allocated below ground while silvopastoral system sequester an additional 0.74 Mg C $ha^{-1}year^{-1}$ and 0.52 Mg C ha^{-1} $year^{-1}$ than the forest and pasture respectively (Houghton and Hackler, 2000; Sharrow and Ismail, 2004). The spatial C distribution and as such C sequestration, both above and below ground depends upon the design and management practices involved. The tree components in the system play a significant role in C sequestration. Soil organic C contents were 1033, 1376 and 1318 Mg ha^{-1} to a depth of 1.25m in open pasture, centre of the pasture alley and in between trees in trees row respectively (Haile *et al*., 2010). Therefore, the adaptive strategies to be adopted to enhance C sequestration may include altered rotation of pastures, modification of times of grazing and timing of reproduction, alteration of forage and animal species/ breeds, reassessing fertilizer application and care of adequate water supplies. The grazing land and cropland dedicated to the production of feed, represents approximately 70% of all agricultural land in the world (Conant *et al.,* 2005). The intensity and timing of grazing can influence the growth, C allocation and flora of grasslands, thereby affecting the amount of C accrual in soils (Conant *et al.,* 2005; Reeder *et al.,* 2004). Further, research is to be focused to translate stocking rate, rotational grazing and fertilizer application in terms of C sequestration enhancement.

The other agro-forestry practices *viz.,* improved fallow, taungya, multipurpose tree on croplands, shelterbelts and wind breaks, aqua-forestry etc designed on the same basic principle of agro-forestry system for a particular purpose of enhancement of biophysical, economical and socio-ecological components also act as buffer to climate change. Verchot *et al*., (2007) estimated soil organic C accretions through improved fallow between 0.73 to 12.46 Mg/ha depending on sampling depth besides curbing land degradation and improving farm productivity. Moreover, taungya (cereals like maize in association with trees) and improved fallow have proven C additionality as compared to traditional system in above ground biomass. The adaptation strategy demand further research in terms of agro-forestry prototypes, species to be planted, appropriate spatial and temporal arrangements for planting and selected designs that reflect the biophysical, technical and socio-economic conditions of the locality (Vanclay *et al.,* 2006). Windbreaks and shelterbelts albeit at a limited spatial scale on the landscape also contribute to the soil organic C pool. Shelterbelt contained 12% more soil organic C in 7.5-15cm depth compared to the crop field. In a growing period of 35 years, shelterbelt 3.71 Mg more soil organic C at 0-15cm soil depth ha^{-1} than the cultivated region which represent an annual sequestration of 0.11 Mg ha^{-1}. C sequestration potential under windbreaks is estimated about 4 Tg C yr^{-1} under 85 million ha (Nair and Nair, 2003). Limited literature and research pertaining to species selection and area under windbreaks and shelterbelts for maximizing C sequestration potential underlines the importance of the subject.

Constraints and opportunities

The aspect of adaptive agro-forestry system is yet developing as a science and our understanding of C storage and dynamics is still minimal. Therefore, a comprehensive scientific research is needed to find out the C distribution in world agro-forestry systems for the development of suitable mitigation strategies associated with agro-forestry practices. The data pertaining to above and below ground biomass for different trees and shrubs under agro-forestry system needs to be documented. Specifically, data related to stems, branches, leaves etc and materials that are not removed from the site. The factors affecting the final estimates like bulk density, soil moisture, sampling depth, intensity and time and age of the system needs to be quantified. There is an increasing need to standardize the experimental designs and data collecting protocol for regional comparisons to frame correct conclusions over longer areas. Application and proper use of remote sensing and GIS need to be used to estimate the stocks and C sequestration potential by agro-forestry practices. Models predicting tree growth and their calibration and validation to draw specific conclusions of long term effects are required to be developed. Lastly, agro-forestry statistics and design taking criteria like perennial desirable vegetation, region and practice specific and other complementary effects into consideration that affect the optical C accrual should be developed.

Conclusion

There is increasing necessity for an efficacious focus on adapting agro-forest system to future climate change. The quandary of climate change can be well addressed by resorting to the various RMPs and moderation practices. The C sequestration potential of cropland soils largely via SOC sequestration and grazing land, forest lands, degraded lands, wetlands is 0.6–1.2x10^9 tonnes/year and ~3x10^9 tonnes/year respectively. The total biophysical mitigation potential of agriculture is ~5.5–6x10^9 tonnes CO_2-eq. $year^{-1}$ by 2030. Reforestation/afforestation of non-forest lands will prevent land degradation and thereby sequester and reduce the net C emission to atmosphere. Agro-forestry offers important opportunities of creating synergies between both adaptation and mitigation actions with a technical mitigation potential of 1.2 to 1.2 pg C in terrestrial ecosystem over the most 50 years. The subject is to be coupled with the proper data of world C stocks together with the models and statistical procedures to draw correct conclusions about the C sequestration potential by these systems. Keeping in view the pressure on ecological balance, it is possible to reduce the current pace of global warming by focusing on carbon sink potentials of the terrestrial biosphere while at the same time balancing economic development and environmental concerns.

References

Albrecht, A. and S. T. Kandji. 2003. Carbon sequestration in tropical agroforestry systems. *Agric. Ecosyst. Environ.* 99:15–27

Aulakh, M. S., R. Wassmann, C. Bueno and H. Rennenberg. 2001. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. *Plant Soil* 230: 77–86.

Bambrick, A. D., J. K. Whalen, R. L. Bradley, A. Cogliastro, A. M. Gordon, A. Olivier and N. V. Thevathasan. 2010. Spatial heterogeneity of soil organic carbon in tree-based intercropping systems in Quebec and Ontario, Canada. *Agroforest. Syst.* 79:343–353

Batjes, N. H. 1996. The total C and N in soils of the world. *Eur. J. Soil Sci.* 47: 151–163.

Butt, T. A., B. A. McCarl, J. Angerer, P. T. Dyke and J. W. Stuth. 2005. The economic and food security implications of climate change in Mali. *Climate Change* 68: 355-378.

Buyanoski, H. A. and G. H. Wagner. 1998. Carbon cycling in cultivated land and its global significance. *Global Change Biol.* 4: 131–141.

Chhabra, A., S. Palria and V. K. Dadhwal. 2002. Growing stock based forest biomass estimate for Indian forests. *Biomass and Bioenergy* 22(3): 187-194.

Conant, R. T., K. Paustian, S. J. Del Grosso and W. J. Parton. 2005. Nitrogen pools and fluxes in grassland soils sequestering carbon. *Nutr. Cycl. Agroecosyst.* 71: 239–248.

Dixon, R. K., J. K. Winjum and P. E. Schroeder. 1993. Conservation and sequestration of carbon: the potential of forest and agroforest management practices. *Glob Environ Change Human Policy Dimension* 3:159–173

Drinkwater, L. E., P. Wagoner and M. Sarrantonio. 1998. Legume based cropping systems have reduced carbon and nitrogen losses. *Nature* 396: 262–264.

Duiker, S. W. and R. Lal. 1999. Crop residue and tillage effects on carbon sequestration in a Luvisol in central Ohio. *Soil and Tillage Research* 52: 73-81.

Easterling, W., P. Aggarwal, P. Batima, K. Brander, L. Erda, M. Howden, A. Kirilenko, J. Morton, J-F. Soussana, J. Schmidhuber and F. Tubiello. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability*, eds Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (Cambridge University Press, Cambridge, UK), pp 273–313.

Falkowski, P. *et al.* 2000. The global carbon cycle: a test of our knowledge of earth as a system. *Science* 290, 291–296.

Giese, L. A. B., W. M. Aust, R. K. Kolka and C. C. Trettin. 2003. Biomass and carbon pools of disturbed riparian forests. *For. Ecol. Manag.* 180:493–508

Gordon, A. M. and S. M. Newman. 1997. *Temperate Agroforestry Systems*. CAB International, ISBN 0851991475, Wallingford, U. K.

Grainger, A. 1995. Modeling the anthropogenic degradation of drylands and the potential to mitigate global climate change. In: *Global climate change by combating land degradation* (eds V. R. Squires, E. P. Glenn & T. A. Ayoub), pp. 193–199. Nairobi, Kenya: UNEP.

Greene, C. H. and A. J. Pershing. 2007. Climate drives sea change. *Science* 315: 1084-1085.

Haile, S. G., P. K. R. Nair and V. D. Nair. 2008. Carbon storage of different soil-size fractions in Florida silvopastoral systems. *J. Environ. Qual.* 37:1789–1797

Haile, S. G., V. D. Nair and P. K. R. Nair. 2010. Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA. *Glob. Change Biol.* 16:427–438

Houghton, R. A. and J. L. Hackler. 2000. Changes in terrestrial carbon storage in the United States. 1. The role of agriculture and forestry. *Glob. Ecol. Biogeogr.* 9:125–144

IPCC. 1996. *Climate change 1995: the science of climate change. Contribution of working group I to the 2nd assessment report of the IPCC.* Cambridge, UK: Cambridge University Press.

IPCC. 2000. In: Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds.) *Land use, land-use change, and forestry. A special report of the IPCC.* Cambridge University Press, Cambridge, 375 p

IPCC. 2001. *Climate change 2001: the scientific basis. Intergovernment panel on climate change.* Cambridge, UK: Cambridge University Press.

IPCC. 2007. *Climate change 2007. Climate change impacts, adaptation and vulnerability. Working Group II.* Geneva, Switzerland: IPCC.

Jha, M. N., M. K. Gupta, A. Saxena and R. Kumar. 2003. Soil organic carbon store in different forests in India. *Indian Forester* 129 (6): 714-724.

Jose, S., A. R. Gillespie and S. G. Pallardy. 2004. Interspecific interactions in temperate agroforestry. *Agroforest. Syst.* 61:237–255

Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforest. Syst.* 76:1–10.

Kerr, R. A. 2007. Scientists tell policy makers we're all warming the world. *Science* 315: 754–757.

Kluger, J. 2007. Global warming: what now? Our feverish planet badly needs a cure. *Time Magazine* 9: 50–109.

Kort, J. and R. Turnock. 1999. Carbon reservoir and biomass in Canadian prairie shelterbelts. *Agroforest. Syst.* 44:175–186.

Krankina, O. N. and R. K. Dixon. 1994. Forest management options to conserve and sequester terrestrial carbon in the Russian Federation. *World Resour. Rev.* 6: 88–101.

Lal, R. 2008. Carbon Sequestration. *Philosophical Transactions of the Royal Society*. 363: 815-830.

Lal, R. 2003. Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Crit. Rev. Plant Sci.* 22: 151–184.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623–1627.

Lamb, D., P. D. Erskine and J. A. Parrotta. 2005. Restoration of degraded tropical forest landscape. *Science* 310: 1628–1632.

Li, C., S. Frolking and K. Butterbach-Bahl. 2005. Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Clim. Change* 72:321-338.

Marland, G., B. A. McCarl and U. A. Schneider. 2001. Soil carbon: policy and economics. *Climate Change* 51: 101–117.

Monreal, C. M., R. P. Zentner and J. A. Robertson. 1997. An analysis of soil organic matter dynamics in relation to management, erosion and yield of wheat in long-term crop rotation plots *Can. J. Soil Sci.* 77: 553.

Moreno, G., J. J. Obrador, E. Cubera and C. Dupraz. 2005. Fine root distribution in dehesas of central western Spain. *Plant Soil* 277:153–162

Morris, D. R., R. A. Gilbert, D. C. Reicosky and R. W. Gesch. 2004. Oxidation potentials of soil organic matter in histosols under different tillage methods. *Soil Sci. Soc. Am. J.* 68: 817–826.

Naiman, R. J., H. Decamps and M. E. McClain. 2005. Structural patterns. In: Naiman RJ, Decamps H, McClain ME (eds.) *Riparia: ecology, conservation, and management of streamside communities.* Elsevier, New York, pp 79–123.

Nair, P. K. R. and V. D. Nair. 2003. Carbon storage in North American agroforestry systems. In: Kimble JM, Heath LS, Birdsey RA, Lal R (eds.). *The potential of U.S. Forest soils to sequester carbon and mitigate the greenhouse effect.* CRC Press, Boca Raton, pp 333–346.

Nair, P. K. R. 1993. *An Introduction to Agroforestry*. Kluwer Academic Publishers, ISBN 0792321340, Dordrecht, NL, pp 499

Oelbermann, M., R. P. Voroney, D. C. L. Kass and A. M. Schlönvoigt. 2006a. Soil carbon and nitrogen dynamics using stable isotopes in 19- and 10-yr old tropical agroforestry systems. *Geoderma* 130:356–367.

Oelbermann, M., R. P. Voroney, N. V. Thevathasan, A. M. Gordon, D. C. L. Kass and A. M. Schlönvoigt. 2006b. Soil carbon dynamics and residue stabilization in a Costa Rican and southern Canadian alley cropping system. *Agroforest. Syst.* 68:27–36.

Oelbermann, M. 2002. *Linking carbon inputs to sustainable agriculture in Canadian and Costa Rican agro-forestry systems*. PhD Dissertation, Dept Land Res Sci, University of Guelph, Canada, 208 p

Oost, K.V. *et al*., 2007. The impact of Agriculture Soil erosion on the Global Carbon Cycle. *Science*. **318**: 626-629.

Pacala, S. and R. Socolow. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science* 305: 968–972.

Paustian, K. et al. 2004. Agricultural mitigation of green house gases: Science and policy option. Council of Agricultural Science and Technology (CAST) report, R 141 2004, ISBN 1-887383-26-3 P. 120, May, 2004.

Peichl, M, N. V. Thevathasan, A. M. Gordon, J. Huss and R. A. Abohassan. 2006. Carbon sequestration potentials in temperate tree-based intercropping systems. southern Ontario, Canada. *Agroforest. Syst.* 66:243–257.

Ponting, C. 2007. A new green history of the world: The environment and collapse of great civilizations. Penguin Books, New York. United Nations. 2008. *World population prospects: The 2008 revision, population database.* United Nations Population Division.

Reeder, J. D., G. E. Schuman, J. A. Morgan and D. R. Lecain. 2004. Response of organic and inorganic carbon and nitrogen to long-term grazing of the shortgrass steppe. *Environ. Manage.* 33, 485–495.

Rodríguez, A. R., E. Fernández-Núñez, P. González-Hernández, J. H. McAdam and M. R. Mosquera-Losada. 2009. Agroforestry systems in Europe: productive, ecological and social perspectives. In: Rigueiro-Rodríguez A, McAdam J, Mosquera-Losada MR (eds.) *Agroforestry in Europe. Current status and future prospects.* Springer, Dordrecht, pp 43-66.

Ruddiman, W. 2003. The anthropogenic greenhouse era began thousands of years ago. *Climatic Change* 61: 261–293.

Running, S. M. 2006. Is global warming causing more large wildfires? *Science* 313: 927–928.

Scholes, R. J. and I. R. Noble. 2001 Storing carbon on land. *Science* 294: 1012-1013.

Schrag, D. P. 2007. Preparing to capture carbon. *Science* 315: 812-813.

Schroeder, P. 1993. Agroforestry systems: integrated land use to store and conserve carbon. *Climate Research* 3:53-60.

Schroeder, P. 1994. Carbon storage benefits of agroforestry systems. *Agroforest. Syst*. 27:89–97.

Sharrow, S. H., D. Brauer and T. R. Clason. 2009. Silvopastural practices. In: Garrett H.E. (ed.) *North American agroforestry: An integrated science and practice,* 2nd edn. American Society of Agronomy, Madison, pp 105-131

Sharrow, S. H., and S. Ismail. 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. *Agroforest. Syst.* 60:123-130.

Shugart, H., R. Sedjo and B. Sohngen. 2003. *Forests and Global Climate Change, Potential Impacts on US Forest Resources* (Pew Center on Global Climate Change, Arlington, VA).

Smith, K. A. and F. Conen. 2004. Impacts of land management on fluxes of trace greenhouse gases. *Soil Use Manage*. 20, 255–263.

Stocking, M. A. 2003. Tropical Soils and Food Security: The Next 50 Years. *Science* 302:1356-1359.

Thevathasan, N. V. and A. M. Gordon. 1997. Poplar leaf biomass distribution and nitrogen dynamics in a poplar-barley intercropped system in southern Ontario, Canada. *Agroforest. Syst.* 37:79–90

Travasso, M. I., G. O. Magrin, W. E. Baethgen, J. P. Castan˜o, G. R. Rodriguez, J. L. Pires, A. Gimenez, G. Cunha and M. Fernandes. 2006. *Working Paper no 28* (Assessments of Impacts and Adaptations to Climate Change) www.aiaccproject.org/ working_papers/ working_papers.html.

Udawatta R. P., R. J. Kremer, B. W. Adamson and S. H. Anderson. 2008. Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. *Appl. Soil Ecol.* 39:153–160.

Udawatta, R. P., R. J. Kremer, H. E. Garrett and S. H. Anderson. 2009. Soil enzyme activities and physical properties in a watershed managed under agroforestry and row-crop system. *Agric. Ecosyst. Environ.* 131:98-104.

Udawatta, R. P. and S. Jose. 2011. *Carbon Sequestration Potential of Agroforestry Practices in Tsemperate North America*, eds Kumar and Nair (Springer Dordrecht Heidelberg New York, London) pp. 17-42

Vanclay, J., R. Prabhu and F. Sinclair. 2006. *Realizing community futures. A practical guide to harnessing natural resources.* Earthscan, London, 162 p

Verchot, L. V., M. van Noordwijk, S. Kandji, T. Tomich, C. Ong, A. Albrecht, J. Mackensen, C. Bantilan and C. Palm. 2007. Climate change: Linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change* 12:902-918, ISSN 1381-2386.

Walsh, B. 2007. Greenhouse airlines: traveling by jet is a dirty business. As passenger load increases, environs look for ways to cut back the carbon. *Time,* 12 Feb. 2007, 57.

Weih, M. 2004. Intensive short rotation forestry in Boreal climates: Present and Future perspectives. *Can. J. For. Res.* 34:1369–1378.

West, T. O. and W. M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci. Soc. Am. J.* 66: 1930–1946.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan and T. W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313: 940–943.

Winjum, J. K., R. K. Dixon, and P. E. Schroeder. 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. *Water Air Soil Pollut.* 64: 213-28.

WMO. 2006. Greenhouse gas bulletin: the state of greenhouse gases in the atmosphere using global observations up to December 2004. Geneva, Switzerland: World Meteorological Organization.

Yan X., H. Akiyama, K. Yagi and H. Akimoto 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change guidelines. *Global Biogeochem Cycles*, 10.1029/2008GB003299

Yan, X., T. Ohara and H. Akimoto. 2003. Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and South Asian countries. *Global Change Biol.* 9: 237–254.