REVIEW ARTICLE

CHANGES IN SOIL PROPERTIES AND CARBON SEQUESTRATION POTENTIAL UNDER INTENSIVE AGRICULTURE AND AGROFORESTRY

Sunita Sheoran[1]*, Dhram Prakash[2] and Ashok Kumar[3]

[1]Department of Soil Science, CCS HAU, Hisar, Haryana (India),
[2]Department of Soil Science, [3]Department of Forestry and Natural Resources,
PAU, Ludhiana, Punjab (India)
Email: sheoransunita27@gmail.com

Received-28.01.2017, Revised-13.02.2017

Abstract: Agroforestry has been recognized as a means to reduce CO_2 emissions as well as enhancing carbon sinks although the rice-wheat cropping system increases the green house gases level. Agroforestry is a large sink of carbon and its role in carbon cycles is well recognized. The article reviews the impact of different land use systems on properties such as EC, pH and the carbon sequestration potential of soils. Agroforestry provides a unique opportunity to combine the twin objectives for capturing atmospheric CO_2 to ameliorate environment and, improving the soil nutrient status as well. Soil organic carbon has been recorded abundantly in agroforestry systems than other land use systems. The emphasis of land use systems that led to higher carbon content than other cropping systems can help to achieve net gains in carbon in soils specifically and, significant increases in carbon storage can be achieved by moving from lower biomass land uses.

Keywords: Land-use systems, Agroforestry, Soil properties, Carbon sequestration potential

INTRODUCTION

Studies carried out in the plains and hills indicate declining soil fertility due to soil erosion. Farmlands have reportedly been lossing soils at the rate of 8-12 t ha^{-1} y^{-1} (Carson, 1992). As a result, yields of staple crops, like rice, maize, wheat and millet have followed a decreased trend (Vaidya *et al.*, 1995). Constant loss of soil fertility has been a serious land management constraint for sustaining agricultural production in the plains and hills (Schreier *et al.*, 1995) which is likely to be aggravated further. Improvements in vegetative cover through better agronomic practices and contour hedgerows were found desirable (Angus *et al*., 1998).

At a global level, reviewing the fertilizer impacts on the environment based on data from Bockman *et al*. (1990) and Ayoub (1999) showed that in 1970, 48% of the nutrients used by crops were derived from the soil, 13% from manure, and 39% from inorganic fertilizers. By 1990, the percentages had changed to 30% from soil, 10% from manure and 60% from inorganic fertilizer. The projection for 2020 is 21% from the soil, 9% from an organic source, and 70% from an inorganic fertilizer source. Considering that only about half of the applied fertilizer is taken up by the crop in a given season (Bockman *et al.*, 1990), the negative impact of fertilizer use on environmental quality is likely to increase with time on a global scale.

The cropping system occupies around 13.5 Mha in the Indo-Gangetic Plains (IGP) of Bangladesh, India, Nepal and Pakistan. The cropping system is of utmost importance for ensuring regional food security. There are reports of stagnating or declining rice and wheat yields in the IGP (Ladha *et al*., 2003), which have presumably been related to declining soil organic matter (SOM) content and decreased soil fertility (Bhandari *et al*. 2002; Regmi *et al*., 2002). However, temporal analysis of 25-years data on organic C content of the regional soils showed that the stagnating productivity was not related to SOC (Benbi and Brar, 2009). So far there is no information available on the quality of SOM under rice-wheat system in comparison to other agroecosystems. Maize-wheat is another important cropping system in the region. Rice and maize result in alternating soil aeration status viz., anaerobic conditions during rice season and aerobic conditions in maize fields that can significantly influence decomposition and accumulation of SOM.

According to Nair and Graetz (2004), U.S. Natural Resources Conservation Service (NRCS) has the responsibility to provide planning assistance to land-use decision-makers that will protect the five major resource concerns of Soil, Water, Air, Plants, and Animals (SWAPA). According to a study by the World Agroforestry Centre (ICRAF), 43% of the planet's agricultural land has more than 10% tree cover (Zomer *et al.,* 2009), 160 million hectares land area has more than 50% tree cover. Within the array of benefits brought by trees, an important element is the positive effect of trees on soil properties and consequently benefits for crops.

Maintenance of soil fertility requires preservation of its organic matter, physical properties and nutrient levels. Soils do not support intensive annual plant cultivation without fertilizer applications (Sanchez *et al*., 1983; Alfaia *et al.,* 1988), and even these may not maintain sustainability. Due to the fragility of soils, all agricultural projects must consider soil fertility and its maintenance as a priority. Thus, the use of diverse tree species and other practices

*Corresponding Author

employed in agroforestry systems can represent alternative forms of increasing soil fertility and maintaining agricultural production, with important practical applications for the sustainability of tropical agriculture. Agroforestry offers not only a sustained productivity, but also an increase in productivity per unit area. Considering all above aspects, we tried to review the impacts of different landuse systems on soil properties.

Land uses v/s soil properties

The basic properties of the surface soils under different cropping systems viz. rice-wheat, maize-wheat and cotton-wheat and a poplar based agroforestry system are presented in Table 1. The soils under all the land-uses were non-saline and near-neutral to alkaline in reaction. However, the soils under agroforestry had significantly lower pH than the other land-uses that did not differ significantly (Prakash, 2016). Soils under all the land-uses were sandy loam in texture with sand content ranging between 60 and 64.6% and silt content between 21.8 and 25.1%. Soils under all the land-uses were medium to high (9.8 to 16.0 mg P kg^{-1}) in available P and high in available K (83 to 100 mg K kg^{-1}). However, available P concentration was significantly lower in soils under agroforestry, compared to the other land-uses. The relatively greater P concentration under sole cropping systems may be attributed to regular use of organic manure (FYM) and fertilizer P during crop production. Contrarily, available P concentration was significantly lower in soils under agroforestry, compared to the other land-uses (Prakash, 2016). Lower concentration of available P in soils under agroforestry may be due to wide C: P ratio. Wide C: P ratio reduces P mineralization leading to decrease in available P concentration in soil (Broder *et al.*, 2012). Available K concentration was significantly higher in soils under agroforestry compared with other land-uses. The $CaCO_3$ concentration in soils under different land-uses did not differ significantly and ranged between 0 and 19.5 g kg^{-1} soil (Prakash, 2016).

In an evaluation of more than 20,000 globally distributed soil profiles, the greater part in temperate climates, Jobbagy and Jackson (2001) found that cycling mediated by plants exerts a marked influence on the vertical distribution of nutrients in the soil, especially in the case of more limiting nutrients such as P and K. Studies of forests in temperate climates indicate variations in soil that can be related to individual tree species. Besides the expected correlations, such as greater levels of N under legumes (Ulery *et al.,* 1995) or lower pH under species that produce acidifying litter, such as *Pinus* spp. (Ulery *et al.,* 1995; Reich *et al.,* 2005), other interesting interactions show that different species can alter soil in distinct ways, with variations in the increment of soil carbon (C) (Ulery *et al.,* 1995) exchangeable Ca and Mg and per cent base saturation (Finzi *et al.,* 1998, Reich *et al*., 2005).

In a study of 14 tree species in Poland, Reich *et al.,* (2005) found varied effects on soil characteristics; however, these effects were significantly related to the level of Ca in litter, independent of the species. Trees producing litter rich in Ca were associated with soils with greater pH, exchangeable Ca, and per cent base saturation, as well as greater rates of forest floor turnover and greater diversity and abundance of earthworms. Dijkstra (2003) emphasized that the rate of mineralization of organic Ca is a fundamental factor in this process, since it determines the immediate availability of this nutrient in the soil and can vary between species. In the areas where the biophysical condition is suitable for tree and shrub species, agroforestry can contribute to enhance soil fertility. Subsequent studies also demonstrated patterns in the variation of soil characteristics as influenced by trees, such as in tropical savannas (Belsky *et al.,* 1989; Burke *et al.,* 1998), deserts (Schlesinger *et al.,* 1996), and areas of temperate forests (Ulery *et al.,* 1995; Finzi *et al.,* 1998; Dijkstra, 2003; Reich *et al.,* 2005). In analyzing soil characteristics under individual tree crowns in Kenyan savannas, Belsky *et al.,* (1989) found greater levels of mineralizable N, microbial biomass, P, K, and Ca underneath the crowns when compared to open savanna.

In the arid region of India, the effect of *Prosopis cineraria*, *Tecomella undulata*, *Acacia albida* and *Azadirachta indica* on the productivity of *Hordeum vulgare* (barley) was found to be positive. *P. cineraria* enhanced grain yield by 86.0%, *T. undulata* by 48.8%, *A. albida* by 57.9% and *A. indica* by 16.8% over the control. Biological yield was also higher under trees than that in the open area. Soils under different tree canopies were rich in organic carbon content, moisture availability and nutrient status (Kumar *et al.,* 1998). There is robust evidence that agroforestry systems have the potential for improving water use efficiency by reducing the unproductive components of the water balance (run-off, soil evaporation and drainage) (Turner and Ward, 2002). That is why such systems are more beneficial as compared to agricultural cropping systems. Increases in soil nutrients especially soil available nutrient, soil microbial biomass carbon, microbial quotient, soil basal respiration, microbe numbers and enzyme activities were reported high in tree-crop combinations. The greater soil microbial biomass carbon (SMBC) reflects the response of more input of organic matter to the soils under tree-crop combinations (Wang *et al.,* 2005). Ocio and Brookes (1990) have also reported that SMBC influenced much more quickly by organic inputs in comparison to the agricultural management induced changes in soil organic matter.

Land uses v/s soil carbon pools

Soil carbon pool in an ecosystem is controlled by the balance between the C inputs derived from litter fall, root biomass and root exudates and the outputs through heterotrophic respiration. Soils in agroforestry and maize-wheat systems had approximately 28% higher concentration of total carbon than those in rice-wheat system but these differences were statistically insignificant. Total organic carbon (TOC) differed significantly with respect to land-use practices. In contrast, soils in the rice-wheat system exhibited significantly lower SOC concentrations than those in the other two agro-ecosystems (Table 2). Compared to the rice-wheat system, agroforestry and maize-wheat systems were 88% and 65% higher in SOC, respectively (Figure 1). The higher SOC concentration under agroforestry may be attributed to input of C through litter fall that occurs at the beginning of winter season and greater root biomass compared to sole annual crops. Poplar trees, grown in the region, add 2.9-3.3 t ha^{-1} of litter fall every year (Ralhan *et al.*, 1996; Tandon *et al.*, 1991) and supply 2.3 t C ha^{-1} y^{-1} through roots and leaves (Chauhan *et al.*, 2011). Soils in the maize-wheat system also exhibited higher SOC stocks than those in the rice-wheat system, probably because of C input through farmyard manure application to maize. Positive effect of manure application on SOC build-up under maize-wheat system in semi-arid India has earlier been reported by Benbi *et al*., (1998).

The effect of different land-use systems on SOC concentration and its labile pools viz. hot water soluble carbon (HWSC) and $KMnO_4$-C are given in Table 3. Averaged across sites, SOC concentration was the highest under agroforestry and the lowest under cotton-wheat cropping system, while maize-wheat and cotton-wheat systems exhibited similar SOC concentration. The rice-wheat system had significant higher SOC concentration than two cropping systems but significantly lower than agroforestry systems. Significantly higher concentration of SOC in soils under agroforestry compared to sole cropping systems could be attributed to the effect of large return of plant biomass C through leaf litter and reduced tillage practices under agroforestry. Bene *et al* (2011) has reported that soil organic matter is closely related to the amount of above and below ground organic matter inputs. Lobato *et al* (2014) has reported that reduced tillage and its duration tends to build-up SOC under agroforestry than the sole cropping systems. In many long-term experiments, researchers have shown a significant relationship between C input through plant biomass and organic manures with SOC sequestration (Benbi *et al.*, 2012; Huang *et al.*, 2014). The results of the present investigation corroborates the findings of Benbi *et al* (2012), who also reported higher SOC concentration under agroforestry than in soils under rice-wheat cropping system. The comparison of three cropping systems revealed significantly higher SOC concentration in the soils under rice-wheat than the maize-wheat and cotton-wheat cropping systems. This could be attributed to retarded rate of soil organic matter decomposition due to prevailing anaerobic conditions during rice cultivation (Manlay *et al.,* 2002). Since rice-wheat cropping involves cultivation of wetland and upland crops in sequence, it experiences alternate wetting and drying and thus differential stabilization of soil organic matter, compared to the other two cropping systems which are grown under upland conditions.

The concentration of HWSC was significantly higher in soils under agroforestry and rice-wheat than the maize-wheat and cotton-wheat copping systems (Table 3). Lower HWSC under sole cropping systems than agroforestry could be possibly due to intensive cultivation which includes several times tillage practices per year leads to greater breakdown of SOM or decomposition of native SOC (Wardle 1992; Haynes 2000; Ghani *et al* 2003; Shi *et al* 2015). Greater rhizo-deposition of root mass and exudates in soils under agroforestry also influences turnover rate of C (Kuzyakov *et al.,* 2001). The concentration of $KMnO_4$-C was significantly higher in soils under agroforestry than the other land-uses. The soils under maize-wheat and cotton-wheat cropping systems did not differ significantly for their effect on $KMnO_4$-C. Higher concentration of HWSC and $KMnO_4$-C in soils under agroforestry indicates the quantitative as well as qualitative differences in soil organic matter compared to other land-uses.

Sharma e*t al* (2009) studied the soil fertility and quality assessment under tree, crop and pasture-based land-use systems in a rain-fed environment, observed that among the land-use systems, agroforestry system resulted in the highest SOC content (9.6 g kg^{-1}) compared to arable land (3.66 g kg^{-1}). Tchienkoua and Zech (2004) observed that SOC significantly (P=0.05) higher in soils under *Eucalyptus grandis* plantations (73.3 g kg^{-1}) followed by *Camellia sinensis* plantations (69.1 g kg^{-1}) compared with semi-permanent, maize (*Zea mays* L.)-based, mixed food crop fields (39.4 g kg^{-1}), Under *Eucalyptus* treatment, greater litters with high C: N ratio (64) was a major factor of high SOC build up, lower OC in *Camellia sinensis* system was associated with reduced litter input due to harvest of young shoots as well as its rapid turnover rate as indicated by the low C: N ratio (26) for tea leaves.

Microbial activity plays a major role in nutrient turnover in general and in P transformation and redistribution into different inorganic and organic forms in particular (Stewart and Tiessen, 1987). Cardoso *et al* (2003) observed that organic P/total P was lower in the conventional systems than in the agroforestry systems, suggested that agroforestry systems influence the dynamics of P through the conversion of part of the inorganic P into organic P.

Agroforestry systems are expected to have more microbial activity than the conventional systems. Availability of soil P increased by intercropping with potential of some non-crop plants in agroforestry systems to release P from recalcitrant pools, thus making it available to crops (Palm, 1995). Bene *et al.,* (2011) has reported that soil organic matter is closely related to the amount of above and below ground organic matter inputs. Lobato *et al.,* (2014) has reported that reduced tillage and its duration tend to build-up SOC under agroforestry than the sole cropping systems.

In many long-term experiments, researchers have shown a significant relationship between C input through plant biomass and organic manures with SOC sequestration (Benbi *et al.,* 2012, Huang *et al.,* 2014). The results of the present investigation corroborates the findings of Benbi *et al.,* (2012), who also reported higher SOC concentration under agroforestry than in soils under rice-wheat cropping system. The comparison of three cropping systems revealed significantly higher SOC concentration in the soils under rice-wheat than the maize-wheat and cotton-wheat cropping systems. This could be attributed to retarded rate of soil organic matter decomposition due to prevailing anaerobic conditions during rice cultivation (Manlay *et al.,* 2002). Since rice-wheat cropping involves cultivation of wetland and upland crops in sequence, it experiences alternate wetting and drying and thus differential stabilization of soil organic matter, compared to the other two cropping systems which are grown under upland conditions.

Agroforestry as carbon sink

Trees add organic matter to the soil system in various manners, whether in the form of roots or litter or as root exudates in the rhizosphere as rhizodeposition (Bertin *et al.,* 2003). Fast growing trees including *Populus, Eucalyptus, Melia, Leucena, Paulonia* etc. have an important role for capturing atmospheric carbon dioxide to ameliorate environment. Although carbon (C) constitutes almost 50% of the dry weight of branches, 30% of foliage, the greater part of C sequestration (around 2/3) occurs belowground, involving living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons (Nair *et al.,* 2010). Therefore, agroforestry systems are known to maintain soil organic matter and promote nutrient cycling (Chander *et al.,* 1998).

In homegardens in India, Saha *et al.,* (2010) found levels of SOC to be 30% and 114% greater than in coconut plantations and rice paddies, respectively. In the Northeast of Spain, Howlett *et al.,* (2011) studied the levels of SOC in silvopastoral systems composed of different species, and found that systems with birch (*Betula pendula*) presented greater levels of soil C than systems with pine (*Pinus radiata*).

Several studies have shown that the inclusion of trees in the agricultural landscapes often improves the productivity of systems while providing opportunities to create carbon sinks (Schoreder, 1994; Montagnini and Nair, 2004; Chauhan *et al.,* 2007a; Jose, 2009; Schoeneberger, 2009; Nair *et al.,* 2010; Sharma and Sharma, 2011). The amount of carbon sequestered largely depends on the agroforestry put in places, the structure and function, which to a great extent are determined by environmental and socio-economic factors. The carbon sequestration potential for agroforestry practices is more variable, depending on the planting density, production objective, components in system, productivity, etc. Actually, the carbon storage in plant biomass is better feasible in the perennial agroforestry systems (perennial-crop combinations, agroforestry, windbreaks, hedgerow inter-cropping, horti-silvicultural system, etc.), which allow full time tree growth where the wood component represents an important part of the total biomass. However, the cost of carbon sequestered through agroforestry appears to be much lower than other CO_2 mitigation options.

Organic carbon varied according to soil type, with higher concentrations in the Oxisol than in the Inceptsol (Alfaia *et al*., 2004). In the Oxisol, C was significantly higher in areas with forest and agroforestry systems (AFS) than in pastures, while no significant differences among land use systems were observed in the Inceptsol. Changes in SOC after conversion of primary forest to agricultural systems in Amazonia are after contrasted (Desjardins *et al.,* 2000). With the change of forest to pasture, a gradual increase in C in the soil after burning has been observed (Koutika *et al.,* 1977), while others report relative stability (Eden *et al.,* 1991) or a pronounced decrease (Falesi and Veiga, 1986). Isotopic tracer studies revealed that the amount of forest-derived C remaining in the soil decreases quickly in the first years after pasture establishment, and slows as the supply of pasture-derived organic matter decomposition increases (Desjardins *et al.,* 1994). The effect of AFS on changes in soil C in comparison with pasture or primary forest is not as well known. McGrath *et al.,* (2001) did not find significant differences in C concentration between AFS and primary forest. Recco *et al.,* (2000) observed that older AFS showed a trend of recovery and maintenance of organic C similar to that in primary forest in western Amazonia.

The area under the poplar based agroforestry system is increasing every year because of huge demand from industry. Singh and Lodhiyal (2009); Rizvi *et al.*, (2010); Benbi *et al.*, (2012) also suggested great potential of poplar based intercropping systems in reducing the atmospheric CO_2 concentration compared to sole cropping systems. However, data is insufficient, and an understanding of plant/climate relationships is essentially required to guide the future policies. Some studies have been conducted to explore carbon sequestration potential in poplar-wheat based system. Total CO_2 assimilation by the biomass in the poplar-wheat based agroforestry system and mono-cropping of poplar and wheat was estimated at 28.6, 17.2 and 17.8t ha^{-1} yr^{-1}, respectively as shown in Figure 2 (Chauhan and Chauhan, 2009). Therefore, even when only the accumulation of biomass carbon is considered, an agri-silvicultural system is very efficient in terms of carbon sequestration (Chauhan and Chauhan, 2009). However, these figures hold true if harvested products are transformed into durable products. Litter (leaves, branches and bark) and roots are added and allowed to decompose in the soil to sequester carbon.

Gera *et al.* (2011) reported 66 and 37 t ha^{-1} carbon sequestration potential (2.20 and 1.37 t C ha^{-1} yr^{-1}, respectively) under poplar block and poplar boundary plantations, respectively. Chauhan *et al.*, (2010a) after seven years, estimated timber carbon content of 23.57 t ha^{-1}, whereas, carbon content of the roots, leaves, and bark was 23.9 t ha^{-1} and branches 15.01t/ha. Hence, total biomass carbon storage after seven years was equivalent to 62.48 t ha^{-1} (8.92 t ha^{-1} yr^{-1}). The combined contribution of poplar and wheat was substantially high within the intercropping system. This may be due to the additional carbon pool in the trees and the increased soil carbon pool resulting from litter fall and fine root turnover. The high carbon storage may also be due to the increased growth and assimilation rates of intercropped components as compared to mono-cropping systems. Moreover, poplar timber locks up carbon in its wood products for longer periods, thereby making it the major carbon assimilator of this type of agroforestry system. Poplar-wheat based agroforestry system, thus fare better than traditional agricultural systems, providing the best land use option for increased carbon sequestration.

Clonal variation in carbon sequestering has been recorded in poplar clones by Pal *et al.,* (2009). The carbon content in different components estimated by Chauhan and Chauhan (2009) were found to ranged from 44.08 to 47.82 (stem, branches, root, leaves and bark values were 45.67,46.56,47.82,44.08 and 46.93 per cent, respectively). Rizvi *et al.,* (2011) estimated 27-32 t ha^{-1} and 66-83 t ha^{-1} carbon storage in boundary and block poplar plantations, respectively at a rotation of seven years. Dhiman (2009) estimated that only 1.04 mt C out of 2.5 mt C is locked in poplar based products for different durations and the remaining is released back in the form of fuel and only a marginal fraction of 0.3 mt C is added to soil through leaf litter every year. Gupta *et al.,* (2009) found that the average soil organic carbon increased from 0.36 in sole crop to 0.66 per cent in *P. deltoides* based agroforestry soils. The soil organic carbon increased with increase in tree age. The soils under agroforestry had 2.9-4.8 t ha^{-1} higher soil organic carbon than in sole crop. The poplar trees could sequester higher soil organic carbon in 0-30 cm profile during the first year of their plantation (6.07 t ha^{-1} yr^{-1}) than the subsequent years (1.95-2.63 t ha^{-1} yr^{-1}) (Gupta *et al.,* 2006). However, it is important to mention that less than 50% of the total timber is locked for longer period and remaining biomass is used as fuel to meet the energy requirements and replaces fossil fuel. Therefore, an estimate of carbon sequestration for wood used for energy as well was calculated (Table 4) and it was found that poplar block and boundary plantation sequester substantial amount of carbon in long lived biomass and replace fossil fuel (3.38 and 1.03 t ha^{-1} yr^{-1} in poplar based system with block and boundary plantations, respectively).

CONCLUSION

Land use management and soil depth influence contents of total, particulate and mineral associated soil organic carbon fractions. Crop cultivation led to a decrease in total soil organic carbon, but the value was higher than the contents obtained in the fallow land. There are agricultural management practices that show promise for restoring soils and sequestering a very significant portion of atmospheric carbon. Therefore, it is important to take into account the importance of agroforestry to sequester the C and improving the soil properties.

Table 1. Physical and chemical properties of the surface (0-15 cm) soils under different land-use in Indian Punjab. Numbers in parenthesis indicate standard error.

Soil properties	**Land use**							
	Rice-wheat		**Maize-wheat**		**Cotton-wheat**		**Agroforestry**	
	Range[†]	**Mean**[¶]	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**
pH	7.26-8.24	7.76^{b} (0.05)	7.24-8.23	7.73^{b} (0.06)	7.24-8.23	7.72^{b} (0.06)	7.13-7.63	7.29^{a} (0.03)
E.C. (dS m^{-1})	0.23-0.43	0.31^{ab} (0.01)	0.25-0.48	0.34^{b} (0.01)	0.21-0.45	0.28^{a} (0.01)	0.25-0.45	0.33^{b} (0.01)
Sand (%)	47.8-71.5	60.0^{a} (1.4)	53.4-72.0	63.0^{ab} (1.1)	56.1-74.5	63.3^{ab} (1.2)	53.4-73.3	64.6^{b} (1.2)
Silt (%)	18.4-30.5	25.1^{b} (0.72)	17.1-27.8	23.1^{ab} (0.62)	16.4-27.9	23.3^{ab} (0.70)	17.7-27.5	21.8^{a} (0.63)
Clay (%)	8.2-21.7	14.1^{a} (0.79)	9.5-18.9	13.1^{a} (0.58)	8.1-20.1	13.5^{a} (0.64)	8.2-19.9	13.6^{a} (0.69)

$CaCO_3$(g kg^{-1})	0-12.3	1.41[a] (0.08)	0.0-18.3	2.53[a] (0.12)	0.0-17.3	1.22[a] (0.08)	0.0-19.5	1.73[a] (0.10)
SOC (g C kg^{-1})	2.83-6.35	4.74[b] (0.02) [Δ]	2.15-5.45	3.98[a] (0.02)	2.38-5.68	3.94[a] (0.02)	3.05-7.18	5.78[c] (0.02)
								Source: Prakash (2016)

[†]Range represents the minimum-maximum values in the data set

[¶]Mean values for a soil property in a row followed by different letter are significantly (*$p<0.05$*) different by Duncan's multiple range test (DMRT).

[Δ] Value represents standard error from mean

Table 2: Total C, inorganic C (SIC), total organic C (TOC), soil organic C (SOC) and total N concentration in soils of agroforestry, rice-wheat, and maize-wheat systems in the Rupnagar district of Indian Punjab (Benbi *et al.*, 2012)

Soil carbon pool	**Land-use**			
	Rice-wheat	Maize-wheat	Agroforestry	LSD (0.05)
Total C (g kg^{-1} soil)	6.90[a] (1.32)	8.95 [a] (0.79)	8.83 [a] (0.83)	NS
Total organic C (g kg^{-1} soil)	6.50 [a] (1.41)	8.06 [a] (0.70)	8.35 [a] (0.80)	NS
Soil organic C (g kg^{-1} soil)	3.88 [a] (0.89)	6.52 [a] (0.51)	6.56 [a] (0.53)	1.89

Mean values in a column followed by same letter are not significantly different at P\0.05. NS = non-significant
Values in parenthesis indicate standard error of mean

Table 3. Soil organic carbon (SOC), hot water soluble carbon (HWSC) and potassium permanganate oxidizable carbon ($KMnO_4$-C) in the surface (0-15 cm) soils under different land-uses (Praksh, 2016)

Soil carbon pool	Land-use							
	Rice-wheat		Maize-wheat		Cotton-wheat		Agroforestry	
	Range[¶]	Mean[†]	Range	Mean	Range	Mean	Range	Mean
SOC (g C kg^{-1})	2.83-6.35	4.74[b] (0.02) [Δ]	2.15-5.45	3.98[a] (0.02)	2.38-5.68	3.94[a] (0.02)	3.05-7.18	5.78[c] (0.02)
HWSC (mg C kg^{-1})	168-327	246[b] (10.4)	117-267	197[a] (9.1)	111-264	193[a] (9.5)	159-324	267[b] (10.9)
$KMnO_4$-C (mg C kg^{-1})	557-1048	819[b] (0.03)	206-974	665[a] (0.04)	408-959	681[a] (0.04)	566-1213	922[c] (0.04)

[¶]Range represents the minimum-maximum values in the data set

[†]Mean values for a soil property followed by different letters differ significantly (*$p<0.05$*) by Duncan's multiple range test (DMRT)

[Δ] Value represents standard error from mean

Table 4. Carbon sequestration in poplar based agroforestry models

Treatments*		Total biomass** (t ha^{-1})	Long lived timber C Storage (ton C ha^{-1})	Heat from biomass combustion ($x10^9$)	Carbon storage from coal substitute (ton C ha^{-1})	Total C Sequestration*** (t C ha^{-1})	Total C sequestration (t C ha^{-1} yr^{-1})
Block plantation	Trees + wheat straw	77.14	9.23	1022.04	17.17	28.96	4.82
	Trees without wheat straw	48.49	9.23	506.34	8.50	20.27	3.38
Boundary plantation	Trees +wheat + Rice straw	86.47	3.18	1444.32	24.26	27.86	4.64
	Trees + rice straw	57.49	3.18	922.68	15.50	19.10	3.18
	Trees without Rice and wheat straw	14.83	3.18	154.80	2.60	6.20	1.03

* Calculations made with the presumption that wheat straw is used as fodder, whereas rice straw is used as fuel

** Tree and crop (grain + straw) biomass

*** Includes soil as well as long lived carbon storage in timber

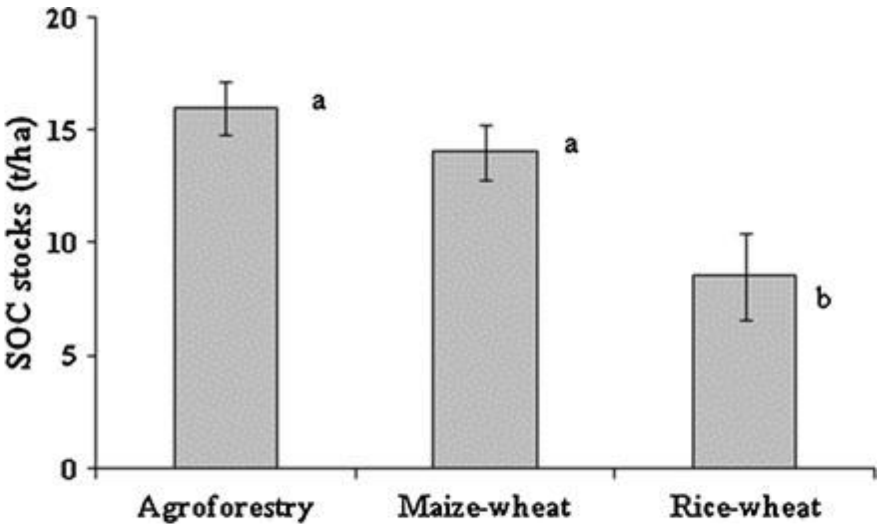

Fig 1. Soil organic carbon (SOC) stocks in agroforestry, maize-wheat, and rice-wheat systems in the Rupnagar district of Indian Punjab. Bars labeled with the same letter are not significantly different at P\0.05 (LSD 4.2). Line bars indicate standard error of mean.

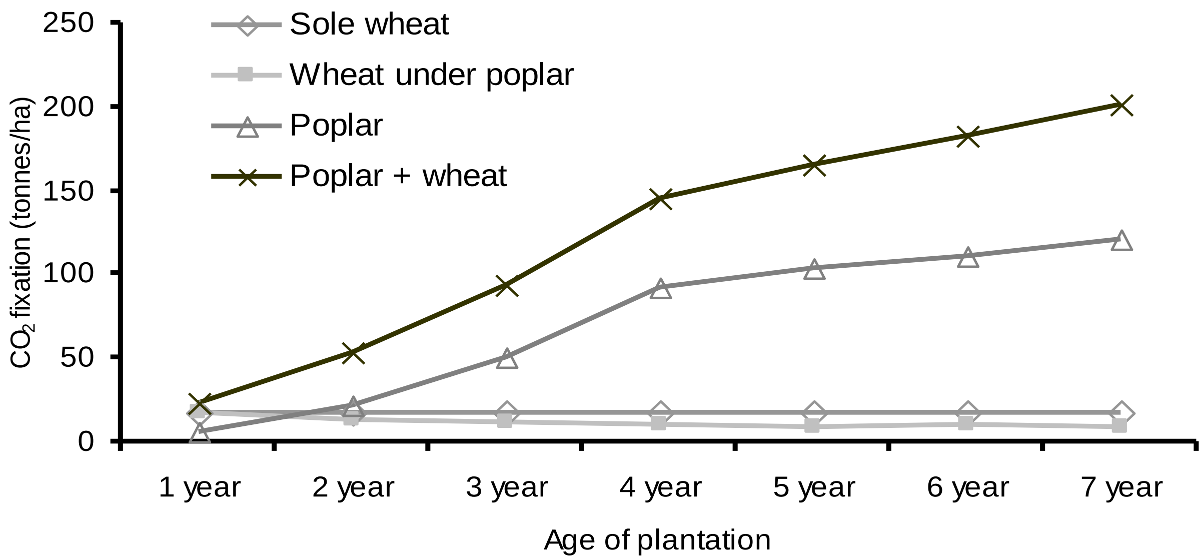

Fig 2. Total CO_2 assimilation (t ha^{-1}) by poplar-wheat (above- and below-ground biomass) in agroforestry system and sole wheat crop (Chauhan and Chauhan, 2009).

REFERENCES

Alfaia, S. S., Gilberto A. Ribeiro, Antonio D. Nobre, Regina C. Luizão, Flávio J. Luizão (2004). Evaluation of soil fertility in smallholder agroforestry systems and pastures in western Amazonia. Agriculture, Ecosystems and Environment 102: 409–414.

Alfaia, S.S., Magalhães, F.M.M., Yuyama, K. and Muraoka, T. (1988). Efeito da aplicação de calagem e micronutrientes na cultura da soja em Latossolo Amarelo. Acta Amazonica 18: 13–25.

Angus, F., Garrity, D.P., Cassel, D.K. and Mercado, A. (1998) Grain crop response to contour hedgerow systems on sloping Oxisols. Agroforestry Systems 42(2): 107-120.

Ayoub, A.T. (1999). Fertilizers and the environment. Nutr Cycl Agroecosyst 55: 117–121.

Belsky, A. J., Amundson, R. G., Duxbury, J. M., Riha, S. J., Ali, A. R. and Mwonga, S. M. (1989) The effects of trees on their physical, chemical, and biological environments in a semi-arid savanna in Kenya," *Journal of Applied Ecology* 26(3): 1005–1024.

Benbi, D.K., Brar, K., Toor, A.S., Singh, P. and Singh, H. (2012). Soil carbon pools under poplar-based agroforestry, rice-wheat, and maize-wheat cropping systems in semi-arid India. Nutr Cycl Agroecosyst 92: 107–118.

Benbi, D.K., Biswas, C.R., Bawa, S.S. and Kumar, K. (1998). Influence of farmyard manure, inorganic fertilizers and weed control practices on some soil physical properties in a long-term experiment. Soil Soil Use Manage 14: 52–54.

Benbi, D.K. and Brar, J.S. (2009). A 25-year record of carbon sequestration and soil properties in intensive-agriculture. Agron Sustain Develop 29: 257–265.

Benbi, D.K. and Brar, J. S. (2009). A 25-year record of carbon sequestration and soil properties in intensive agriculture. Agron Sustain Dev 29: 257-265.

Bene, C.D., Tavarini, S., Mazzoncini, M. and Angelini, L.G. (2011). Changes in soil chemical parameters and organic matter balance after 13 years of ramie [Boehmeria nivea (L.) Gaud.] cultivation in the Mediterranean region. *Europ J Agron* 35: 154-63.

Bertin, C., Yang, X. and Weston, L. A. (2003). The role of root exudates and allelochemicals in the rhizosphere," Plant and Soil 256(1): 67–83.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D. and Gupta, R.K. (2002). Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Sci Soc Am J 66: 162–170

Bhandari, A.L., Ladha, J. K., Pathak, H., Padre, A.T., Dawe, D. and Gupta, R. K. (2002). Yield and soil nutrient changes in a long-term rice-wheat rotation in India. *Soil Sci. Soc. Am. J.* 66: 162-170.

Bockman, O.C., Kaarstad, O., Lie, O.H. and Richards, I. (1990). Agriculture and Fertilizers. Agricultural Group, Norsk Hydro a.s. Oslo, Norway, 245 pp.

Broder, T., Blodau, C., Biester, H., and Knorr, K. H. (2012). Peat decomposition records in three pristine ombrotrophic bogs in southern Patagonia, *Biogeosciences* 9: 1479-91.

Burke, I. C., Lauenroth, W. K., Vinton, M. A. *et al.* (1998). Plant-soil interactions in temperate grasslands," *Biogeochemistry* 42(1-2): 121–143.

Carson, B. (1992). The Land, the Farmers, and the Future: A Soil Fertility Management Strategy for Nepal. ICIMOD Occasional Paper No. 21. Nepal.

Chander, K., Goyal, S., Nandal, D.P. and Kapoor, K.K. (1998). Soil organic matter, microbial biomass and enzyme activities in a tropical agroforestry system. Biology and Fertility of Soils 27: 168–172.

Chauhan, S.K. and Chauhan, R. (2009). Exploring carbon sequestration in poplar-wheat based integrated cropping system. *Asia-Pacific Agroforestry News* 35: 9-10.

Chauhan, S.K., Beri, V. and Sharma, S.C. (2007a). Studies on carbon sequestration under different farm/agroforestry interventions. Final *report of Adhoc Research Project submitted to ICAR New Delhi*. 131p. Department of Forestry and Natural Resources, PAU Ludhiana.

Chauhan, S.K., Gupta, N., Walia, R., Yadav, S., Chauhan, R., Mangat, P.S. (2011). Biomass and carbon sequestration potential of poplar-wheat intercropping system in irrigated agroecosystem in India. J Agric Sci Technol A 1: 575–586.

Chauhan, S.K., Sharma, S.C., Chauhan, R., Gupta, N. and Ritu (2010a). Accounting poplar and wheat productivity for carbon sequestration agri-silvicultural system. *Ind. For.*136: 1174-1182.

Desjardins, T., Lavelle, P., Barros, E., Brossard, M., Chapuis-Lardy, L., Chauvel, A., Grimaldi, M., Guimarães, F., Martins, P., Mitja, D., Muller, M., Sarrazin, M., Tavares Filho, J. and Topall, O. (2000). Dégradadion des pˆaturages amazoniens. Étude et Gestion des Sols 7: 353–378.

Dhiman, R.C. (2009). Carbon footprint of planted poplar in India 2009. *ENVIS Forestry Bulletin*. 9(2): 70-81.

Dijkstra, F. A. (2003). Calcium mineralization in the forest floor and surface soil beneath different tree species in the northeastern US," *Forest Ecology and Management* 175(1–3): 185–194.

Eden, M.J., Furley, P.A., McGregor, D.F.M., Miliken, W. and Ratter, J. (1991). Effect of forest clearance and burning on soil properties in northern Roraima, Brazil. For. Ecol. Manage. 38: 283–290.

Falesi, I.C. and Veiga, J.B. (1986). O solo da Amazˆonia e as pastagens cultivadas. In: Peixoto, A.M., Moura, J.C., Varia, V.P. (Eds.), Pastagens na Amazˆonia. FEALQ, Piracicaba, SP, Brazil, pp. 1–26.

Finzi, A. C., Canham, C. D. and Van Breemen, N. (1998). Canopy tree-soil interactions within temperate forests: species effects on pH and cations," *Ecological Applications* 8(2): 447–454.

Gera, M., Mohan, G., Bist, N.S. and Gera, N. (2011). Carbon sequestration potential of Agroforestry under CDM in Punjab state of India. *Inian journal of forestry.* 34: 1-10.

Ghani, A., Dexter, M. and Perrott, K.W. (2003). Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. *Soil Biol Biochem* 35: 1231-43.

Gupta, N., Kukal, S.S. and Singh, P. (2006). Soil erodibility in relation to poplar based agroforestry system in north western India. *Int. J. Agri. and Biol.* 8: 859-861.

Gupta, N., Kukal, S.S., Bawa, S.S. and Dhaliwal, G.S. (2009). Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. *Agrof. Systems* 76(1): 27-35.

Haynes, R.J. (2000). Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. *Soil Biol Biochem* 32: 211-19.

Howlett, D. S., Mosquera-Losada, M. R., Nair, P. K. R., Nair, V. D. and Rigueiro-Rodrigues, A. (2011). Soil carbon storage in silvopastoral systems and a treeless pasture in northwestern Spain," Journal of Environmental Quality 40(3): 825–832.

Huang, Q., Li, D., Liu, K., Yu, X., Ye, H., Hu, H., Xu, X., Wang, S., Zhou, L., Duan, Y. and Zhang,

W. (2014) Effects of long-term organic amendments on soil organic carbon in apaddy field: A case study on red soil. *J Integ Agric* 13: 570-76.

Jobbagy, E. G. and Jackson, R. B. (2001). The distribution of soil nutrients with depth: global patterns and the imprint of plants," Biogeochemistry 53(1): 51–77.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *Agrof. Systems* 76: 1-15.

Koutika, L.S., Bartoli, F., Andreux, F., Cerri, C.C., Burtin, G., Choné, T., Philippy, R. (1977). Organic matter dynamics and aggregation in soil under rain forest and pasture of increasing age in the eastern Amazon Basin. Geoderma 76: 87–112.

Kumar, A., Hooda, M. S. and Bahadur, R. (1998). Impact of multipurpose trees on productivity of barley in arid ecosystem. Ann. Arid Zone 37: 153-157.

Kuzyakov, Y., Ehrensburger, H. and Stahr, K. (2001). Carbon partitioning and below-ground translocation by *Lolium perenne*. *Soil Biol Biochem* 33: 61-74.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L. *et al*. (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crop Res 81: 159–180

Lobato, E.M.S.G., Fernandes, A. R., Lobato, A. K. S., Guedes, R. S., Netto, J. R. C., Moura, A. S., Marques, D. J., Ávila, F. W. and Borgo, J. D. H. (2014). The chemical properties of a clayey oxisol from Amazonia and the attributes of its phosphorus fractions. *J Food Agric Environ* 2: 1328-35.

Manlay, R. J., Chotte, J., Masse, D., Laurent, J. and Feller, C. (2002). Carbon, nitrogen and phosphorus allocation in agro-ecosystems of a West African savanna. III. Plant and soil components under continuous cultivation. *Agri Ecosyst Envi* 88: 249-69.

McGrath, D.A., Duryea, M.L. and Cropper, W.P. (2001). Soil phosphorus availability and fine root proliferation in Amazonian agroforest 6 years following forest conversion. Agric. Ecosyst. Environ. 83: 271–284.

Montagnini, F. and Nair, P.K.R. (2004). Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agrof. Systems* 61: 281-295.

Nair, P. K. R., Nair, V. D., Mohan Kumar, B. and Showalter, J. M. (2010). Carbon sequestration in agroforestry systems," Advances in Agronomy 108: 237–307.

Nair, V.D. and Graetz, D.A. (2004). Agroforestry as an approach to minimizing nutrient loss from heavily fertilized soils: The Florida experience. Agroforestry Systems 61: 269–279.

Ocio, J.A. and Brookes, P.C. (1990). An evaluation of methods for measuring the microbial biomass in soils following recent additions of wheat straw and the characterization of the biomass that develops. Soil biology and Biochemistry 22: 685–694.

Pal, R., Melkania, U. and Dhiman, R.C. (2009). Inter-clonal variation in carbon pool of *Populus deltoides* Bartr. *Ind. For.* 135: 1209-1216.

Palm, C. A. (1995). Contribution of agroforestry trees to nutrients requirements of intercropped plants. *Agroforestry syst* 30: 105-24.

Prakash, D. (2016). Dynamics of soil phosphorous and relation to carbon under different cropping systems. PhD Thesis, Punjab Agricultural University, Ludhiana-141004, Punjab, India.

Ralhan, P.K., Rasool, A. and Singh, A. (1996). Return of nutrients through leaf litter on an age series of Poplar plantation in agri-silviculture system in certain parts of Punjab. In: IUFRO-DNAES international meet on resource inventory techniques to support agroforestry and environment activities, pp. 159–163.

Recco, R.D., Amaral, E.F., Pinto, E.M. and Melo, A.W.F. (2000). Avaliação do n´ıvel de carbono em solos tropicais submetidos a plantio de sistemas agroflorestais em diferentes idades na Amazˆonia Ocidental. In: III Congresso Brasileiro de Sistemas Agroflorestais. EMBRAPA, Manaus, Brazil, pp. 55–57.

Regmi, A.P., Ladha, J.K., Pathak, H., Pasquin, E., Bueno, C., Dawe, D., Hobbs, P.R., Joshy, D., Maskey, S.L., Pandey, S.P. (2002). Yield and soil fertility trends in 20-year rice-rice-wheat experiments in Nepal. Soil Sci Soc Am J 66: 857–867

Regmi, A. P., Ladha J. K., Pathak, H., Pasquin, E., Bueno, C., Dawe, D., Hobbs, P. R., Joshy, D., Maskey, S. L. and Pandey, S. P. (2002). Yield and soil fertility trends in 20-year rice-rice-wheat experiments in Nepal. *Soil Sci. Soc. Am. J.* 66: 857-867.

Reich, P. B., Oleksyn, J., Modrzynski, J. *et al.* (2005). "Linking litter calcium, earthworms and soil properties: a common garden test with 14 tree species," *Ecology Letters* 8(8): 811– 818.

Rizvi, R.H., Dhyani, S.K., Yadav, R.S. and Singh, Ramesh (2011). Biomass production and carbon stock of poplar agroforestry systems in Yamunanagar and Saharanpur districts of northwestern India. *Curr. Sci.* 100: 736-742.

Rizvi, R.H., Khare, D. and Handa, A.K. (2010). Construction and validation of models for timber volume of poplar (*Populus deltoides*) planted in agroforestry in Haryana. *Ind.J. Agri. Sci.* 80: 841-844.

Saha, S. K., Nair, P. K. R., Nair, V. D. and Kumar, B. M. (2010). Carbon storage in relation to soil size-fractions under tropical tree based land-use systems," Plant and Soil 328(1): 433–446.

Sanchez, P.A., Villachica, J.H. and Band, D.E. (1983). Soil fertility dynamics after clearing a tropical rainforest in Peru. Soil Sci. Soc. Am. J. 47: 1171–1178.

Schlesinger, W. H., Raikks, J. A., Hartley, A. E. and Cross, A. F. (1996). On the spatial pattern of soil nutrients in desert ecosystems," *Ecology* 77(2): 364–374.

Schoeneberger, M.M. (2009). Agroforestry: working trees for sequestering carbon on agricultural lands. *Agrof. Systems* 75: 27-37.

Schoreder, P. (1994). Carbon storage benefits of agroforestry system. *Agrof. Systems* 27: 89-97.

Schreier, H., Brown, S. and Shah, P.B. (1995). Identification of key resource issues: discussions and recommendations, pp. 247-252. *In* H. Scheier, P.B. Shah and S. Brown (eds.). Challenges in Mountain Resource Management in Nepal: Processes Trends and Dynamics in Middle Mountain Watersheds, Proceeding of a Workshop held in Kathmandu, Nepal, ICIMOD/IDRC/UBC, Kathmandu.

Sharma, G., Sharma, R. and Sharma, E. (2009). Impact of stand age on soil C, N and P dynamics in a 40-year chronosequence of alder-cardamom agroforestry stands of the Sikkim Himalaya. *Pedobiologia* 52: 401-14.

Sharma, U. and Sharma, V. (2011). Soil as a sink for carbon sequestration: how agroforestry can help? *Ind. J. Agrof.* 13: 65-77.

Shi, Y., Lalande, R., Hamel, C. and Ziadi, N. (2015). Winter effect on soil microorganisms under different tillage and phosphorus management practices in eastern Canada. *Can J Microbiol* 61: 1-12.

Singh, P. and Lodhiyal, L.S. (2009). Bioamss and carbon allocation in 8 year old poplar (*Populus deltoides* Marsh) plantation in Tarai agroforestry systems of central Himalaya, India. *New York Sci. J.* 2: 49-53.

Stewart, J. W. B. and Tiessen, H. (1987). Dynamics of soil organic phosphorus.*Biochemistry* 41: 41-60.

Tandon, V.N., Pandey, M.C., Rawat, H.S., Sharma, D.C. (1991). Organic productivity and mineral cycling in plantations of .*Populus deltoides* in tarai region of Uttar Pradesh. Indian Forester 117: 596–608.

Tchienkoua, M. and Zech, W. (2004). Organic carbon and plant nutrient dynamics under three land uses in the highlands of West Cameroon. *Agric Ecosyst Environ* 104: 673-79.

Turner, N. C. and Ward, P. R. (2002). The role of agroforestry and perennial pasture in mitigating water-logging and secondary salinity: Summary. Agric. Water Manage 53: 271-275.

Ulery, A. L., Graham, R. C., Chadwick, O. A. and Wood, H. B. (1995). Decade-scale changes of soil carbon, nitrogen and exchangeable cations under chaparral and pine. *Geoderma* 65(1-2): 121–134.

Vaidya, A., Turton, C., Joshi, K.D. and Tuladhar, J.K. (1995). A system analysis of soil fertility issues in the hills of Nepal: implications for future research, pp. 63-80. *In* H. Scheier, P.B. Shah and S. Brown (eds.). Challenges in Mountain Resource Management in Nepal: Processes Trends and Dynamics in Middle Mountain Watersheds, Proceeding of a Workshop Held in Kathmandu Nepal, ICIMOD/IDRC/UBC.

Wang, H., Huang, Y., Huang, H., Wang, K.M. and Zhou, S.Y. (2005). Soil properties under young Chinese fir-based agroforestry system in mid-subtropical China. Agroforestry Systems 64: 131–141.

Wardle, D. A. (1992). A comparative assessment of factors which influence microbial biomass carbon and nitrogen levels in soil. *Bioll Review* 41: 321-58.

Zomer, R. J., Trabucco, A.. Coe, R. and Place, F. (2009). *Trees on Farm: Analysis of Global Extent and Geographical Patterns of Agroforestry*, ICRAF Working Paper no. 89, World Agroforestry Centre, Nairobi, Kenya.