Effect of Agroforestry Systems on Soil Quality –Monitoring and Assessment

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Introduction

Arable farming is the dominant form of agriculture in India. It is only recently that alternate land use systems comprising of pastures & perennials are receiving attention vigorously especially in rainfed areas. Soils of semiarid tropical regions of the world are nearly exhausted of soil organic matter and fertility. This is primarily attributed to fast oxidation of organic matter, washing away of nutrient rich top soil with runoff water, poor recycling back of crop residues, continuous and intensive cultivation of crops without replenishment of nutrients through chemical fertilizers. Climatic aberrations and frequent droughts result in failure of annual crops. In rainfed lands, where the possibility of raising more than one crop per year is remote, land use systems with more than one component have a distinct advantage. This led to the adoption of diversified land use systems such as agro-forestry, agri-horticulture, agri–silviculture, silvi-pastoral, pastoral, etc., apart from agriculture, by the farming community, since these systems provide stability and sustainability to the farming systems in the semi-arid tropics, specially when there are frequent droughts. These diversified land use systems not only help the farming community in providing assured income in the events of drought, but also protect the land from degradation and enhance the soil quality. Further, the allocation of the scarce land resource based on its capability class, to alternate land uses not only checks its degradation but also increases its productivity in terms of food, fuel, fodder, and fruit (Das et al., 1993).

Role of agroforestry systems in influencing overall soil quality

The land use systems comprising of tree, crops and pastures play an important role in improving soil fertility and its quality by several ways. According to Young (1991), while studying the influence of agroforestry systems, one must look for whether agroforestry systems control soil erosion, maintain soil organic matter, maintain soil physical properties, augment nitrogen fixation, augment soil nutrient inputs, promote efficient nutrient cycling, reduce soil toxicities, promote desirable soil faunal activity, augment soil water availability to crops, and the role of root systems in agroforestry. Nair (1984) reported that agro-forestry, agri-horticultural and agri-pastoral systems have the potential to reduce erosion and runoff, and to maintain soil organic matter, improve soil physical properties and augment nitrogen fixation and promote efficient nutrient cycling. Many other workers have emphasized the importance of alley cropping (Kang et al., 1981 & 1984; Kang and Wilson, 1987; Kessler and Breman 1991), ley farming (Jaradat, 1990) and agri-horticultural and agro- forestry systems (Mac Dicken, 1990: Das et al., 1993). Further, some research studies have revealed that management practices such as use of Fly-Ash in trees has helped in improving nutrients status in soil and enhanced the growth of the trees (Ramesh et al 2007, Ramesh et al 2008).

Out of the several benefits accrued from agroforestry systems in terms of soil quality, nutrient cycling is the most predominant. In a soil-plant system, plant nutrients are in a state of continuous, dynamic transfer. Plants take up nutrients from the soil and use them for metabolic activities. In-turn, these nutrients are returned back to the soil either naturally as litter fall in unmanaged systems, deliberately as pruning in some agro-forestry systems or through root senescence in both managed and unmanaged systems. These plant parts are decomposed as a result of microbial activities and release the nutrients held in them into the soil. The nutrient then becomes available for plant uptake once again (Nair et al., 1999). The nutrient cycling in general has been defined as continuous transfer of nutrients that are already present within a soil-plant system such as farmer's field (Nair, 1993; Nair et al., 1995; Sanchez and Palm, 1996; Buresh and Tian, 1997). However, in a broader sense, nutrient cycling involves the continuous transfer of nutrients within and between different components of an ecosystem and includes processes such as weathering of minerals, activities of soil biota and other transformation occurring in the biosphere, lithosphere and hydrosphere (Jordan, 1985). Natural forest ecosystems of the tropics represent self-sustaining and efficient nutrient cycling systems. These are "closed" nutrient cycling systems with relatively little loss or gain of the actively cycling nutrients, and with high rates of nutrients turnover within the system. In contrast, most of the agricultural systems represent 'open" or "leaky" system with comparatively high nutrient losses. Nutrient cycling in agro-forestry systems falls between these "extremes" (Nair et al., 1995). Thus, the land use systems play a tremendous role in influencing the nutrient flows, and overall soil quality.

Another important contribution of agroforestry systems is towards organic matter. Young (1991) emphasized that agroforestry systems have the potential to control both water and wind erosion, which ultimately reduces the loss of soil organic matter and nutrients. Soil organic matter has many roles in maintaining fertility. These include the beneficial effects on soil physical properties, including water-holding capacity, the slow release of nutrients, particularly significant in low input farming systems, enhancement of cation exchange capacity, significant where fertilizers are applied, and the provision of a favourable environment for soil faunal activity. It is hypothesized that, under agroforestry systems, soil organic carbon can be maintained at levels that are satisfactory for soil fertility due to the contribution of decomposed residues from the tree component. This contribution may come from above-ground litter and prunings, root residues, or indirectly as farmyard manure where prunings are fed to livestock. But the validation or rejection of this hypothesis summons a substantial research under different climatic conditions and soil types and for different agroforestry systems. Agroforestry research should also include measurements of soil physical properties as a matter of regular practice. The physical properties of soil are influenced not only by the effects of organic matter, but also the effects of roots. It is established that physical conditions of soils, independent of nutrient content, can substantially affect fertility (Lal and Greenland, 1979). These systems maintain more favourable soil physical properties than agricultural systems through maintenance of organic matter and the effects of roots. Tree roots may penetrate and possibly break up compact soil layers such as stone lines and nodular laterite and this process can improve both physical properties and nutrient intake from the B/C horizons. More research evidence on the improvement of physical properties by agroforestry systems is still needed, while the effects of litter on soil physical properties is substantial through mulching and zero tillage studies.

Another important aspect of agro-forestry systems is contribution towards nitrogen economy through atmospheric nitrogen fixation. Nitrogen, a commonly limiting nutrient in tropical soils, to which growth response is immediately obtained on previously unfertilized soils. Where fertilizers are unavailable to farmers, due to cost or other reasons, improving the nitrogen economy can make a substantial contribution to crop production. Nitrogen fixing trees can be incorporated in all types of agroforestry practices. In hedgerow intercropping, fixed nitrogen is transferred to intercrops, but the effectiveness for the soils nitrogen economy is obviously reduced if prunings are removed for fodder purpose. Nitrogen fixation by the tree components represents a clear gain to the nutrient economy in agroforestry systems, with substantial economic value. Its effectiveness is proven and research into improvement of rates of fixation, through species selection and inoculation should be continued.

Agroforestry systems, on the other hand, can lead to more efficient nutrient cycling, thereby slowing the rate of crop yield decline, or leading to a steady state in low-input systems, or making more effective use of fertilizers in high- input systems. Under low input agricultural systems, without inorganic fertilizers, crop yields normally decline, leading either to abandonment of the land, as in the various forms of shifting cultivation, or to a condition of low-level equilibrium with stable, but unsatisfactory low yields. The benefits to low-input systems would be substantial, if under certain conditions, nutrient cycling were so efficient that harvest removal would be compensated by natural inputs.

In agroforestry systems, there is a good amount of cycling of basic cations. The cycling of bases in tree litter can assist in i) ameliorating soil acidity or checking acidification and ii) reclaiming saline or alkaline soils. Trees have been successfully incorporated in the reclamation of saline and alkaline soils with associated cereal intercropping. Agroforestry systems have shown beneficial effects on soil fauna with consequent improvements in soil fertility. On the other hand, it is possible that trees, whether intimately mixed with crops or planted in rows will improve the total water supply by reducing evaporation.

The role of roots in maintaining soil fertility in agroforestry systems is at least as important as that of above ground biomass. Roots play a part in nearly most of the processes, particularly in organic matter input, soil physical conditions, nitrogen fixation, and nutrient retrieval and cycling. At the same time, competition between tree and crop roots for nutrients is a potentially adverse feature of agroforestry with respect to fertility and crop production, although no such case has yet been demonstrated (Young, 1991).

The success in soil management to maintain soil quality depends on an understanding of how soil responds to agricultural practices over time. For this reason, recent interest in evaluating the quality of our soil resources has been stimulated by increasing awareness that soil is a critically important component of the earth's biosphere, functioning not only in the production of food and fibre but also in the maintenance of local, regional and worldwide environmental quality (Doran and Parkin, 1994). On the other hand, feeding the ever-increasing human population is most challenging in developing countries because of soil degradation.

Assessment of soil quality of an agroforestry system

Before dealing with information on soil quality assessment, it is important to understand the basic concept of soil well. Soil quality as defined by Karlen et al. (1997), is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation. Soil quality can be monitored by a set of measurable attributes termed as 'indicators' (Dalal and Moloney, 2000). These indicators can be broadly classified under physical, chemical and biological indicators (Dalal and Moloney, 2000) and one can assess overall soil quality by measuring changes in these indicators (Larson and Pierce, 1991; Doran and Parkin, 1994; Sarrantonio et al., 1996; Karlen et al., 1998; Ditzler and Tugel, 2002) and transforming them into a single values known as soil quality index. One has a freedom to choose the selective set of indicators depending upon the set functional goal to be achieved. With the advancement of concept of soil quality, researchers have used differential terminologies for soil quality index viz., index of soil physical quality (Dexter, 2004), soil quality morphological index (Seybold et al., 2004), and so on based upon the set of indicators chosen for their study. Most of the research on the effects of tree based systems on soil quality remained restricted to monitoring some of the soil properties. Not many efforts have been made to assess the effects of different tree based land use systems on soil quality systematically using the soil profile data, as the task is obviously difficult.

The rate of soil quality degradation depends on land use systems, soil types, topography and climatic conditions. Under agro-forestry, agri-horticultural and pastoral systems, soil organic carbon can be maintained at levels that are satisfactory for soil fertility through the contribution of decomposed residues from the tree components. Soil organic matter is considered as storehouse of essential plant nutrients and plays an important role in maintaining soil fertility. As discussed under 'nutrient cycling' organic matter regulates nutrient release pattern by influencing cation exchange capacity. Apart from these, some of the beneficial effects of organic matter have been clearly observed on soil physical properties including water holding capacity and soil microbial activity.

The information pertaining to the influence of land use systems on soil fertility and overall soil chemical quality especially in rainfed regions is limited. The research efforts made so far in this regard are mainly focused on annual crops. Recently, Sharma et al (in press) have made some systematic efforts to compute Soil Quality Index using the data on various soil quality parameters of different layers of soil profiles influenced by different land use systems in semi-arid tropics. Some of the steps of computation of soil quality have been presented briefly in the following section

Methods of soil quality studies

Computation of Soil Quality Index (SQI)- Methodology demonstration

A case study has been chosen to demonstrate the methodology of computation of soil quality. In this case study, four existing ten-year-old land use systems were undertaken for conducting the study. These systems included i) agri-horticulture system: (guava, Psidium guajava) + sorghum, Sorghum bicolor L.)/black gram, Vigna mungo L. / horse gram, Macrotyloma uniflorum L.), ii) agro-forestry system: (Acacia auriculiformis + sorghum /black gram /horse gram.), iii) Pastoral system (Stylosanthes hamata) and iv) arable land (sorghum - black gram /horsegram). In agri-horticulture system, fruit trees were planted in a definite pattern in 4 x 4m and inter spaces (alleys) were used to grow food grains such as sorghum, black gram and horse gram. In agro-forestry system, Acacia auriculiformis was planted in 4 x 4m geometry and the interspaces were used to grow sorghum, black gram and horse gram. In pastoral system, Stylosanthes hamata, which is a predominant fodder crop of rainfed region, was grown. In arable land, black gram and horse gram were grown in rotation with sorghum. Soil samples were collected from four depths 0-0.05, 0.05-0.15, 0.15-0.30 and 0.30-0.60 m from each of the profiles opened at a distance of 2 m away from the trunk of the tree in case of agri-horticultural and agro-forestry systems, while in case of pastoral system and arable land, soil profiles were dug at a representative spot and soil samples were collected using standard procedure. In all, 12 soil profiles (4 systems x 3 profiles) were sampled. The soil samples were air dried, ground with wooden motor and pestle sieved to 2 mm sieve and stored in cloth bags for the laboratory analysis.

For estimation of organic carbon and micronutrients, soils were passed through 0.5mm sieve. However, for total nutrient analysis, soil samples passed through 0.1mm sieve were used. These samples were analyzed for various parameters such as pH, EC, organic C, Cation Exchange Capacity, exchangeable cations such as Ca, Mg and Na, total nutrients such as total N, total P, total K, total micronutrients cations viz. Cu, Zn, Fe and Mn. Besides these parameters, soils were also analyzed for NH_4-N, total Hydrolysable N pools, organic matter pools viz humic acid, fulvic acid, and humin. These data were subjected to various statistical analyses.

Since the land use systems were comprised of many components such as trees, pasture and arable crops, due weightage was given to all the soil profile layers while assessing the soil quality for which weighted means of the data were computed as illustrated below:

In order to study the effect of different land use systems on soil chemical properties, nutrient status and organic matter, data were statistically analyzed following one-way analysis of variance technique. As the soil depths follow a set pattern and do not permit randomization, data were not analyzed between the depths. Therefore, for depths, only ranges and weighted means were presented. Weighted means were calculated by assigning weights to each layer (1 for 0-0.05 m, 2.13 for 0.05-0.15 m, 3.44 for 0.15-0.30 m and 7.22 for 0.30-0.60 m) considering respective bulk density values. The weighted mean was calculated as:

$$\overline{X}_w = \frac{\sum_0^{0.60} x_i w_i}{\sum w_i}$$

Where X_w is the weighted mean. X_i represents the values for any parameter (say total N) for the i^{th} layer. w_i is the weight assigned to the i^{th} layer. As an example, the calculations for weighted mean of total N in agri-horticulture system have been illustrated below:

Depths (m)	Bulk density Mg m^{-3}	Vol of soil in each layer m^3 (area x depth)	Mass of soil in each depth (kg ha^{-1})	Weights (w_i)	Total N (mg kg^{-1}) (xi)	xiwi
0-0.05	1.43	500	0.715×10^6	1	670	670.0
0.05-0.15	1.52	1000	1.52×10^6	2.13	660	1403.1
0.15-0.30	1.64	1500	2.46×10^6	3.44	540	1857.9
0.30-0.60	1.72	3000	5.16×10^6	7.22	470	3391.9
				Σwi = 13.78		Σxiwi = 7322.9

Weighted mean = 7322.9/13.78 = 531.4

In this study, as only the changes in physico-chemical and chemical parameters were assessed, the soil quality index thus developed was given the term Chemical Soil Quality Index' (CSQI). To compute CSQI, the weighted mean values of the parameters were transformed using linear scoring method as suggested by Andrews et al. (2002b). To achieve this, the weighted mean values of soil parameters were arranged in an ascending order and 'more is better' approach was followed, if the increase in the magnitude of the parameter is desirable for improving soil quality. On the other hand, those parameters whose decrease is considered as desirable feature, were arranged in descending order and 'less is better' approach was followed. In case of 'more is better' parameters, each observation was divided by the highest observed value such that the highest observed value received a maximum score of 1. For ‘less is better’ parameters, the lowest observed value (in the numerator) was divided by each observation (in the denominator) such that the lowest observed value received a maximum score of 1. In this case study, ‘more is better’ approach was followed for all the parameters except for EC and exchangeable Na, where ‘less is better’ approach was followed. Once transformed, each of these values were multiplied with the respective score assigned to each parameter as listed in Table 1. In order to assign the scores, the parameters were ranked from 1 to 10 depending on their importance using different ten selection criteria and responsiveness towards soil aggradation or degradation as described by Dalal and Moloney (2000) and followed by Sharma et al. (2005), Jaladhi Choudhary et al. (2005). The product so obtained were summed up and divided by the sum total of the scores. Thus, the single value obtained for each land use system was referred to as Chemical Soil Quality Index. These single value indices obtained for each land use system were used to compare the effect on soil quality.

$$CSQI = \Sigma \frac{\text{Linear score x Score value of the respective parameter}}{\text{Sum total of the scores}}$$

Table 1: Scoring chart of indicators of chemical soil quality

Sno.	Selection criteria	pH	Electrical conductivity (EC)	Adsorption capacity	Organic matter	Available nutrients	Total nutrients
1	Responsiveness	7	5	4	7	8	6
2	Ease of capture	8	6	4	7	6	4
3	Interpretation	8	9	5	8	8	6
4	Measurement error	7	6	5	8	7	5
5	Stable to measure	9	9	5	10	7	5
6	Frequency	8	8	9	8	6	3
7	Cost	8	7	3	6	5	4
8	Aggregation	6	8	4	9	5	4
9	Mappable	9	8	5	9	5	4
10	Acceptance	9	8	5	10	9	5
	Total Score	79	74	49	82	66	51
	Average Score*	7.9	7.4	4.9	8.2	6.6	5.1

* Average score used to multiply with deviations were: pH 7.9, EC 7.4, organic carbon 8.2, CEC 4.9, exchangeable Ca, Mg, Na, and K each 6.6, and for total nutrients viz., N, P, K, Ca, Mg, Mn, Zn, Fe each 5.1.

Effect on Chemical Soil Quality

In order to study the effect of land use systems on chemical soil quality, weighted mean data on physico-chemical properties (pH, EC, OC and CEC), exchangeable nutrients (Ca, Mg, Na and K) and total nutrients (N, P, K, Ca, Mg, Fe, Mn, Zn and Cu) were used (Table 2). From the data, it was found that CSQI varied from 0.76 in arable land to 0.92 in agro-forestry system. From the viewpoint of aggradation of soil profile in terms of chemical soil quality, the order was: agro-forestry system (CSQI: 0.92) > agri-horticulture system (CSQI: 0.86) > pastoral system (CSQI: 0.80) > arable land (CSQI: 0.76). In other words, agro-forestry system proved superior most in terms of maintaining higher chemical soil quality index compared to other land use systems. Arable land, which is continuously under agriculture, maintained the lowest soil quality index.

Table 2: Weighted means of chemical soil quality parameters used for computing chemical soil quality index (CSQI)

	Physico chemical properties				Exchangeable nutrients				Total nutrients					Total micronutrients				CSQI
	pH	EC	OC	CEC	Ca	Mg	Na	K	N	P	K	Ca	Mg	Cu	Mn	Zn	Fe	
Agrihorticultural system	5.4	0.04	8.0	12.7	5.36	3.84	0.18	0.18	531.3	673.6	4.57	13.4	4.64	16.0	136	37.2	13.6	0.86
Agroforestry system	7.5	0.11	9.6	13.7	5.86	4.71	0.18	0.23	565.0	787.3	4.60	14.0	5.22	17.4	160	40.2	13.8	0.92
Pastoral system	6.8	0.07	8.1	9.2	4.50	2.83	0.16	0.16	607.5	880.0	4.38	11.5	5.14	10.5	99	36.7	12.3	0.80
Arable land	6.4	0.04	3.7	10.8	7.44	2.46	0.21	0.15	483.7	473.5	4.64	14.4	4.51	9.7	104	35.0	11.7	0.76

Note: EC: dS m^{-1}; OC: g kg^{-1}; CEC: cmol kg^{-1}; Exchangeable nutrients (Ca, Mg, Na, K): c mol kg^{-1}; Total nutrients (N, P, K, Ca, Mg): mg kg^{-1}; Total micronutrients (Cu, Mn, Zn, Fe): mg kg^{-1} of soil

How systems influenced soil quality in this case study

In this case study, it was clearly understood that the land use systems helped in increasing the soil organic carbon content, cation exchange capacity, exchangeable cations, total nutrients as well as hydrolysable N pools of soil over the arable land. Further, it was inferred that if suitable tree species like Acacia auriculiformis and horticulture fruit trees like Psidium guajava L. and pasture or grass species like Stylosanthes hamata are properly included in the cropping systems with existing arable crops in SAT Alfisols, soil fertility could be improved by the addition of organic matter and nutrients. The mechanisms leading to the improvement of soil fertility and overall chemical soil quality by virtue of adopting these land use systems could be i) nutrient mining from subsurface layers and their efficient cycling, ii) biological nitrogen fixation by tree legumes, iii) solubilization of difficultly available plant nutrients through the root exudates and acid secretions, and iv) indirect effect of tree canopies in reducing the nutrient losses through runoff and sediments. Brinson et al. (1980) has emphasized that the major recognized avenue for addition of organic matter to the soil from the trees standing on it was through litter fall, i.e., through dead and falling leaves, twigs branches and so on. Studies on nutrient enrichment of soil due to agro-forestry and agri-horticultural systems are limited. However, there are many reports on tree components of tropical and other forests which include Malaisse et al. (1975) in Africa; Kira and Shidei (1967) and Kira (1969) in Asia; Edwards (1977) in New Guinea; Klinge and Rodrigue (1968), Medine (1968), Corn forth (1970), Klinge (1977) and Kunkel-Westphal and Kunkel (1979) in south America; Ma et al., (2007), Shanmughavel et al., (2001) and others. The observations on the tendency of accumulation of organic carbon and nutrients in surface layer of soil, corroborates the earlier findings made by Foelster et al. (1976) and Chijioke (1980) stating that the bulk of the organic matter and nutrients that are added or contributed by inclusion of tree species are mostly located in the top soil. Nutrients like potassium, calcium and magnesium on the other hand, are believed to concentrate in biomass. In the present study, the differential behavior of the land use systems in influencing the physico-chemical and chemical properties and nutrient status in profile was very much evident. The above observation is in conformity with that earlier recorded by Kellman (1979) stating that trees showed preferential enrichment of the soil below them in terms of Ca, Mg, K, Na, P and N. Szott et al. (1991) observed better enrichment of soil through nutrient cycling in agroforestry systems provided the native fertility of the soils is in desirable range.

Conclusion

Thus, the tree based agriculture play an important role, not only in improving the productivity and overall returns from the system, but also protects the soil from further degradation and improve the quality of the soil across the profile layers. Though in the present case study, focus was only on chemical soil quality, if possible, while assessing and monitoring soil quality as influenced by agroforestry systems, one should focus on nutrient input-output system, nutrient cycling, organic matter build up, improvement in soil physical and biological conditions (faunal activity, etc), erosion control, nitrogen fixation, reduction in soil toxicities through bioremediation, soil water availability to crops, contribution of root systems towards organic matter build up and improvement in soil physical conditions, etc.

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