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AGROFORESTRY: A LAND USE SYSTEM FOR IMPROVING SOIL HEALTH#

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Abstract

Agroforestry's potential to improve soil quality has been widely recognized as a major benefit since its inception as a scientifically recognized discipline and practice (Young 1989; Nair 2011). Agroforestry practices have been promoted for decades both in the tropics and temperate regions of the world for their perceived benefits of not only improving soil quality, but also providing other ecosystem services (Jose, 2009). Many of the environmental benefits and ecosystem services expected from agroforestry would not be materialized unless these practices improved the capacity of soils to be productive and healthy over the long term.

#General Article

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Introduction

Soil health has received renewed interest in recent years as land managers have become aware of the importance of the resilience of the soil for future sustainability and for long-term human survival. Soil health is critical for plant and animal production, ecosystem services delivery and human health/well-being. Long-term sustainable soil use is vital for human health as these systems can suppress disease-causing soil organisms and influence the quantity and quality of the food we consume, the air we breathe and the water we use (Wall *et al.,* 2015). Healthy soil is arguably one of the most critical resources for the health of natural and agro ecosystems, so that they can sustain food production as well as provision of ecosystem services. Although the term 'soil health' has been used synonymously with soil quality, The formal definition of soil quality from the Soil Science Society of America is 'the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health' (Soil Science Society of America, 2008). The USDA-NRCS defines soil quality or soil health as '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. In short, the capacity of the soil to function' (USDA-NRCS, 2017). While soil quality is used in the context of both natural and managed ecosystems, soil health is primarily used in the context of managed ecosystems, primarily agroecosystems (Lal and Stewart, 2011).

Agroforestry can play a significant role in improving soil health for future sustainable production and ecosystem services (Gold and Hanover, 1987). Agroforestry's role in improving soil properties on the landscape for agroecosystems can influence soil health. Sustaining future plant and animal production is critical for the future of humans due to anticipated population growth (Godfray *et al.*, 2010). Agroforestry will play a vital role in sustaining this future by improving soil health.

Soil and nutrient loss is considered a major challenge for maintaining agricultural productivity (Yost *et al.*, 2016; Conway *et al.*, 2017). Some land managers view that restoring native perennial plants to the landscape will restore the soil to a healthy state; however, significant soil erosion thus the loss of valuable topsoil prevent the soil from returning to its native condition (Chandrasoma *et al.*, 2016). This issue must be considered in evaluating soil health. Increased demand for food, fibre and fuel will necessitate maintaining and improving productivity and is a significant challenge for agriculture (Godfray *et al.*, 2010; McLaughlin and Kinzelbach, 2015). Future sustainable production requires conservation of natural resources in order to prevent the loss of productive soil. Agroforestry buffers have been shown to be a significant conservation tool (Akdemir *et al.*, 2016). Conservation buffers, including agroforestry buffers, are considered a good strategy to reduce water runoff and associated soil erosion (Evans and Sadler, 2008).

A land management system which utilizes trees and/or shrubs as well as traditional row crop and pasture crops simultaneously in the landscape for economic and environmental benefits is agroforestry (Nair, 1993; Gold and Hanover, 1987). Conservation buffers, which include agroforestry buffers, have been shown to improve soil health through the enhancement of levels of organic matter as well as improved soil microbial activity (Paudel *et al.*, 2012).

Buffer conservation strips are narrow strips of permanent vegetation widely prescribed to increase water infiltration and reduce surface runoff (Schmitt *et al.*, 1999). These conservation buffer systems include agroforestry buffers as well as grass buffers, which have perennial plants to decrease soil erosion from land under row crop production (Seobi et al., 2005). The influence of perennial root systems from shallower grass roots and deeper tree roots provide soil quality benefits from these buffer systems.
The purpose of this chapter is to review how agroforestry practices improve soil health. Several studies are reviewed in this presentation to illustrate how soil health can be improved using agroforestry.

Process of Soil Improvement

In agroforestry system nutrient addition takes place through leaf litter, pruning of woody compounds and atmospheric fixation. Some nutrients otherwise considered unavailable to crop because they are below the rooting zone of the annual crop, might be brought into the system from deeper layers in the soil with the help of tree roots. Trees able to return nutrients through dead organic matter (leaf, branch, twig, fruits and flower) and thus helps in enrichment of top soil layer, available for the agriculture crops. Thus most important beneficial effect of the trees on the soil can include improvement of soil structure availability of nutrients (Nair, 1993).

The objective, designing agroforestry system is to modify cycling in such a way as to make more efficient use of the nutrients whether these originate from natural removal process or from fertilizer. Trees in agroforestry system promote more closed nutrient cycling than pure agriculture systems. The process of soil improvement under agroforestry systems is recognized through:

- Increasing inputs viz., organic matter, biological nitrogen fixation and atmospheric fixation.
- Reducing losses of nutrient and organic matter.
- Improving soil physical properties and water holding capacity by organic additions.
- Recycling of nutrients.

Biological Nitrogen Fixing

Agroforestry trees, particularly leguminous trees, enrich soil through biological nitrogen fixation, addition of organic matter and recycling of nutrients. Some trees such as *Leucaena* species, *Acacia* species and *Alnus* species has been reported to fix as much as 400-500 kg, 270 kg and 100-300 kg nitrogen per hectare per year respectively (Mishra, 2011). The fixed nitrogen may benefit symbiotically to the crops growing in its association and helps in soil fertility improvement.

The amount of nitrogen added from the legumes or pruning of trees species taken up by the first crop is reported quite low and large portion is left in the soil organic matter indicating a long term nitrogen benefit than immediate. Different tree components viz., leaf, twigs, fruit and wood have different decomposition rates which helps to distribute the release of nutrient over time. Some important nitrogen fixing plant species are given in Table 1. Biological nitrogen fixation takes place through symbiotic and non-symbiotic means. Symbiotic fixation occurs through the association of plant roots with nitrogen-fixing microorganisms. Many legumes form an association with the bacteria Rhizobium while the symbionts of a few non-leguminous species belong to a genus of actinomycetes, Frankia. Non-symbiotic fixation is effected by free-living soil organisms, and can be a significant factor in natural ecosystems, which have relatively modest nitrogen requirements from outside systems (Nair, 1993).

Table 1. Important N_2 Fixing Plant Species

Botanical Name	Family	Nitrogen fixed (kg N/ha/yr)
Acacia mearnsii	Mimosoideae	200
Casurina equisetifolia	Casuarinaceae	60-110
Erythrina poeppigiana	Pipilionaceae	60
Gliricidia sepium	Fabaceae	13
Inga jincicuil	Mimosoideae	34-50
Leucaena leucocephala	Mimosoideae	100-500
Alnus nepalensis	Betulaceae	-
Vicia faba	Fabaceae	68-88

Nutrient Pumping

Tree root systems are involved in some favorable effects on soils such as carbon enrichment in soil through root turnover, the interception of leached nutrients, or the physical improvement of compact soil layers. Trees have deep and spreading roots and hence are capable of taking up nutrients and water from deeper soil layers usually where herbaceous crop roots cannot reach. This process of taking up nutrients from deeper soil profile and eventually depositing on the surface layers through litter-fall and other mechanisms is referred to as 'nutrient pumping' by trees. This process is mainly depends on characteristics of tree species and other soil, climatic and topographic factors. Trees of low moisture content soils have deep root systems and helps in nutrient and water pumping as compared to high moisture soils (Makumba *et al.*, 2009; Schroth and Sinclair, 2003).

Role of Agro Forestry in Maintaining Soil Fertility

Soil fertility is the capacity of soil to support the growth of plants, on a sustained basis, under given conditions of climate and other relevant properties of land. The inclusion of a sustained basis in this definition refers to the capacity for continuing support for plants. Some initially productive soils have unprotected stores of nutrients and rapidly lose their fertility if transferred from natural vegetation to managed ecosystems. Others, notably nitosols on basic rocks, possess natural recuperative powers, enabling them to restore nutrients from rock weathering.

Soil fertility depletion is the fundamental cause of food insecurity and low income of farmers in Africa. The loss of nutrients due to continuous cropping gradually renders the soil less fertile, resulting in poor yields. The magnitude of nutrient losses from agricultural soils is huge with annual average loss of 22 kg N, 2.5 kg P, and 15 kg K for the whole of Africa region (Stoorvogel and Smaling, 1990).

The role of agro forestry in enhancing and maintaining long-term soil productivity and sustainability has been well documented. The incorporation of trees and crops that are able to biologically fix nitrogen is fairly common in tropical agro forestry systems. Non N-fixing trees can also enhance soil physical, chemical and biological properties by adding significant amount of above and belowground organic matter and releasing and recycling nutrients in agroforestry systems. A large body of literature, comprised of both original research and synthesis articles, has described the effects of agro forestry on soils in the tropics (e.g. Nair and Latt, 1997; Young, 1997; Buck *et al.,* 1998; Schroth and Sinclair, 2003).

Effects of Trees on Soils

According to Nair (1984), the association between trees and soil fertility is indicated by the high status of soils under natural forest, they relatively closed nutrient cycles, the soil-restoring power of forest fallow in shifting cultivation, and the success of reclamation forestry. More detailed evidence is provided by comparisons of soil properties beneath and outside tree canopies. Trees maintain or improve soils by processes which:

- Augment additions of organic matter and nutrients to the soil.
- Reduce losses from the soil, leading to more closed cycling of organic matter and nutrients.
- Improve soil physical conditions.
- Improve soil chemical conditions.
- Affect soil biological processes and conditions.

Parkland is random scattering of trees in fields with crops grown under storey. Management of trees in this system requires pruning of branches and the tops to reduce shading. The trees provide valuable products such as fuelwood, charcoal, construction materials and fodder for livestock. The service functions of trees include improving soil fertility, conserving soil moisture and improving micro-climate resulting in increased crop yields.

Processes by which Trees Maintain or Improve Soil Fertility

(A) Processes, which augment additions to the soil

- Maintenance or increase of soil organic matter through carbon fixation in photosynthesis and its transfer *via.* litter and root decay.
- Nitrogen fixation by some leguminous and a few non-leguminous trees.
- Nutrient uptake: the taking up of nutrients released by rock weathering in deeper layers of the soil.
- Atmospheric input: the provision by trees of favourable conditions for input of nutrients by rainfall and dust, including via through fall and stem flow.
- Exudation of growth-promoting substances by the rhizosphere.

(B) Processes that reduce losses from the soil

- Protection from erosion and thereby from loss of organic matter and nutrients.
- Nutrient retrieval: trapping and recycling nutrients which would otherwise be lost by leaching including through the action of mycorrhizal systems associated with tree roots and through root exudation.
- Reduction of the rate of organic matter decomposition by shading.

(C) Processes that affect soil physical conditions

- Maintenance or improvement of soil physical properties (structure, porosity, moisture retention capacity and permeability) through a combination of maintenance of organic matter and effects of roots.
- Breaking up of compact or indurate layers by roots.
- Modification of extremes of soil temperature through a combination of shading by canopy and litter cover.

(D) Processes which affect soil chemical conditions

- Reduction of acidity, through addition of bases in tree litter.
- Reduction of salinity or sodicity.

(E) Soil biological processes and effects

- Production of a range of different qualities of plant litter through supply of a mixture of woody and herbaceous material, including root residues.
- Timing of nutrient release: the potential to control litter decay through selection of tree species and management of pruning and thereby to synchronize nutrient release from litter decay with requirements of plants for nutrient uptake.
- Effects upon soil fauna.
- Transfer of assimilate between root systems.

Agro Forestry Practices for Erosion Control

Many countries, however, have begun to adopt agroforestry practices in erosion control, on a trial, demonstration or extension basis. In some cases these attempts are not based on controlled experimental data, whilst in others there may be unpublished local station records. In many small-scale demonstrations, there is no monitoring of erosion rates. However, observations on the apparent success of these developments, even if only qualitative, give an indication of the range of practices available.

There is a distinction between supplementary and direct use of trees and shrubs in erosion control. In *supplementary use,* the trees and shrubs are not the primary means of checking runoff and erosion, but fulfil the functions of stabilizing conservation structures and making productive use of the land with these occupy. This applies mainly to the practice here called 'trees on erosion-control structures'. In *direct use,* the trees, shrubs or hedgerows are in themselves a major method of reducing erosion. This applies particularly to the practices of plantation crop combinations, multi-story tree gardens, hedgerow intercropping, windbreaks and shelterbelts, and reclamation forestry with multiple use (Aina, *et al.*, 1979).

Effect Of Agroforestry on Soil Properties

The major effect of agroforestry on soil health can be categorized into (Fig-1) the following properties

a) Soil physical properties
b) Soil chemical properties
c) Soil biological properties

(a) Soil Physical Properties

For the restoration of soil structure from any destructive factors, water stability of soil aggregates is very important (Franzluebbers, 2002). Improvement of soil structure depends on the amount of organic matter present to the soil which in turn increases the microbial properties of the soil. Improvement of soil organic matter also depends on the biomass returns from the tree species and the crop which are growing in the field. So, choosing the right species of trees following with the crop to be grown with is very important (Franzel *et al.*, 1996). After improvement of the Soil organic matter only, the microbial and mega faunal (earthworm) of the soil will increase. Certain symbiotic association of higher plants with microbes present in the soil will improve nutrient efficiency which ultimately improves the structural stability of the soil (Lambers *et al.*, 2009). With the increase of earthworm population in the soil the decomposition rate of the organic matter will increase and the lining of mucigel or any organic material in the soil is very much important for the structural stability (Oades, 1993). It has been reported that the mean weight diameter (MWD) of the soil under agroforestry systems increases (Hosur and Dasog, 1995). Long term agroforestry plantation system has 2.4 times higher MWD than the soil of agroforestry of only 1 year. With increase in the year of the plantation the soil structure increases. As comparison with the agricultural soil, the MWD of agroforestry soil is higher than agriculture (Gupta *et al.*, 2009). Due to certain mechanical manipulation of soil in agriculture and its intensive cultivation makes the soil degrade. The impact of rain drops during the fallow period of the soil makes low structure stability. The improvement of aggregate stability in agroforestry systems is more in loamy sand than the sandy clay soil. The root penetration in agroforestry reaches up to deeper layer which is the reason for higher MWD of soil in the subsurface soil than the surface soil agroforestry systems. Decomposition of older root biomass in the subsurface soil is also can be the reason (Sanchez, 1987). A strong positive correlation lies between the litter falls in the soil with the MWD of the soil (Gupta *et al.*, 2009). Surface soil aggregate is more than the subsurface. The biomass return from the tree species and crop is more in the surface soil than the subsurface which makes the surface soil more stable (Paul, 2001). Bigger size aggregates are more confined to the surface soil due to more leaf litter in agroforestry than agriculture cropping systems (Yadav and Banerjee, 1968).

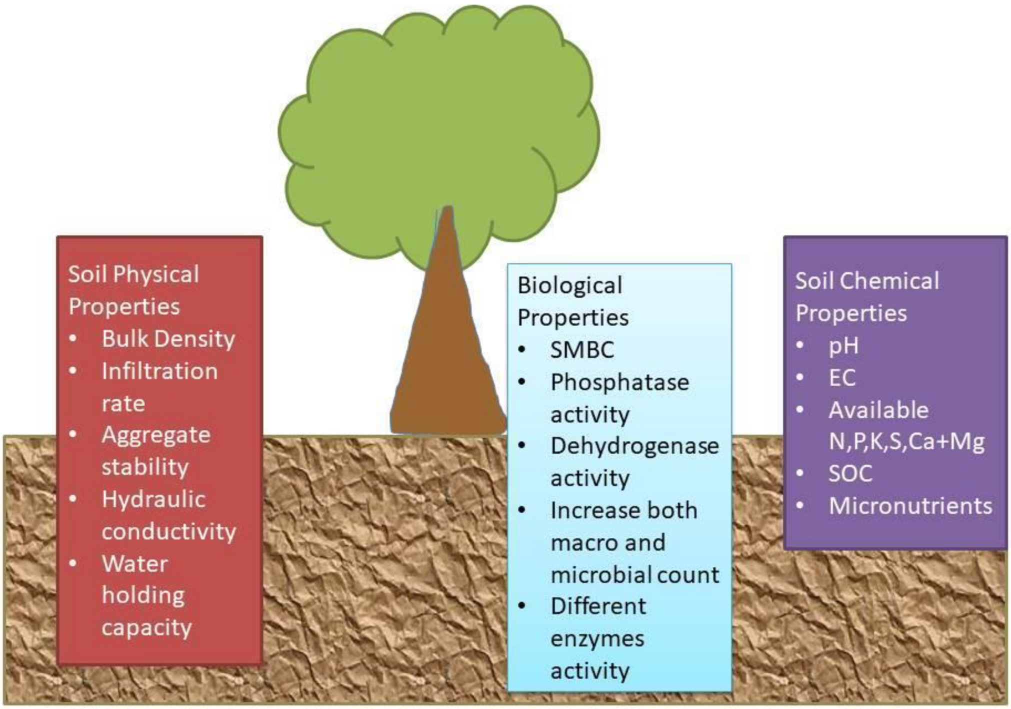

Fig.1. Effect of Agroforestry on Soil Health Attributes

It is well documented that with increase in the percent slope, the erosion rate of the soil will increase. Especially in hilly region the main problem face is the soil erosion, landslide, mudslide etc. which directly or indirectly affect the socio economic development of the region as well the health of the population. With the introduction of the agroforestry system it is known that the roots of the tree species has the ability to binds the soils reducing the flow of surface soil from top to the bottom of the undulating topography. The erosion rate of the soil depends directly on the physical condition of the soil. Soils with higher amount of organic matter will have good soil physical properties. Agroforestry with high biomass return both in surface and sub-surface will improve the structural stability of the soil. Increased organic matter makes the soil low in bulk density with concomitant increase of pores (both micro and macro pores) in the soil. With high pores in the soil the infiltration capacity and permeability of the soil increases making low surface erosion and landslide.

(b) Soil Chemical Properties

Out of the chemical soil health attributes, soil organic carbon (SOC) is known to be the most important soil properties (Krull *et al.*, 2004). With the introduction of agroforestry, biomass returns of both above and below ground to the soil increases in the form of leaf litter and root litter which in turn increases SOC. As compare to sole crop in agriculture the agroforestry tree species will provide huge amount of litter to the soil which makes the soil high in soil organic matter (Meetei *et al.*, 2020). The introduction of organic matter in the soil through biomass return from leaves and roots will be a source of food to the microorganism in the soil. Different microorganisms multiply with the presence of the carbon (C) substrate from the litter fall or root biomass (Jacoby *et al.*, 2017). So, with sufficient species microbes (bacteria, fungi and actinomycetes) the nutrient cycle of the soil increases. The nutrient cycling is generally defined as the transfer of nutrients in the soil from unavailable form to available with the process of mineralization which is accelerated by the microorganism in the soil (Yang, 2019). Again the available nutrients in the soil can be converted into non available by the process call as immobilization (Hartwig, 1996). Certain microbes also have the ability to convert the nutrients into gas which is lost to the atmosphere through the process of volatilization, denitrification in case of nitrogen. The primary source of nutrients to the soil is considered to be SOM (Lehmann and Kleber, 2015). With increase in SOM content, other available nutrients such as nitrogen, sulphur and other micronutrients increase. In agroforestry system the soil-plant system of nutrients transfer is a dynamic process (Isaac and Borden, 2019). Plant takes up nutrients from the soil and utilized for their metabolic processes. Again these nutrients are returns to the soil as a biomass return through roots or leaves. The returned plant parts are decomposed by the certain microorganisms in the soil and release the nutrients to the soil through mineralization (Nair *et al.*, 1999). In other sense nutrient cycling is the continuous transfer of nutrients within different ecosystem through the process of weathering, decomposition, mineralization activities of soil biota.

Agroforestry ecosystem represents self-sustaining and efficient nutrient cycling systems. Naturally there are close and open nutrient cycling system. In close nutrients cycling which is mainly for natural forest where the nutrients are relatively little lost or gain of most of the actively cycling nutrients. In agroforestry systems there is both close and open nutrient cycling. Thus the land use systems play a pivotal role in cycling nutrients from the soil and to the plat from the soil (Nair *et al.*, 2009). The potential of agroforestry systems to increase the soil structure have the ability to control both wind and water erosion. With the inclusion of agroforestry there is reduction in loss of organic matter and other nutrients from the soil (Jose, 2009). Soil organic matter has certain role in the soil. It maintains the physical properties of soil, including water holding capacity, with higher mean weight diameter of the soil. Physically strong soil is favorable for certain microbes. So, with microbes in the soil with physical stability the loss of nutrients through wind or water erosion is reducing. It is predicted that the agroforestry system have the ability to maintained the soil fertility in an optimum level due to the contribution from the high biomass return (roots, twigs and leaves) with multiple number of microbes in the soil. With tree species the pH of the soil increases which is mainly govern by the organic matter in the soil also there is substantial enrichment of cations like Ca, Mg and K on surface of the soil which depends on species to species.

The rate of mineralization, especially available nitrogen increases with increasing the tree canopy promoting microbial activities in organic matter breakdown and consequently released more mineralized nutrients to the soil for understory growth (Nair and Rao, 1977). Certain tree based land use systems have fertility restoration capacity making good soil health for sustainable production (Singh *et al.*, 1994).

(C) Soil Biological Properties

Soil is dynamic systems with physical, chemical and biological properties prevail. Presently, different scientist has focus on the biological properties of the soil for its important role in improving the quality of soil (Bonmati *et al.*, 1991). Different microbial attributes are there which will improve the soil health. Of these soil enzymatic activities with the respiration of soil provides the most reliable index for activity of microbes in soil (Casida, 1977). The soil microbial biomass is also plays a certain role for its source and sink of nutrients. Any change in this can predict the effect of soil ecosystems (Rice *et al.*, 1997). The activities of soil enzymes play a vital role in improving fertility of the soil (Dkhar and Mishra, 1983). Among the enzymes the role of dehydrogenase activity in soil is well known which is the enzymes of respiration pathways of microorganisms with both aerobic and anaerobic (Wolinska and Stepniewska, 2011). Both the microflora and microfauna in the soil conducted different metabolic reactions and interaction which is called as the microbial activity (Nannipieri *et al.*, 1990). For different reactions in soil, microorganisms play a very important role. Microorganisms take part in different nutrients mineralization process also the organic matter transformation which is the physical architecture of the soil structure (Patiram and Choudhury, 2010). The primary and secondary decomposers in the soil include the microbial biomass which is an important component in the cycling of nutrients in the soil and help in the breaking down of certain forms of organic matter and other nutrients mineralization. Due to the leaf litter returns to the soil of the agroforestry systems the microbes are mostly confined to the surface soil. The dense and deeper network of fine roots of tree species in agroforestry systems increases the nutrients cycling from the deeper layer to shallow. With the abundant of micorrhizal association the absorbing capacity as well as the nutrients availability in the soil increases to the understory of crops. Different land use systems have different soil biological properties. Microbial biomass carbon and dehydrogenase activity in the soil increases in the undisturbed forest soil and also in the agroforestry systems when compared with the agriculture soil and jhum cultivation in the hilly ecosystem on north east India (Meetei *et al.*, 2020). The soil microbial biomass carbon is the labile fraction of carbon with its potential to increase the fertility of soil. It takes part in the transformation of organic material with concomitant increase in the plant nutrients especially available nitrogen content in the soil. It plays N cycling in the soil making more nitrogen availability and mineralization (Robertson and Groffman, 2007). Microbial biomass C, N and P were found to be highest in soil with tree species than any other land use systems like agriculture, shifting cultivation (Arunachalam, 2002).

Beyond the soil microbial community there lays another type of community that covered a range of soil functions (Anderson, 2003). The microfauna (nematodes, rotifers, protozoa) act as secondary consumers. They feed largely on fungi and bacteria, which help to increase the speed of the turnover rate of the microbial biomass and ultimately increase in the availability of the nutrients. Collembol and the Enchytraeidae belong to mesofauna and they are omnivores, they feeds on the microflora and fauna, also on other mesofauna, which increase the organic matter turnover in the soil by fragmenting plant residues. Those organisms in the soil with size greater than 200 nm belong to macrofauna which includes earthworm, ants and termites. They have a profound effect on the soil structure. Earthworms are considered as the engineer to the farmers increasing the structural stability to the soil. Earthworms are found everywhere and are an indicator of healthy soil. Soil degradation due to different anthropogenic activities like, deforestation, land use changes, conventional tillage etc. leads to the reduction of population of different microflora as well as macrofauna which leads to deterioration of soil (Curry and Good, 1992). Population of soil flora and fauna is an indicator of the condition and the fertility status of the soil. Most of the soil organisms both flora and fauna population is high in the land use systems where tree species is deliberately combined with other horticultural crops as compared to other land use systems. The populations of these micro and macro organisms are related with the lignin content of the leaf litter from the trees species.

Conclusion

Agroforestry is an ecologically based, natural resources management system that sustains production and benefits all those who use the land by integrating trees on farms and in the agricultural land scape. In addition to provide timber, fodder, fuelwood, medicines, etc., it conserves soil and enhances soil fertility. With the adoption of agroforestry and proper selection of tree species, the physical, chemical and biological properties of the soil increases. The biomass returns, both surface and sub-surface increase the organic matter to the soil making good soil structure for proper infiltration and permeability. With high permeability the erosion rate of the soil decreases with the increment of fertility capacity of the soil. Organic matter also acts as a source of food for the beneficial microorganisms which helps to decompose and transformation of different minerals and nutrients in the soil. Mineralization process of the soil increase with the availability of certain beneficial microbes (both macro and micro) making good soil health. So, agroforestry is the most important soil health management strategy for sustainable agriculture production. With high amount of C returns to the soil through C sequestration it is also have a positive effect on environmental sustainability. Different tree species with capability of N-fixing from the atmosphere will also increase the fertility of the soil. So, as a management strategy for improving soil health, adoption of agroforestry system is very important.

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