CHAPTER– 1

1. INTRODUCTION

1.1 Introduction

Forest ecosystem has a number of beneficial functions for the environment and society. Forests provide a variety of products and services to human societies; sustain diverse flora and fauna, and influence climate and the composition of the atmosphere (Foley, *et al.*, 2005; Bonan, 2008). Currently, forests cover about 4 billion hectare area with an average net annual loss of 5.2 million hectares between 2000 and 2010 (FAO, 2010). If the forest area continues to decline by this rate, it will take 775 years to disappear all of the world's forests (FAO, 2012). Tropical forests comprise 52% of total global forests. Tropical forests are mainly found in the developing countries located in neotropics (about 50%) and South-East Asia (about 30%). Nepal has around 50000 sq km area under forest (Jha & Paudyal, 2013). Tropical forests in Nepal are confined to the Terai and Siwaliks, which together comprise 1878000 ha of natural forest (FRSC, 1994). Both size and diversity of tropical forests are decreasing due to disturbances.

Disturbance is defined as any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (Pickett & White, 1985). Both natural and anthropogenic processes act as agents of disturbance. Flood, fire, storms, landslides and the alien invasive species are some natural agents (Dutta & Devi, 2013). Anthropogenic disturbances includes introduction of exotic species, overexploitation of biological resources, habitat reduction by land use change, overgrazing, expansion of cultivation, deforestation and other human activities (Pitopang, 2012).

There are three major dimensions of disturbance e.g. spatial extent, temporal extent and magnitude (intensity and severity). Forest ecosystem disturbances are considered on the basis of intensity (light, moderate and severe), size (small, intermediate and large) and duration (short, intermediate and long) (Jordan, 1985). A light disturbance (e.g. tree fall) does not disrupt the basic structure of the forest. Moderate disturbance (e.g. replacing natural forest with tree crops) destroys the forest structure but the soil is not degraded. After a severe or a high intensity disturbance (lava flow, forest clearing with heavy machinery, landslides, etc.) not only the forest structure is destroyed but the soil is also severely damaged (Jordan, 1985).

Disturbance may occur at small or large scale based on agent of disturbance. Small scale comprises the formation of gap in the forest canopy due to tree fall by wind throw. Large scale disturbances comprise landslides, earthquake, volcanic eruptions, large-scale human manipulation of the environment, geographically wide-spread mortality induced by disease, major hurricanes or climatic abnormalities which cause major destruction to the ecosystem. Disturbances that affect large areas are generally the least frequent and more severe, damaging the large mass, number as observed in some terrestrial plant communities (White, 1979).

1.1.1 Forest ecosystem in the context of disturbance

Disturbances lead to changes in structure and functioning of forest ecosystem. Regarding the structural changes, canopy thinning, creation of distinct canopy gaps, destruction of much of the top strata directly affect the hydrological cycle within the forest ecosystem. As a result, canopy evaporation is reduced, water reaching the forest floor is increased, most of the water is lost by runoff, often the litter layer rapidly dries up and organic matter input to soil is decreased.

Disturbance also damages the functional aspects of the forest ecosystems by creating very rigorous conditions for both plant and microbial growth due to decreased organic matter content of soil, unfavorable Ph and low nutrient supply. Re-establishment of forest species is hindered due to nutrient deficiency (often N and P). Disturbance disrupts soil-plant-microbe cycle forcing many deviations in nutrient cycling. Due to canopy removal, decomposition of detritus and mineralization of nutrients are accelerated partly due to the increase in temperature and moisture content in the litter layer. Besides, runoff of water increases and the nutrients are leached and lost from the forest ecosystem. The disturbances such as deforestation and habitat loss may lead to the extinction of tropical forest species (Wright, 2006).

Undisturbed climax forests are characterized by unchanging species composition and density, stand biomass and productivity, and the rates of nutrient input/output into the ecosystem. Generally, the climax forests are dominated by long lived tree species with very high density wood, low annual growth and great insect resistance (Jordan, 1985). Such forests maintain constant structure and functional features year after year as they are in a state of dynamic equilibrium with their environments.

Disturbed forests show changes in species composition and density, stand biomass and productivity and in the patterns of nutrient cycling. Such changes are often rapid at the beginning of the disturbances. Generally, the recently disturbed forests are typically dominated by relatively short-lived tree species with low density wood, low resistance to insects and disease and having high growth rate (Jordan, 1985). Unstable forests, showing changing structure and function, are not in dynamic equilibrium with their environments, and are also called secondary successional forests.

Another major effect of disturbance is on species richness and diversity. The intermediate disturbance hypothesis (IDH) originally proposed by Connell (1978), predicts that diversity will be maximum at intermediate levels of disturbance. It has been postulated that at high levels of disturbance species diversity is reduced because only good colonizers or highly tolerant species can persist. On the other hand at low disturbance frequency, species diversity is expected to be low because dominant species exclude the inferior species. Thus, at intermediate level of disturbance, the species diversity is expected to maximum because it has mixture of colonizers and competitors.

1.1.2 Soil physicochemical characters

Soil nutrients play an important role in the formation of plant communities, their species and structural diversity in all types of ecosystems. Soil conservation has fundamental significance for biodiversity conservation. Additionally, change in diversity may be related to initial nutrient condition of the soil. Theresa and Bowman (1997) observed that nutrient enrichment increase the biodiversity in poor soils. Homeier *et al.* (2010) reported the positive correlation between soil variables and tree diversity. The growth of *Shorea robusta* (Sal) and other tree species, such as *Terminalia tomentosa* and *Syzygium cumini* in tropical forests are highly influenced by nitrogen (N), phosphorus (P), potassium (K), and soil pH (Bhatnagar, 1965).

Physicochemical characteristics of forest soils vary in space and time due to variations in topography, climate, physical weathering processes, vegetation cover, microbial activities, and several other biotic and abiotic variables. Soil- vegetation system plays an important role in the global C cycle. Soil is the largest pool of terrestrial organic C and contains about 1.5-3 times more organic carbon than vegetation (Wang *et al.*, 2004) and about twice as much C than is present in the atmosphere (Lal, 2004).

It is estimated that the world's forest store 283 G t of C in their biomass alone, and 638 G t carbon in the ecosystem as a whole including dead wood, litter and soil up to 30 cm depth (FSI, 2005). Carbon in the form of organic matter is a key element to healthy soil. Conversion of natural forests to agricultural land results in the mineralization of soil organic carbon (SOC), thus reducing SOC stocks and increasing atmospheric CO_2 concentrations (Don *et al.*, 2011). Climate and soil factors affect the decrease in SOC stocks. The largest decrease in SOC stocks was observed in temperate regions (52% decrease), followed by tropical regions (41% decrease) and boreal regions (31% decrease) (Wei *et al.*, 2014).

1.1.3 Microbial biomass

Microorganisms play a major role in nutrient cycling. Bacteria, fungi, actinomycetes, rotifers and protozoa are the major soil organisms which constitute the soil microbial biomass. Live root fractions and organisms larger than $5 \times 10^3 \mu m^3$ sizes are excluded from this category (Jenkinson & Ladd, 1981). Soil microbial biomass is an active, living and labile fraction of soil organic matter (SOM). Soil microbial biomass follows the distribution of roots up to 1m depth (Xu *et al.*, 2013). Soil microbial biomass, though represents a small fraction of total SOM pool but is an active fraction due to its rapid turnover rate and fast release of available nutrients to the plants and thus contributing to nutrient cycling process far greater than its size (Walley *et. al.*, 1996). The size and turnover of soil microbial biomass affect the quantity of available nutrients in the soil and thus it has been used as an index of soil fertility (Hassink *et. al.*, 1991).

Being an active fraction, soil microbial biomass shows quicker response than does the total SOM to any change in the ecosystem (Powlson & Jenkinson, 1981). Estimation of soil microbial biomass may provide the information needed for ecosystem level monitoring for initial disturbance and recovery (Smith & Paul, 1990).

Current models of SOM dynamics e.g. Century model, divide SOM into three fractions with different turnover times (a) active fractions representing the live soil microbial biomass with most rapid turnover time (0.14 year), (b) slow fraction representing physically protected and or in chemical forms with more biological resistance to decomposition having an intermediate turnover time (5 years), and (c) passive fraction representing highly stabilized, physically protected and chemically recalcitrant organic matter with longer turnover time (150 years) (Parton *et al.*, 1989). Because of the low turnover time, soil microbial biomass is the most readily available part of the soil organic matter.

1.1.3.1 Microbial biomass as a source of plant nutrients

Soil microorganisms play a key role in the decomposition and mineralization of plant and animal residues in soil and thus help to link the soil- plant nutrient cycling (Duffkova & Macurova, 2011), by acting both as a sink (immobilization) and as a source (mineralization) of plant nutrients. It may play an active role in preventing nutrient leaching through immobilization. The level of soil microbial biomass, C, N and P can be taken as functional indices of restoration of soil fertility. An increase in the size of soil microbial biomass is a critical factor in recovery of drastically disturbed soils as it aids in the re-establishment of nutrient cycling (Jenkinson & Ladd, 1981).

Mineralization of soil organic N into plant available N (NO^-_3 and NH^+_4) is an important component of nitrogen cycle. N-mineralization begins with the formation of NH^+_4 (Ammonification) from soil organic N conducted by heterotrophic organisms mostly the ammonifying bacteria. The NH^+_4 thus formed is oxidized into NO^-_3 which is conducted by chemoautotrophic nitrifying bacteria also called nitrifiers (Nitrification). Nitrification occurs in two steps: first the NH^+_4 is oxidized into NO^-_2 by nitrosomonas and then the NO^-_2 is further oxidized into NO^-_3 by nitrobacter. Only the available forms of nutrients are taken up by the plants. Thus, the amount of available nutrients determines the fertility status of the soil.

Soil microbial biomass represents a small fraction (2-3%) of SOC and total N. It is a composite of several groups of organisms and each microbial group may have a different C: N or C: P ratio. C: N of bacteria is often ranges from 3 to 5, while in fungi it ranges from 7 to 15. Low C: N ratio reflects the bacterial dominance in soil microbial biomass as bacterial tissue is richer in protein than fungi. Bacterial population increases significantly under low nutrient regimes and environmental extremes than fungi and actinomycetes.

1.1.3.2 Factors affecting the microbial biomass

Soil microbial biomass and its activities may be influenced by vegetation type and the quantity and quality of organic matter inputs. Besides this, seasonal variations in temperature and rainfall, and also the organic matter accumulation from litter fall and fine roots may also have great influence on soil microbial biomass. As the growth and functioning of microbial biomass is limited by carbon in the soil, vegetation types, quality and quantity of litter and amount of fine root necromass all these parameters influence the status and activities of soil microbial biomass (Jin *et. al.*, 2010).

1.1.3.3 Recovery in soil microbial biomass and nutrient regeneration

As reported by Mandal (1999), forest disturbance due to landslide reduce the size of soil microbial biomass. Due to removal of surface soil and associated vegetation, loss of SOM and nutrients, soil microbial biomass declined drastically in 1-year old landslide site which increased 3 folds in 15-year old site and 4–5 times in 58 year-old site. Even then, after reaching to 58 year-old age, the soil microbial biomass was 17–22% lesser in comparison to mature sal forest. Disturbance altered both the size and composition of the microbial biomass as also reported by Walley *et al.* (1996) in the disturbed site of the Prince Albert Model Forest in Canada.

Nutrient availability in the soil is facilitated through the microbial activities in the form of decomposition, immobilization and mineralization. But the carbon dioxide enrichment due to forest loss leads to an increase in soil microbial respiration and a marked decline in sequestration of root-derived carbon in the soil (Heath *et al.*, 2005). As growth and functioning of microbial biomass is limited by C in the soil, the microbial management through residue placement has great potential for the management of organic matter and nutrients in the soil system.

1.1.4 Composition and structure of forest

Tropical forests are species-rich terrestrial communities and contain about two thirds of the global plant species. Especially, tropical and subtropical humid forests contain high species richness, heterogeneity, and complex community organization. Species rich communities of the tropical forests are not only being reduced in area but they are also becoming species poor and less diverse due to rapid deforestation and forest fragmentation (Raghubanshi & Tripathi, 2009).

Natural communities are inherently dynamic systems with respect to their species composition, structure and functional characteristics. The age-structure and densities of different populations constituting the communities change with time. Even when the physical conditions are relatively uniform, opportunities for growth, reproduction and survival of species vary spatially, reflecting variation in the intensity of biological interactions, resource availability and microclimatological conditions.

Temporal and spatial variabilities are essential features of population and community dynamics. Many species would cease to exist in the absence of such variability. This type of change which is driven by the properties of the species present and their effects on site environment causes autogenic vegetational change. Autogenesis occurs where the environment is normal, non-disruptive to succession and stable, and within this environment the community development results into a compositionally stable climax (White, 1979). Besides the endogenous factors, changes in communities may be caused by outside forces, or exogenous causal factors, which regulate the allogenic changes in the community. Due to disturbance the environment becomes abnormal, unstable and disruptive to progressive succession.

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Land use change, which includes both conversions and modifications, is the primary driving force causing species extinctions and loss of biological diversity (Sala *et al.*, 2000). Loss of biological diversity is the most important consequence of the degradation of tropical forests as it influences all ecological services and the livelihood of forest dwellers (Sagar & Singh, 2006). Invasion of non-indigenous species, which account for 20% or more of the plant species in many continental areas (Vitousek *et al.*, 1997), alter the structure and functioning of ecosystems, leading to further loss of species diversity. Disturbance is a major cause of spatial heterogeneity, and long-term fluctuations in the structure and functioning of ecosystems. Its impact on ecosystem processes depends on the disturbance regime (its severity, frequency, type, size, timing, and intensities) (Chapin III *et al.*, 2002).

Because of high anthropogenic pressure, tropical forests are being cleared at the rate of 1–2% per year. Man-mediated disturbances in the forests are the root cause of habitat fragmentation which leads to spatial and temporal variation in species richness, composition, and productivity at local and regional levels (Anbarashan & Parthasarathy, 2013). It also reduces the effective colonization rates of all species. Tilman *et al.* (1994) argued that habitat destruction may lead to the loss of the strongest competitors and play key roles in ecosystem function. In spite of these negative arguments, Huston (1979) considered disturbance as a positive force that might increase species richness and species diversity in the forest by preventing competitive exclusion by dominant species.

1.1.4.1 Forest in Nepal

Nepal is rich in vegetation due to its unique geography with drastic changes in elevation and varying types of climate. Moreover, the country is standing at the crossroads of the Indo-Malayan and the Palearctic biogeographic regions which made it a mixing place of species originating in both regions. In Nepal, the following bioclimatic zones are recognized by Tree Improvement and Silviculture Component (TISC) (2002): Lower Tropical (below 500 m), Upper Tropical (500-1000 m), Lower Sub-tropical (1000-1500 m), Upper Sub-tropical (1500-2000 m), Lower Temperate (2000-2500 m), Upper Temperate (2500-3000 m), Lower Sub-alpine (3000-3500 m), Upper Sub-alpine (3500-4000 m), Lower Alpine (4000-4500 m), Upper Alpine (4500-5000 m) and Nival/arctic (above 5000 m). Giant mountains, deep valleys and gorges, cold deserts, and alluvial plains are found within a few hundred square kilometers, consequently a wide variety of biomes are squeezed together to make this country a complex ecological laboratory.

Important forest types of Nepal are: Sal forest, Tropical deciduous riverine, Tropical evergreen, Sub-tropical deciduous hill, Sub-tropical semi-evergreen hill, Sub-tropical evergreen, Lower temperate mixed broadleaved, Upper temperate mixed broadleaved, Temperate and alpine conifer, Moist alpine scrub and Dry alpine scrub (Stainton, 1972). In Nepal, 29% land is under natural forests and additional 10.6% is under shrubs (Land Reform Mapping Project; LRMP, 1986). Forest resources play an important role in the economy of Nepal. Forest and agriculture including fishery employ 80% of population and contribute 35 % to total gross domestic product (GDP) (CBS, 2011).

According to LRMP (1986), “Terai” refers to Terai Physiographic region of Nepal. It occupies 2,016,998 ha of the total land area of the country. In Terai, forest occupies 20.41% (411,580 ha) of the total area. Terai forest was found to have decreased by 16,500 ha at an annual rate of 0.44% in between 2001 and 2010 while the annual decrease rate of forest cover for eastern Terai and Sunsari district were 0.24% and 0.57%, respectively during the same period (FRA/DFRS, 2014).

Terai region forest is mainly dominated by mixed hardwood forest (46.86%) and Sal forest (45.71%). The mean stem volume in Terai forest was 167.42 m^3 ha^{-1} with highest value for Sal forests (208.68 m^3/ha) followed by Sal-Terai Mixed Hardwood (STMH) forests (183.33 m^3/ha) (FRA/DFRS, 2014). The average number of stems per hectare was reported as 583 and the basal area per hectare, 18.38 m^2. The air-dried and oven-dried biomass were reported as 208.73 Mg ha^{-1} and 189.75 Mg ha^{-1}, respectively. In Terai forests, total carbon stock excluding seedlings and saplings of tree species as well as shrub species having less than 5 cm diameter at breast height (DBH), climbers, fine roots, grasses (including bamboos) and herbs was 50.68 Tg (123.14 C Mg ha^{-1}) (FRA/DFRS, 2014).

Among 380 flowering plant species reported from Terai, 164 species are trees, 72 shrubs, 109 herbs, 30 climbers and 5 epiphytic plants. Terai Forests are highly disturbed by livestock grazing, tree cutting, other human induced damage, sapling and pole cutting, tree lopping and forest fires (FRA/DFRS, 2014).

Sal (*Shorea robusta*) is a major timber resource of Nepal. Sal forests are distributed from east to west on the flat land of Terai, Bhabar, dun valleys and on the outer foothills (Siwaliks) in the Sub-Himalayan tract usually up to 1100 m (Stainton, 1972). In Nepal, Stainton (1972) classified the Sal forests as Hill Sal, Bhabar Sal and Terai Sal. However, TISC (2002) revised the classification and recognized only two types of Sal forests in Nepal: Lower Tropical Sal up to 500 m and Hill Sal distributed between 500-1000 m.

In the Bhabar and Terai region comprising lower tropical zone, Sal trees are much larger (generally > 24 m height) and the species composition are richer, while in hill Sal forests, the trees rarely exceed 15 m in height due to shallowness of soil. However, in the hills north of Dhangarhi in western Nepal at over 914 m elevation, some magnificent stands of Sal comprising about 36 m tall trees are growing. Similarly in the eastern Siwaliks of Nepal large tract of magnificent Sal forest comprising average tree height about 26-37 m, is located at 750 m elevated plateau (Mandal, 1999). The Bhabar belt of Sunsari district in eastern Nepal supports extensive tracts of Sal dominated forest. This forest has been experiencing many disturbances like deforestation, fire, grazing due to the dense settlements around the forest.

1.1.5 Biomass

The amount of accumulated organic matter in the vegetation found in an area at a given time is the standing crop biomass while productivity is the rate at which organic matter is created by photosynthesis. Forest biomass is a complex property affected by forest structure, distribution and ecological processes (Pan *et al.*, 2013).

Accurate information on biomass pools is of great importance to understand the structure and function of ecosystems. Moreover, the reliable information on the forest biomass is helpful to assess forest productivity, C pools, and C sequestration in biomass components including roots, boles, branches and leaves (Návar, 2009). It is also useful for implementing REDD (Reducing Emissions from Deforestation and Forest Degradation) policy introduced in the Kyoto Protocol.

Climate change during the last decades has increased the attention of entire world. Therefore, an accurate estimation of forest biomass is required for climate policy definition. An accurate quantification of the biomass stocks and net primary production of moist tropical forests started in the past decade (Clark, 2004). Allometric equations have been frequently used to estimate aboveground and belowground biomass.

1.1.5.1 Litterfall: aboveground source of soil organic matter

Senesced leaves, dead twigs, bark, flowers and fruits fall to the ground constitute aboveground litter whereas fine roots form the belowground litter. Litterfall is a key parameter to link biogeochemical cycle between plants and soils. Plants loose leaves either periodically or continuously. The lifespan of leaves is different in different groups of plants. In deciduous species the lifespan is only less than 1 year whereas in evergreen plants it varies from around 18 months to several years. The trees in the deciduous forests loose most of their leaves during the short dry season, either before bud break or at about the same time as bud break. In evergreen trees leaf fall occurs after bud break. Leaf production and loss also varies widely among species and even individual trees growing within the same forest.

Litter is a key factor in structuring plant populations, through positive or negative interactions (Baltzinger *et al.*, 2012). Thick layer of litter modifies the growth environment for seeds, seedlings and adult plants, thereby reducing the species diversity and biomass of ground vegetation which is generally observed in the forests of temperate region. On the other hand, the thin layer of litter due to readily decomposition in moist tropical forests favours the growth of seeds, seedlings of adult plants and increase the species diversity and biomass. Litter exerts three main effects on the soil and vegetation: (1) physical effects: determines the amount of light reaching the soil, controls temperature, moisture, and also acts as a barrier for young shoots (2) chemical effects: usually release allelopathic compounds on the soil and (3) biological effects: controls microbial activities.

Litterfall not only constitutes a large fraction of NPP but also serves as a medium for nutrient cycling between the vegetation and soil. It contributes over 80% of the nitrogen and phosphorus, and 77–100% of the calcium returns to the soil (Hansen *et al.*, 2009). Litterfall is suggested to drive soil properties and ecosystem bio-geochemistry (Freschet *et al.*, 2012). Litter decomposition, a major pathway of nutrient fluxes, determines the organic matter input to forest soils, and has a strong influence on forest productivity and soil nutrient status (Vesterdal *et al.*, 2008). As the litter decomposes, the nutrients contained within it enter the soil and become available for uptake by the vegetation or are lost to lower soil layers or forest streams through leaching.

The amount of litterfall closely parallels the biomass of foliage. Litterfall has been used as an index of net primary production (NPP) in a variety of plant communities. Therefore, precise estimates of litterfall rates are essential for a meaningful evaluation of ecosystem NPP and nutrient cycling. For example, Bray and Gorham (1964) found that annual leaf fall approximates total NPP if multiplied by 4.9 for temperate evergreen forest, by 3.7 for temperate deciduous forest and by 3.3 for equatorial forest. Aragao *et al.* (2009) opined that the total NPP is close to 3.1 times of total litterfall for the tropical forests of Amazonia. The quality of litter controls the rate of NPP. Tree species producing high quality litter (lower C:N ratio) result in a higher rates of nutrient availability in the soil and in turn a higher rate of primary productivity.

The major factors affecting litter production are the temperature, age of the stand and soil fertility. Generally, the total litterfall declines with the maturity of the forest. Soil fertility promotes both total and foliar litterfall (Hansen *et al.*, 2009). Litterfall is also determined by the species composition of the forest. Chave *et al.* (2010) found a significant positive relationship between litterfall seasonality and rainfall seasonality across 47 forest plots of tropical South America. Moreover, the addition of P significantly increased the fine-litter production in humid lowland forest of Panama (Wright *et al.*, 2011).

1.1.5.2 Fine root: belowground source of soil organic matter

Fine root is one of the dynamic components of below-ground biomass. The root having < 5 mm diameter is generally considered as fine root (Maycock & Congdon, 2000; Espeleta & Clark 2007; Rieger *et al.*, 2013). Fine root of < 2 mm diameter size is even exemplified as more active component. Fine roots influence the soil organic matter and nutrient cycling in the terrestrial ecosystems (Hendricks *et al.*, 2006). The contribution of fine roots in the C and nutrients input to soil is equivalent or even higher to that from leaf litter in moist tropical forests (Roderstein *et al.*, 2005).

Fine roots comprise about 30% of the aboveground biomass. So far the production is concerned fine roots contribute over 33%, or even between 40-85% of the net primary production (Hendricks *et al.*, 2006). In moist tropical forests, fine roots (≤ 2 mm diameter) comprise up to 50% of the NPP (Gill & Jackson, 2000). It happens because the production and turnover of fine roots flux a considerable amount of carbon to the ecosystems. It becomes clear from the turnover rate of 0.56 yr^{-1} in forest ecosystems (Gill & Jackson, 2000). After analyzing the global data, Finér *et al.* (2011a) also reported turnover rate as 0.77, 1.21, and 1.44 yr^{-1} for boreal, temperate, and tropical forests respectively.

Fine roots absorb water and nutrients from soil. They show quick response to changes in water and nutrient availability (Espeleta & Clark, 2007). Vertical distribution of fine root is dependent on the soil environment and stand age (Yuan & Chen, 2010). Fine root dynamics is usually influenced by soil properties like depth, bulk density, moisture, temperature, clay, nutrient content, and soil microbial biomass (Joslin *et al.*, 2006). Plant species composition, genetic properties and seasonality are also the determining factors for the growth and development of the fine root (Espeleta *et al.*, 2009; Barbuhiya *et al.*, 2012; Lei *et al.*, 2012).

Soil nutrients like N, P, and K have strong influence on fine root biomass. In general, soil nutrients show opposite relationships with fine roots (Jimnez *et al.*, 2009). Hendricks *et al.* (2006) found a negative relationship between N availability and fine root biomass. Lima *et al.* (2010) also found an opposite trend between fine root biomass, and soil moisture, N and P availabilities. Fine roots increase their surface area in water and nutrient deficient soils mainly for nutrient absorption (Kochsiek *et al.*, 2013). The reduction in fine root biomass with nutrient availability may be due to the decrease in carbon share in root production or increased turnover rates (Hendricks *et al.*, 2006). However, the contribution of fine root to NPP remains constant with decreasing nutrient availability (Meier & Leuschner, 2008).

There exist two views regarding the effect of N on fine root production. According to some studies, nitrogen fertilization increases the fine root production and turnover (Uselman *et al.*, 2007; Pei *et al.*, 2012; Yuan & Chen, 2012b), whereas other studies found uncertain and opposite results (Maycock & Congdon, 2000; Nadelhoffer, 2000).

1.1.6 Gross and net primary production

The gross primary productivity (GPP) is total ecosystem photosynthesis and has been found to be approximately 30 Mg C ha^{-1} y^{-1} (Aragao *et al.*, 2009; Malhi *et al.*, 2009) for many tropical forests. Plants respire a large fraction (about 50-70%) of the carbon taken up during photosynthesis. The remaining carbon called NPP is converted into plant biomass, and a smaller fraction to root exudates and volatile organic compounds. Because biomass production (BP) constitutes the largest fraction of NPP, BP is commonly used as a proxy for NPP (Drake *et al.*, 2011). The ratio of NPP to GPP is often termed the carbon use efficiency (CUE), which averages approximately 30 per cent for the few mature Amazonian tropical forests where it has been measured, but may vary with disturbance and fertility (Aragao *et al.*, 2009). Hence around 70 per cent of carbon assimilated by tropical forest during photosynthesis is rapidly returned to the atmosphere through autotrophic respiration (Malhi *et al.*, 2009). The relationship between GPP, NPP and standing live woody biomass is presented in Figure 1.

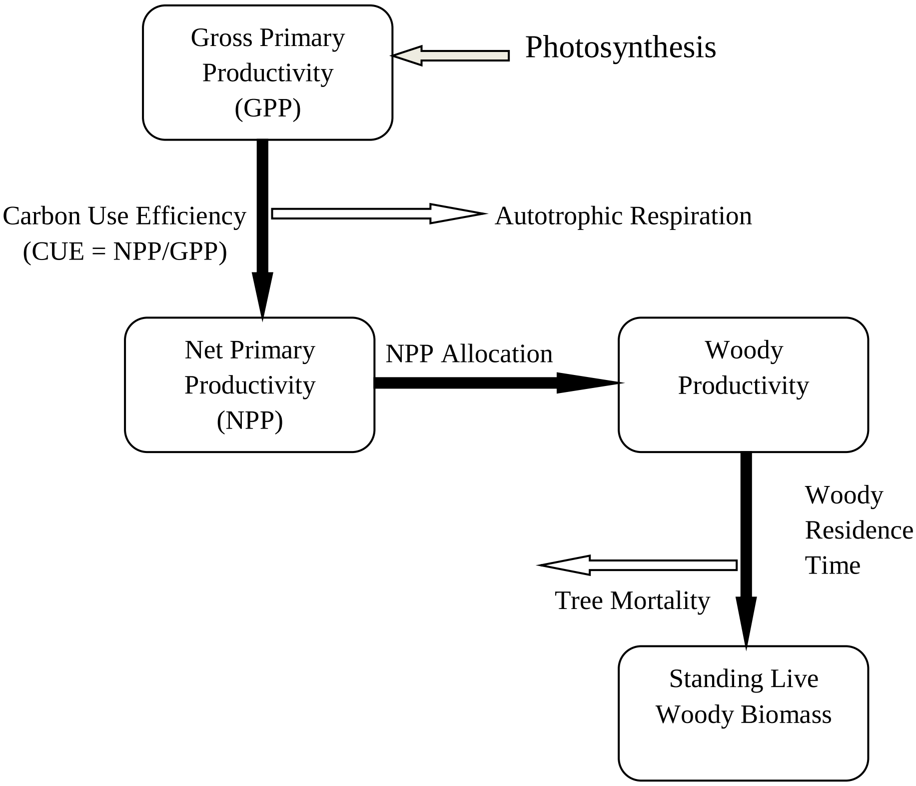

Figure 1. A framework for understanding the carbon cycle of forests. The pathway shows the key processes linking photosynthesis and the woody biomass of a forest. Much effort in terrestrial ecosystem models has gone into accurate representation of the first process in this pathway (photosynthesis) but three other processes can be equally important: autotrophic respiration (or carbon use efficiency), allocation of net primary productivity, and mortality (or woody biomass residence time) (Pathway taken from Malhi *et al.*, 2011).

Net primary production is the difference between total photosynthesis (GPP) and total plant respiration in an ecosystem. In the field, however, NPP cannot be measured in terms of this difference. Therefore, NPP is defined alternately as the change in standing crop between two measurements or NPP is the total organic matter produced over a given interval. The simple and most common method to measure NPP in the field is estimating the change in standing crop biomass.

Net primary production comprises all materials that together represent: (1) the amount of new organic matter that is retained by live plants at the end of the interval, and (2) the amount of organic matter that was both produced and lost by the plants during the same interval. In forests, these materials are: aboveground biomass increment, fine litterfall, aboveground losses to consumers, emissions of biogenic volatile organic compounds (BVOCs), aboveground losses of leached organic compounds, net increments in biomass of coarse and fine roots, dead coarse and fine roots, root losses to consumers, root exudates, carbohydrates exported by plants to their mycorrhizal or nodule symbionts, and any net increases in stores of nonstructural carbohydrates.

Tropical forests are among the most productive ecosystems on the Earth. They account for about one-third of global NPP (Roy & Saugier, 2001), but have been relatively under-sampled compared with their importance. The NPP of an ecosystem is one of the fundamental parameters describing its functioning. It is used to create organic structures in plants, including woody, leaf and root tissues, and also root exudates and volatile organic carbon compounds (VOCs) (Roy & Saugier, 2001). As such, NPP is an important determinant of the amount of the organic material available to higher trophic levels. It also indicates the magnitude and turnover of the carbon and nutrient cycles of that ecosystem.

Climate influences the primary productivity in global patterns. The regions of highest NPP are located in the equatorial zone where the climate supports high rates of photosynthesis (tropical rain forests). Moving north and south from Equator, the seasonality of precipitation increases, decreasing the growing season and subsequently, values of NPP. In addition to climate, the availability of nutrients in the soil has a direct effect on productivity. It influences the rate of nutrient uptake, photosynthesis and plant growth; the net result is a general pattern of increasing NPP with increasing soil nutrient availability. Time and stand age, disturbances such as herbivory and fire also have pronounced effect on NPP. Cleveland *et al.* (2011) reported that mean annual temperature is the strongest predictor of aboveground NPP across all tropical forests, while in lowland tropical forests P availability regulates NPP.

Generally the primary productivity increases during the early stages of stand development followed by a decline as the forest ages and the standing biomass increases. Aboveground NPP decreases up to 76% as stands mature. According to Gower *et al.* (1996), the causes for declining aboveground NPP with stand age include: (1) an altered balance between photosynthetic and respiring tissues, (2) decreasing soil nutrient availability, and (3) increasing stomatal limitation leading to reduced photosynthetic rates.

1.1.6.1 Forests and carbon sequestration

The use of fossil fuels and deforestation activities has increased the carbon dioxide (CO_2) concentration of the atmosphere causing the greenhouse effect. It is well-known that any increase in the level of atmospheric CO_2 and other greenhouse gases also increases atmospheric temperature. Scientists now have estimated that the average global surface temperature is likely to rise by 1.4 to 5.8 °C by the end of the 21st century. Forest ecosystems play a critical role in reducing the greenhouse effect and stabilizing climate by storing atmospheric CO_2 in biomass. (Mohanraj *et al.*, 2011).

Forests sequester and store more C than any other terrestrial ecosystem and are an important natural 'brake' on climate change. Tropical forests represent a major reservoir of global C, containing up to half of the estimated 558 Pg ($1 \text{ Pg} = 1 \times 10^{12}$ kg) of C stored in vegetation (Houghton, 2005). Tropical forests contain about 25% of the C in the terrestrial biosphere, account for about 33% of terrestrial NPP, and can sequester large amounts of carbon annually (Bonan, 2008). Land use changes in the tropics have become an increasing concern for their potential impacts on the global C cycle and climate change.

1.1.6.2 Forest disturbance and C sequestration

An ecological disturbance is defined as a phenomenon of disruption of ecosystem structure and function. There are many kinds of disturbances, including physical disturbance, biogenic disturbance and anthropogenic disturbance. Disturbances can profoundly affect ecosystem C storage and dynamics by generating spatially heterogeneous landscapes, reducing ecosystem production, depleting one or more C pools, and relocating C distribution among these pools (Turner, 2010). Global warming and human activities are increasing the frequencies and severities of disturbances. Improving the understanding of the impacts of disturbances on ecosystem C is required for accurately estimating the feedbacks between C cycle and climate change (Running, 2008).

When forests are cleared, carbon stored above and below ground in leaves, branches, stems and roots is released to the atmosphere as CO_2. As a consequence, forest clearing, especially in the tropics, is a major source of CO_2 to the atmosphere. Tropical deforestation is estimated to have released the 1–2 billion tonnes of carbon per year during the 1990s. Therefore, avoiding deforestation has been proposed as a method of mitigation. The effect of deforestation was also realized by international society and the concept of REDD and REDD-plus was launched in order to reduce the emissions from deforestation.

The global annual rate of forest loss was 0.22% yr^{-1} in the period 1990–2000 and 0.18% yr^{-1} in 2000–2005; the latter being equivalent to 13 million ha yr^{-1} with most loss occurring in the tropics (FAO, 2011). Moreover, clearing of tropical forests also destroys globally important carbon sinks that are currently sequestering CO_2 from the atmosphere and are critical to future climate stabilization (Stephens *et al*, 2007). According to Pan *et al.* (2011), the average rate of CO_2 emission due to tropical deforestation was 2.9 Pg C yr^{-1} for the period of 1990 to 2007, while the re-growth of tropical forests partially compensated a carbon sink of 1.6 Pg C yr^{-1}.

Tropical forests play an important role in the global C cycle. They contain about 40% of global terrestrial C, account for more than half of global gross primary productivity, and sequester large amounts of CO_2 from the atmosphere (Beer *et al.*, 2010; Pan *et al.*, 2011). Carbon is stored in forests predominantly in live biomass and in soils, with smaller amounts in coarse woody debris (Malhi *et al.*, 2009).

1.1.7 Storage and flux of nutrients

Nutrient dynamics is an important phenomenon for the understanding of ecosystem functioning and ecological status. The nutrient status of a forest ecosystem depends on the balance between nutrient inputs (deposition, fixation and weathering) and outputs (leaching and volatilization) (Vitousek & Sanford, 1986). The balance of nutrient supply and loss changes with the age of soils. Weathering of rock is the primary source of P, sulphur (S) and K, and their availability tends to decline with soil age (Hedin *et al.*, 2003).

On the other hand, the primary sources of N are biological fixation and atmospheric deposition, and its supply initially increases in young soils, reaches maximum levels in moderately weathered soils, and declines in some highly weathered soils as other nutrients come to limit biological N fixation (Lambers *et al.*, 2008). The level of N cycling, N losses, N:P ratios in leaves and fine litter are quite faster in some lowland tropical forests as compared to temperate and boreal forests (McGroddy *et al.*, 2004).

Plants adjust to local nutrient availability through changes in species composition, phenotypic plasticity, and adaptation (Wright *et al.*, 2011). For example, tree species growing on nutrient poor soils are characterized by dense wood and low foliar nutrient concentrations as in eastern and central Amazon, while tree species growing on nutrient rich soils of western Amazon are characterized by lighter wood and higher foliar nutrient concentrations (Fyllas *et al.*, 2009, Patino *et al.*, 2009).

To understand the nutrient dynamics in natural forest, a complete knowledge of litterfall and fine root production is essential. Litter fall is a major functional part of any ecosystem as it plays a vital role in regulating nutrient cycling and organic matter content. Litterfall is the main aboveground pathway for the return of organic matter and nutrients from plants to the soil (Vitousek & Sanford, 1986). Litter accumulation on the soil surface serves as temporary sink for nutrients which are liberated gradually by the process of decomposition, leaching and mineralization. Release of nutrients from decomposing litter is a key process governing the availability of nutrients in ecosystems. Moreover, fine roots continuously add nutrients to the soil through their rapid turnover from belowground. Thus, litterfall and fine root decomposition maintain nutrient pools in the soil, influence primary production and regulate energy flow, and nutrient cycling in forest ecosystems. Litterfall dynamics is influenced by species composition, tree density, basal area and ages of trees, altitude, latitude and season (Dent *et al.*, 2006). Disturbance events in the forests such as fire, wind etc. may also induce litterfall.

In mature forests, nutrient uptake from the soil and nutrient loss through litter fall, canopy leaching, root exudation and fine root death balance each other. Natural or anthropogenic disturbance can interrupt the tight nutrient cycle between soil and plant with the possible consequence of a reduction in tree growth or vitality (Meier *et al.*, 2005). Disturbances also destroy the nutrient conserving mechanisms of the undisturbed forest ecosystem and disrupt the soil-microbe-plant nutrient cycling (Jordan, 1985). As a consequence, nutrients tend to be lost from the system. Following a disturbance, in the course of secondary succession recovery in plant biomass, soil organic matter and soil available nutrients occurs with passage of time. Regenerating vegetation accumulates biomass and adds organic matter to the soil through the dead plant parts.

1.2 Rationale

- Tropical forests are being depleted day by day due to biotic pressure.
- The site is not well studied from ecological point of view.
- A complete knowledge of species composition and forest structure is essential to formulate the forest policies.
- The knowledge of biomass estimation using girth at breast height (GBH) will be helpful to the forest users to quantify accurately the supply of products from specified trees before harvesting is carried out.
- Estimation of biomass helps in assessing the condition of a forest, that is, whether it needs protection, plantation or specific harvesting operations.
- Estimates of forest carbon stocks can be used to set mitigate measures for global warming and climate change.
- Information on nutrient dynamics in the tropical forests of Nepal is lacking.

1.3 Management implications

- Species composition of healthy and productive forest can be used to manage and accelerate the productivity of the disturbed forest stands.
- In order to meet the demand of forest product, biomass estimation is helpful to implement the harvesting operation. Such information will help in planning the forest management activities.
- Estimation of forest carbon stocks and sequestration especially in the context of disturbance will help to assess the carbon emissions.
- From the management point of view better policy to reduce the carbon emissions through re-vegetation can be formulated as per the objective of REDD$^+$.

1.4 Objectives

A general objective of the present study was to understand the structure and functioning of the tropical forest ecosystem in context to forest disturbance. The overall research question was: what is the effect of disturbance on the structure and functioning of soil-plant system in moist tropical forest? The specific objectives of the present study were:

- To analyze the species composition and forest structure.
- To determine the levels of plant biomass, net production, litter fall and fine root in the forest
- To assess the levels of soil organic C, soil nutrients (N, P and K), soil microbial biomass and N, P, K in the vegetation
- To determine the nutrient cycling in between soil and vegetation
- To assess the effect of disturbance on species composition, forest structure, plant biomass and production, soil properties, and nutrient cycling in between soil and vegetation.

CHAPTER– 2

2. STUDY AREA

2.1 Location

The present study was conducted in the Sal (*Shorea robusta*) bearing moist tropical forest (locally called Charkoshe jungle), located in the Bhabar region of Sunsari district, eastern Nepal (latitude 26°41’N to 26°48’N and longitude 87°09’E to 87°21’E), within the altitude range of 220 to 370 m, msl confined to lower tropics (Figure 2).

The forest lies in the catchment area of Koshi River, one of the largest rivers in Nepal. The forest is also traversed from north to south by some tributaries like Sehera, Seuti, and Sardu. The forest is bordered by dense settlement areas on the northern and southern sides while it is demarcated by Koshi River in the west and by a tributary, locally called Budhi Khola in the east, which is also the eastern border of Sunsari district (Figure 3). Most part of the northern side is covered by Dharan Sub-Metropolitan City whereas southern side is occupied by the villages of Tarahara, Baklauri, Kaalabanjaar and Bharaul Village Development Committees ranging from east to west, respectively.

2.2 Status of the forest in the study area

The total area occupied by the forest is 11394 ha. The central part (core area) of the forest is treated as undisturbed forest and the peripheral part located near to human settlement is treated as disturbed forest. Parameters used to classify the present forest as undisturbed and disturbed were as follows:

Parameters	**Undisturbed forest**	**Disturbed forest**
Canopy area (m^2 /tree)	154 - 227	28 - 78
Crown cover (%)	70 - 80	30 – 40
Tree density (indi. ha^{-1})	466	234
Tree stumps (ha^{-1})	Absent	70

Disturbance activities like livestock grazing, removal of timber, fuel-wood, litter and lopping for fodder have caused forest degradation in the study area.

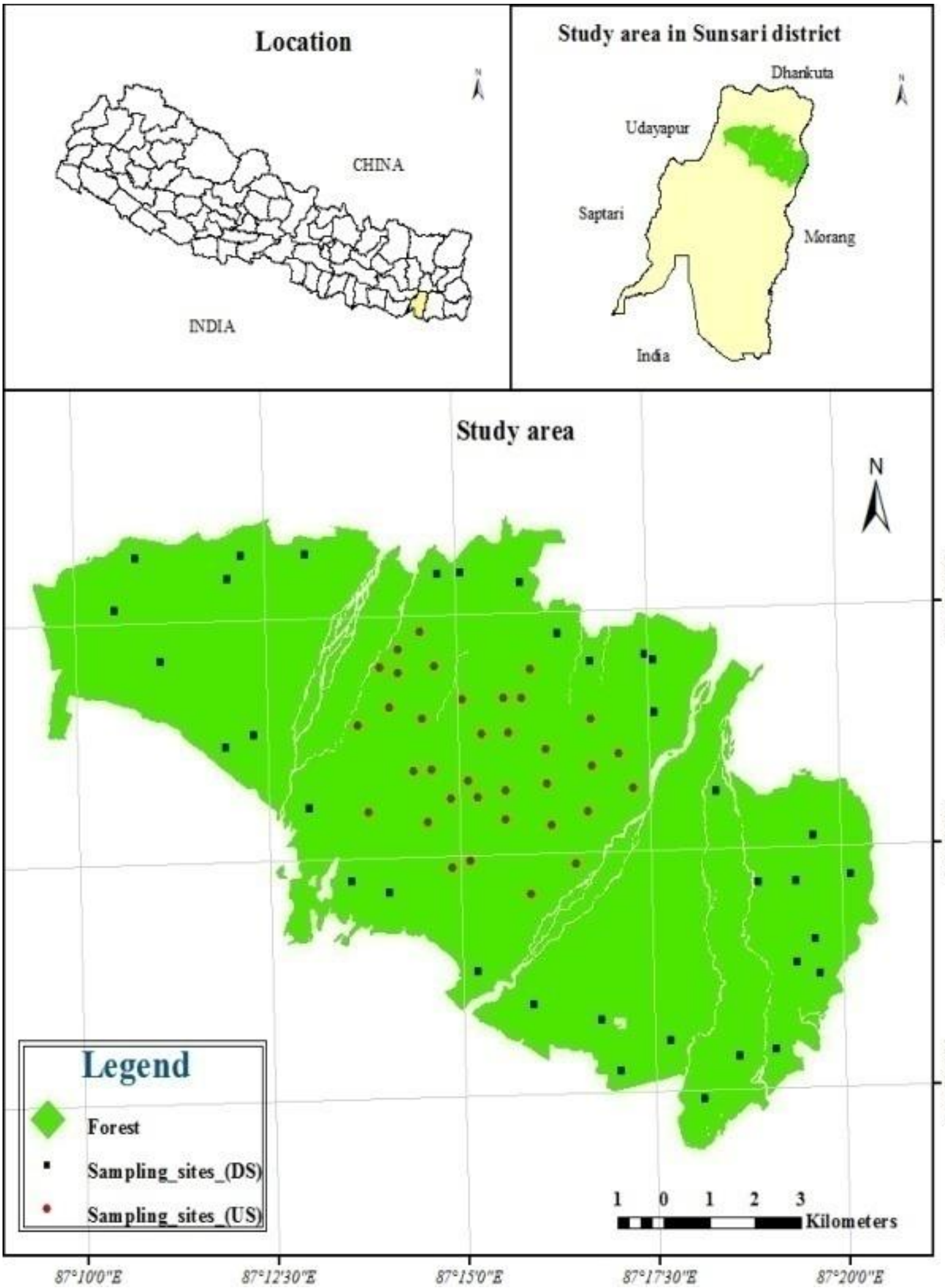

Figure 2. Map of the study area (tropical forest of Sunsari district, eastern Nepal).

Consequently, invasion of exotic species like *Mikania micrantha*, *Lantana camara*, and *Chromolaena odorata* adversely affect the native plant diversity in the forest. Dense cover of *Mikania* and *Lantana* reduce the intensity and duration of light, preventing the establishment of seedlings of tree species thereby altering the structural and floristic composition.

Figure 3. Google map of the study area showing river, tributaries, and settlements above and below the forest.

2.3 Climate

The climate is tropical and monsoonic with three distinct seasons: (i) dry and warm summer season (March to May); (ii) wet and warm rainy season (June to October); and (iii) dry and cool winter (November to February). Based on the data for the period of 2005 to 2014, mean monthly minimum air temperature ranged from 10.9°C to 25.3°C and maximum air temperature ranged from 22.6°C to 33.2°C. The average annual rainfall is 1998.6 mm; of which more than 79% is received during rainy season (Figure 4).

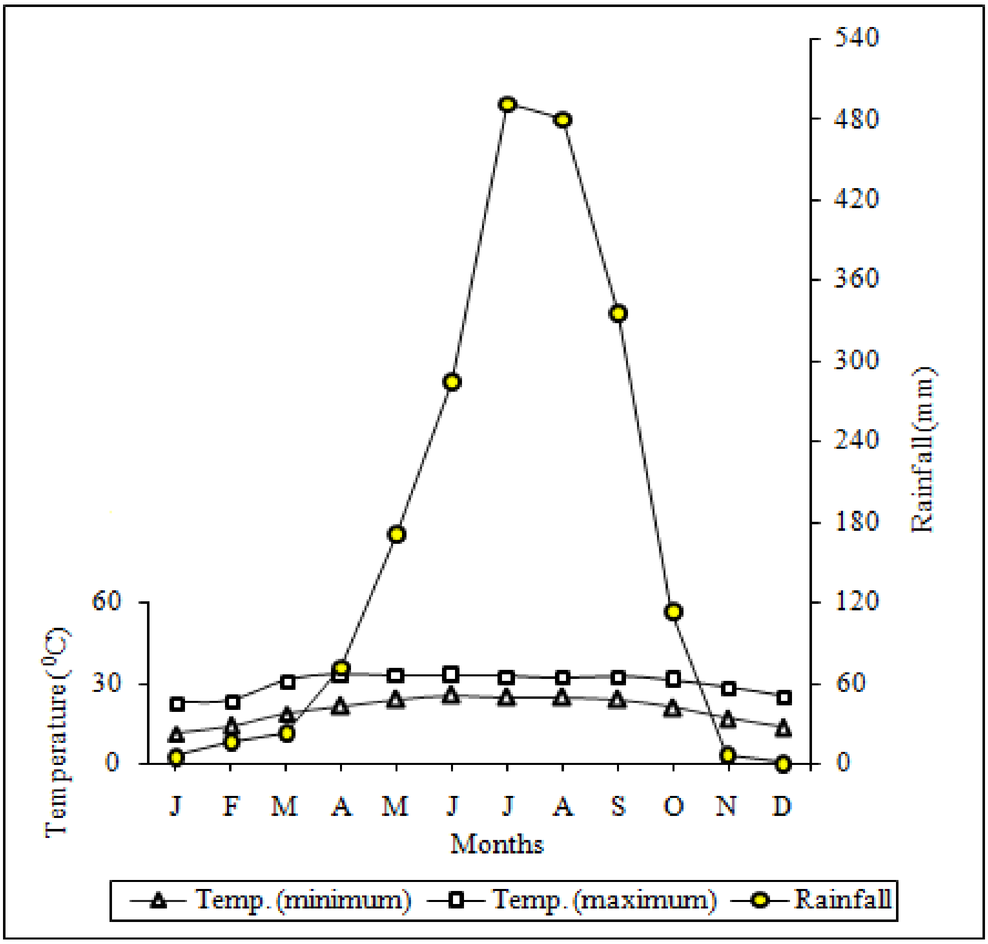

Figure 4. Ombrothermic representation of the climate of moist tropical forest region of Sunsari district, eastern Nepal. The data pertain to the period 2005–2014 (Source: Department of Meteorology, Dharan, Nepal).

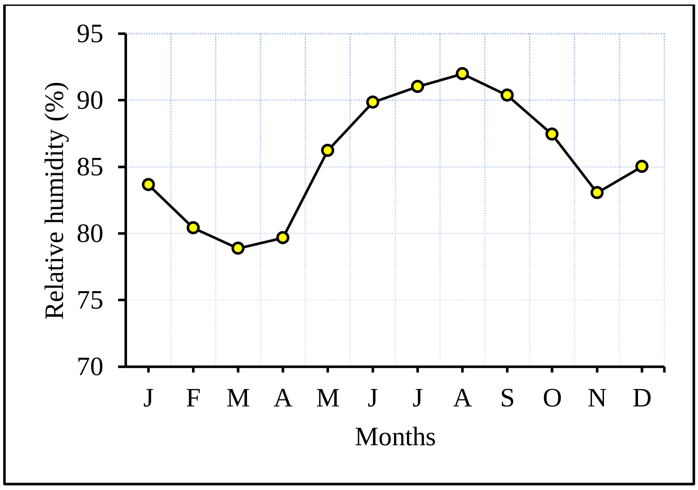

Figure 5. Relative humidity in the study area for the period 2005–2014 (Source: Department of Meteorology, Dharan, Nepal).

Relative humidity is also higher in rainy season with highest value in August (92%) (Figure 5). Data of rainfall, temperature and humidity were provided by the Department of Meteorology, Eastern Regional Office, Dharan, Nepal, located within 1 km distance from the present study area.

2.4 Soil

The study area is bordered by Siwalik hills in the north and Gangetic alluvial plains in the south. The area has been formed from soft erodible sediments of the Siwaliks and is identified by the presence of boulder beds mixed with sand, silt, clay imparting a porous nature. Soil at the present forest is deep alfisols and loamy. Topsoil (0-15 cm depth) of the study area is typical loam. The sand predominates in the soil (45–50%), while the silt and clay contents are 36–38% and 14–17%, respectively. The topsoil has pH range of 5.6–6.1, organic carbon 1.8–3.07%, total nitrogen 0.14–0.24%, total phosphorus 618–6276 $\mu g\ g^{-1}$ and exchangeable potassium 268–346 (Table 1).

2.5 Vegetation

The present forest comes under lower tropical bioclimatic zone (below 500 m) as recognized by TISC (2000). According to the life zone classification of Holdridge *et al.* (1971), this is tropical moist forest. The forest is dominated by *Shorea robusta* Gaertn. f. (Sal). Other main associates are *Haldina cordifolia* (Roxb.) Ridsdale, *Lagerstroemia parviflora* Roxb. and *Baliospermum solanifolium* (Burm.) Suresh. Present forest comprises moisture loving tree species e.g. *Syzygium cumini* (L.) Skeels, *Cassia fistula* L. and *Ehretia laevis* Roxb.; shrubs *Clerodendrum infortunatum* L. and *Murraya koenigii* Spreng; and shade loving grass *Oplismenus compositus* (L.) P. Beauv.

The common shrub species of the forest are *Clerodendrum infortunatum* L., *Murraya koenigii* Spreng and *Leea aequata* L. and herb species includes *Chromolaena odorata* (L.) R.M. King & H. Rob., *Achyranthes aspera* L., *Blumea lacera* (Burm. f.) DC. The forest is also the habitat of some rare plants e.g. *Dalbergia latifolia* Roxb., *Desmodium oojeinensis* (Roxb.) H. Ohashi, *Pterocarpus marsupium* Roxb. etc., and commercially as well as medicinally important plants like *Acacia catechu* (L.) Willd., *Cassia fistula* L., *Holorrhena pubescens* Wall. ex G.Don and *Terminalia chebula* Retz. The herb, shrub and tree species found in the forest are listed in Tables 8–10.

The peripheral part of the forest, which is in the vicinities of dense settlements, lacks some important tree species that are found in the inner core (undisturbed part) of the forest. They include *Alangium salviifolium* (L.f.) Wangerin, *Spondias pinnata* (L.f.) Kurz, *Diospyros tomentosa* Roxb., *Anogeissus latifolius* (Roxb. ex DC.) Bedd., *Desmodium oojeinensis* (Roxb.) H. Ohashi, *Dalbergia latifolia* Roxb., and some others.

CHAPTER– 3

3. SOIL CHARACTERS AND MICROBIAL BIOMASS

3.1 INTRODUCTION

In tropical forest ecosystems, soil nutrients play an important role in the formation of plant communities, their species and structural diversity. Theresa and Bowman (1997) opined that nutrient enrichment increased the biodiversity in poor soils. Homeier *et al.* (2010) reported the positive correlation between soil variables and tree diversity. Physicochemical characteristics of forest soils vary in space and time. Soil-vegetation system plays an important role in the global carbon cycle. Soil is the largest pool of terrestrial organic carbon and contains about 1.5–3 times more organic carbon than vegetation (Wang *et al.*, 2004) and about twice as much carbon than is present in the atmosphere (Lal, 2004). Carbon in the form of organic matter is a key element to healthy soil.

Soil microbial biomass, though represents a small fraction of total soil organic matter (SOM) pool but is an active fraction due to its rapid turnover rate and fast release of available nutrients to the plants and thus contributing to nutrient cycling process far greater than its size (Walley *et al.*, 1996). The size and turnover of soil microbial biomass affects the quantity of available nutrients in the soil and thus it has been used as an index of soil fertility (Hassink *et al.*, 1991).

Soil microbial activities are influenced by the variations in temperature and rainfall, and organic matter inputs from litter decomposition. As the growth and functioning of microbial biomass is limited by carbon in the soil, vegetation types, quality and quantity of litter and amount of fine root necromass, all these influence the status and activities of soil microbial biomass (Hackl *et al.*, 2004).

Being an active fraction, soil microbial biomass shows quicker response than does the total SOM to any change in the ecosystem (Powlson & Jenkinson, 1981). Estimation of soil microbial biomass may provide the information needed for ecosystem level monitoring for initial disturbance and recovery (Smith & Paul, 1990). Disturbance alters both the size and composition of the microbial biomass as suggested by Walley *et al.* (1996) and Mandal (1999).

It is the soil microbial biomass which links the circuit of soil- microbe- plant nutrient cycling and catalyses it by playing a central role in decomposition, mineralization and immobilization. The level of soil microbial biomass, C, N and P can be taken as functional indices of restoration of soil fertility. An increase in the size of soil microbial biomass is a critical factor in recovery of drastically disturbed sites as it aids in the re-establishment of nutrient cycling (Jenkinson & Ladd, 1981).

In the present study, an attempt has been made to document the soil physicochemical characteristics and soil microbial biomass of undisturbed and disturbed forest stands in moist tropical forest region of eastern Nepal with following specific objectives: 1) to examine the status of physical properties of soil; 2) to estimate the levels of soil organic carbon (SOC) and soil nutrients (N, P and K); 3) to estimate the soil microbial biomass C, N and P; 4) to assess the effect of seasonality on microbial biomass; 5) to understand the effect of forest disturbance on soil properties including soil microbial biomass.

3.2 LITERATURE REVIEW

3.2.1 Soil physicochemical characteristics

3.2.1.1 Works done outside Nepal

Vertical distribution patterns of soil nutrients under *Pinus* forest in China was analyzed by Gou *et al.* (2013). The total N, available P, and available K contents were highest in top 0–10 cm layer, decreased with increasing depth, and had significant differences between different layers.

The impacts of tree on SOC in the degraded hills of Chittagong district, Bangladesh were studied by Barua and Haque (2013). Results showed that the change of land use from degraded hill to vegetation cover significantly increased the C concentration and stock in the soil. They concluded that about 17 million Mg C could be sequestered in the degraded hill areas by planting *Acacia auriculiformis* trees in a 15-year rotation.

Soils from five sites (Plantation and under agriculture) in the south-western Australia were analyzed for total organic carbon by combustion chromatography

(Harper & Tibbett, 2013). These soils ranged between 5 and 38 m depth. The mean SOC concentration across all sites was 2.30, 0.41and 0.23% in the surface 0.1, 0.1-0.5 and 0.5 to 1.0 m increments, respectively. The mean value between 1 and 5 m was 0.12%, whereas between 5 and 35 m the values decreased from 0.04% to 0.03%.

Soil C stocks in native vegetation and more than 100 pasture soils in Brazil were estimated by Assad *et al.* (2013). The average vegetation soil C stocks at 10, 30 and 60 cm soil depth were 29, 64, and 92 Mg ha^{-1}, respectively. Key controllers of soil C stock in pasture sites were sand content and mean annual temperature (MAT).

Padmanabhan *et al.* (2013) estimated soil C stock up to the depth of 100 cm in Sarawak, Malaysia. Among the mineral soils, Inceptisols had the highest C contents (about 25 kg m^{-2} m^{-1}), while Oxisols and Ultisols rated second (about 10–15 kg m^{-2} m^{-1}).

Dieleman *et al.* (2013) quantified SOC stocks along an altitudinal gradient at conservation areas in Papua New Guinea. Soil was sampled on 92 forest locations down to 100 cm depth, and down to 30 cm in 13 grassland plots. The forest SOC stocks varied with altitude (4.8–19.4 kg C m^{-2}), and increased by 5.1 kg C m^{-2} per 1000 m increase in altitude. SOC stocks were not significantly different between forests and grasslands along the gradient.

Soil properties in a large soil profile (800 cm deep) of tropical evergreen forests in Cambodia were studied by Toriyama *et al.* (2013). The changes in soil physicochemical properties with depth were small, excluding topsoil. The soil carbon stock was 71.7 and 130.1 Mg C ha^{-1} at depths of 0–150 and 0–800 cm, respectively.

The influence of climate, soil properties and vegetation on SOC in African ecosystems was studied by Saiz *et al.* (2012). They observed strong negative relationships between soil bulk density and SOC. Available water and sand content taken together also explained the total variability in SOC stocks.

Johnson *et al.* (2011) estimated SOC in a humid subtropical forest in Puerto Rico. The SOC was higher at ridges compared to valleys (opposite to commonly observed trends). Soil depth alone accounted for 77% of the observed difference in 0 to 60 cm SOC between ridge soils (deeper) and valley soils (shallower).

Jiménez *et al.* (2011) estimated SOC pool (0–50 cm) from a chronosequence of dry tropical forest of increasing age in Costa Rica. Soil organic C and N concentrations were significantly higher in the oldest forests compared to the other. The highest SOC pool was found in the old-growth and > 80 years-old dry tropical forests, i.e., 228.9 and 150.3 Mg C ha^{-1}, respectively.

Harrison *et al.* (2011) assessed the possibility of shallow soil sampling to underestimate C in the soil profile. They concluded that shallow soil sampling can result in a major underestimate of soil C present in the soil profile in whole-ecosystems.

Vincent *et al.* (2010) studied the role of P in tropical forests by using a large-scale litter manipulation experiment in a tropical moist forest in Central Panama. Three years of litter removal reduced the organic P concentration in the surface 2 cm of mineral soil by 23%. Three years of litter addition (equivalent to adding 6 kg P ha^{-1} yr^{-1}) increased soil organic P by 16%. They concluded that even the 0–2 cm layer of the soil contributes a fifth of the total P needed to sustain aboveground growth in that forest.

Toledo-Aceves and Garcia-Oliva (2008) analyzed the effects of forest-pasture edge on soil nutrient dynamics in a tropical deciduous forest in Mexico. Total C and N pools and microbial biomass C and N in the soil of pasture were lower than in the forest. Soil P concentration was lower in the pasture, while litter P concentration had the inverse pattern. Litterfall C:P and N:P ratios decreased from the edge to the inner forest. These results suggested that the forest–pasture edge disrupts P dynamics in the forest.

Dinakaran and Krishnayya (2008) assessed the influence of vegetal cover and land use patterns on SOC in a tropical forest with some anthropogenic activities in India. A total of 306 soil samples were collected for analysis. The SOC was much higher in soils with natural tree cover. The type of vegetal cover had a significant impact on SOC up to a depth of 1.5 m. Changes in land-use pattern severely reduced sink capacity of soils.

Nitrogen dynamics was studied in tropical forest of India (Arunachalam & Arunachalam, 2006). The soil was sandy loam and acidic. Soil C/N ratio, organic carbon and pH were greater at lower depths than the top 0-10 cm soil layer. Total N concentration was higher in the top soil layer.

The relationships among edaphic conditions were studied in a humid tropical elevation gradient (McGroddy & Silver, 2000). Total soil C and P pool were significantly related to soil moisture.

3.2.1.2 Works done in Nepal

Baral and Katzensteiner (2015) studied the impact of biomass removal on soil physicochemical properties in the forests of central mid-hills of Nepal and found that the biomass removal deteriorated soil characteristics including nutrient contents, and the state of foliar nitrogen content of trees.

Limbu *et al.* (2013) studied carbon (C) stock in soil at three rangelands: Milke (3,000 m), Gorujure (3,500 m) and Jaljale (4,000 m) in eastern Nepal. The estimated total soil C was 17.65, 17.27 and 28.33 t ha^{-1} at Milke, Gorujure and Jaljale, respectively. The highest elevated site with least external disturbance (Jaljale area) had high storage of C in soil.

Gami *et al.* (2009) established the relationships between soil texture and SOC or total N under 99 native forests in Nepal and Bangladesh. Soils were collected to a depth of 60 cm. Positive relationships between soil silt + clay and both SOC and total N were observed. Between 76 and 87%, of the total (0–60 cm) C sequestration potential was estimated to occur in the top 30 cm of the soil profile.

The physiochemical properties of soils were analyzed in pure and mixed Sal forests in Udayapur district of eastern Nepal (Paudel & Sah, 2003). In both forests, soil was sandy loam and acidic with pH range of 4.3–5.3. The quantity of humus, organic matter, N and K were higher (7.3%, 2.4%, 0.117%, 267.7 kg ha^{-1}, respectively) in pure than mixed forest.

The soil characteristics were documented in five landslide-damaged (1–58-year-old) sites and one undisturbed forest in moist tropical Sal forest ecosystem of Nepal Himalaya (Singh *et al.*, 2001). Concentrations of SOC, total N, total P, and K increased with the age of sites. In 58-year-old site, their concentrations were 75–89% of that in undisturbed sal forest.

3.2.2 Soil microbial biomass (MB)

Changhui *et al.* (2014) examined the effects of N and P on MB in grassland in Loess Plateau of northern China. During the whole growing seasons, P addition significantly stimulated microbial biomass carbon (MB-C) while there was no effect with N addition.

Soil MB was examined through quantifying microbial phospholipid fatty acids in arid and semi-arid grassland ecosystems in northern China (Hu *et al.,* 2014). Soil variables mainly SOC was the main positive predictor of MB.

Xu *et al.* (2013) estimated C, N and P and soil MB at global levels using 3422 data points. The fractions of soil C, N and P in soil MB were 1.2, 2.6 and 8.0%, respectively. The C:N:P ratios for soil and soil microbial biomass were 287:17:1 and 42:6:1, respectively, at global scale.

Turner *et al.* (2013) studied P budget for the temperate rainforest chronosequence at New Zealand. Soil microbes contained 68–78% of the total biomass P (i.e. plant plus microbial) which showed that soil microbes were the major biological P pool during ecosystem development.

The effects of different land uses (natural forest, park, agriculture, street green and roadside trees) on soil MB in Beijing, China was studied by Zhao *et al.* (2013). They found that MB depleted in four types of land use compared to natural forest. There were significant correlations between the microbial characteristics and soil physicochemical properties like organic matter, total N and total P, suggesting that lack of nutrients was the major reason for the decrease in MB.

Wang *et al.* (2012) reviewed the effects of fire on MB and total N in soil. Overall, fire significantly increased the soil total N and MB-N, but decreased SOC and MB-C. In general, the effects of fire on SOC, MB-C and total N decreased with increasing soil depth.

Microbial biomass properties and their relation with soil properties were studied among seven different tropical soils of Jharkhand, India (Kujur & Patel, 2012). Across the sites, the MB-C, MB-N and MB-P were positively correlated with SOC. The proportion of SOC contained in the MB ranged from 2.6 to 3.9%. Soil nutrients and microbial C, N and P decreased in disturbed soils.

Griffiths *et al.* (2012) studied MB properties under unbalanced nutrient supply (annual applications of 0, 15 and 30 kg P ha^{-1} with constant N and potassium). Soil and biomass C, N, and P increased with increasing P fertilizer. There was a significant, positive, correlation between MB-P and MB-C.

A study was made to assess changes in MB and its activity in fallow and pasture soils after forest clearing in eastern Brazilian Amazonia by Melo *et al.* (2012). Once fallow began, soil MB and its activity showed little change. In contrast, MB decreased markedly after pasture establishment and continued to decrease with pasture age. They confirmed that MB is a sensitive indicator of soil disturbance caused by land-use change.

Responses of soil MB to P addition in three tropical forests (one old-growth forest and two disturbed forests) in southern China was studied (Liu *et al.*, 2012). Addition of P significantly increased the MB in the old-growth forest, suggesting that P availability is one of the limiting factors for microbial growth. In contrast, P addition had no significant effect on the MB and the microbial community composition in the disturbed forests.

Microbial population was analyzed in natural tropical forest soil, deforested soil and deforested-and-cultivated soil of Orissa, India (Mohanty & Panda, 2011). This study revealed that conversion of natural forest lead to a reduction of soil microbes and rate of soil respiration.

Cusack *et al.* (2011) studied links between microbial responses to N deposition and shifts in SOM in two tropical forests. Microbial biomass increased in response to N fertilization in both forests and corresponded to declines in SOM.

Yang *et al.* (2010) estimated MB-C, MB-N, SOC and total N in two soil depths (0–15 and 15–30 cm) in northeast China. Both MB-C and MB-N declined significantly with increasing soil depth. Moreover, the values of MB-C, MB-C/SOC, and MB-N/TN peaked in summer.

Singh *et al.* (2010) studied variations in MB in natural forest, mixed deciduous forest, disturbed savanna and grassland ecosystems in dry tropical soils of Vindhyan Plateau, India. The mean annual MB-C, MB-N and MB-P at 0–15 cm soil depth varied from 312.05 ± 4.22 to 653.40 ± 3.17, 32.16 ± 6.25 to 75.66 ±7.21 and 18.94 ± 2.94 to 30.83±23.08 μg g^{-1}, respectively. At all the sites, the maximum microbial biomass occurred during the summer season and minimum in rainy. The MB-C, MB-N and MB-P were positively correlated with SOC, but negatively correlated with soil moisture.

Jin *et al.* (2010) studied the effect of litter inputs on soil microbial community in semiarid grassland ecosystem. Litter addition significantly enriched MB-C and MB-N. They concluded that both quality and quantity of belowground litter affects microbial community.

The effects of alternate land uses, such as forest, grassland, cropland and mine spoil on MB-N in dry tropical forest soils of India were studied (Tripathi & Singh, 2009). The mean annual MB-N ranged from 41.25 to 58.87, 34.47 to 47.95, 27.88 to 30.43 and 22.95 to 25.26 µg g^{-1}, respectively.

Singh *et al.* (2009) investigated MB-N in soils of four different vegetation systems including forest (Sal), mixed forest, savanna and cropland ecosystems in the Vindhyan region, India. The MB-N varied from 21.3 to 90.2 µg g^{-1} dry soil, with minimum values in the wet and maximum values in the dry season. Cultivation reduced the MB-N by 63.5%.

The effect of disturbance on soil MB was studied in a tropical rainforest of India (Barbhuiya *et al.*, 2008). With the disturbance, the MB decreased significantly. Microbial biomass C, N, and P ranged between 226-1060, 27-92 and 15-52 µg g^{-1}, respectively in undisturbed and highly disturbed forest stands. Microbial biomass was maximum during winter and minimum during rainy season. There were significant positive correlations among microbial biomass C, N and P, and SOC, total N and P concentrations.

Ruan *et al.* (2004) examined the influence of plant litterfall on annual variation of soil MB in control and litter-excluded plots in a tropical wet forest of Puerto Rico. Aboveground plant litter input had no effect on soil MB. Soil microbial biomass did not correlate with soil temperature, moisture, or rainfall.

Salamanca *et al.* (2002) investigated soil MB in A-horizon soils of six tropical secondary forests of Philippines. The six sites revealed strong differences in SOM and MB. The average ratio of MB-C-to-SOC was 2.8%, exceeding that of MB-N-to-total N of 2.0%.

Singh *et al.* (2001) documented the microbial activities in five landslide-damaged (1–58-year-old) sites and one nearby mature Sal forest as control site in the moist tropical forest ecosystem of Nepal Himalaya. Soil microbial biomass (C, N and P) decreased due to effect of landslide disturbance by 79‒80% in 1 year old site which increased with the age of sites and at 58 year old site it recovered up to 82‒85% in comparison to mature Sal forest. Soil microbial biomass C and N as fraction of SOC and total N increased with age to the maximum values (2.8 and 2.6, respectively) in the 40 year old site, indicating the reestablishment of active fraction of SOM. The soil MB showed seasonal variations at all sites. The restoration of soil MB-C and MB-N was faster than SOC and total N.

3.3 MATERIALS AND METHODS

3.3.1 Soil sampling and analysis

Central part of the forest was treated as undisturbed forest (UF), and ii) peripheral part as disturbed forest (DF). Soil samples were collected from 35 randomly selected sampling plots each in UF and DF as designed for vegetation analysis. The size and number of quadrats were determined following Kershaw (1973) and Misra (1968). At each plot, the soil was collected from three pits (10x10x30 cm^3 each, divided into two depths: upper, 0–15 and lower, 15–30 cm). For each depth, the soils of three pits were mixed and pooled as one replicate. Physicochemical properties were determined for both upper and lower depth soil samples for summer season, whereas microbial biomass was estimated only for the upper depth from the soil samples collected in May, July and January (2011–2012), representing the summer, rainy and winter season, respectively.

Air dried soil samples were sieved through a 2 mm mesh screen and used for further analysis. Texture, moisture, pH and water holding capacity (WHC) were determined following Piper (1966). Bulk density was determined by metallic tube method and SOC by dichromate oxidation method of Kalembasa and Jenkinson (1973). Total N was determined by micro-Kjeldhal method and total phosphorus (P) by ammonium molybdate-stannous chloride blue color method (Jackson, 1958). Potassium was estimated by atomic absorption spectrophotometer. Carbon stock in soil was calculated by multiplying C concentration with bulk density of the soil for both depths.

3.3.2 Determination of soil microbial biomass (C, N and P)

Microbial biomass was estimated from the soil samples of 0–15 cm depth collected in May, July and January (2011–2012), representing the summer, rainy and winter season, respectively. Soil samples were sieved through a 2 mm mesh screen and were preconditioned for 7 days at room temperature. For pre-conditioning, the samples taken in open polythene bags were kept in a large air-tight container in which two small beakers, one containing 20 ml distilled water to maintain 100% relative humidity and the other containing 20 ml KOH solution to absorb CO_2, were kept. The container was opened for few minutes every day for aeration.

Soil microbial biomass C, N and P were estimated by chloroform fumigation extraction method (Brooks *et al.*, 1985; Vance *et al.*, 1987b). Pre-conditioned soil samples (25 g) were saturated with purified liquid $CHCl_3$ for 20 h (Singh & Singh, 1993). After 20 h the $CHCl_3$ was removed by evacuation and the soil was extracted with 0.5M K_2SO_4 (1**:**4, soil**:** extractant) for 30 minutes. This represented the fumigated sample. Another set of unfumigated soil samples were also extracted with 0.5M K_2SO_4. Biomass C and N were estimated from these fumigated and unfumigated soil extracts.

For the estimation of biomass P, soil sample was saturated with purified liquid $CHCl_3$ separately and soil sample was extracted with 0.5M $NaHCO_3$ for 30 min. Unfumigated soil samples were also extracted with 0.5M $NaHCO_3$ (1**:**20, soil**:** extractant).

Soil microbial biomass C was determined in the soil extracts of fumigated and unfumigated samples by dichromate oxidation in a reflux system and titration with ferrous ammonium sulphate. Soil microbial biomass C (MB-C) was then estimated from the equation: MB-C = 2.64 EC (Vance *et al.*, 1987 b) where EC is the difference between C estimated from fumigated and unfumigated soils, both expressed as µg C g^{-1} oven dry soil.

Soil microbial biomass N (MB-N) was determined in the same soil extracts of fumigated and unfumigated samples using kjeldahl digestion method (Brookes *et al.*, 1985). The MB-N value obtained for the unfumigated soil extract was subtracted from the value obtained from that of fumigated soil extract. The difference in value of total N thus estimated was divided by a K_N value of 0.54 (Brookes *et al.*, 1985), assuming that 54% of the biomass N was extracted in K_2SO_4 by $CHCl_3$ treatment.

Soil microbial biomass P (MB-P) was estimated in the $NaHCO_3$ extracts of fumigated and unfumigated soils by ammonium molybdate-stannous chloride method (Sparling *et al.*, 1985). Biomass P was calculated by dividing the value obtained as inorganic P by a K_P value of 0.4 ($NaHCO_3$ inorganic P in fumigated subtracted from that of unfumigated), assuming that 40% of P in the soil microbial biomass is released as inorganic P by $CHCl_3$ (Brookes *et al.*, 1982). A correction was made for P fixation during the $NaHCO_3$ extraction by measuring the recovery of exogenously added inorganic P as KH_2PO_4 (equivalent to 20 µg P g^{-1} soil) as suggested by Brookes *et al.* (1982).

Statistical analyses were done with MS excel 2007 and SPSS (IBM Statistics, ver. 20) packages. Before analysis, all data were tested for outliers, and normality (Shapiro–Wilk test).

3.4 RESULTS

3.4.1 Soil physicochemical characteristics

Environmental variables like soil texture, moisture, SOC, total N and others were studied from upper and lower depth in undisturbed and disturbed forest stands of moist tropical forest in eastern Nepal (Table 1).

The soil was blackish brown in colour and slightly acidic in nature with loamy texture in both forest stands. Sand content increased while silt and clay decreased depth-wise (Table 1). Bulk density and soil pH were minimum in the upper layer which increased depth-wise. Water holding capacity (WHC) was significantly higher (47% in UF and 40.4% in DF) in the upper layer which decreased depth wise (Tables 1 & 2). The moisture content of the soil in the upper layer was 25.6% in UF and 17.8% in DF, which significantly decreased with increasing depth (Tables 1 & 2).

Table 1. Soil variables in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal (mean ± SE) (n = 35).

Variables with unit	Undisturbed forest (cm)		Disturbed forest (cm)	
	0–15	15–30	0–15	15–30
Sand (%)	45.0 ± 0.6	51.2 ± 0.6	49.8 ± 0.6	51.0 ± 0.7
Silt (%)	37.9 ± 0.7	32.9 ± 0.6	36.4 ± 0.7	37.6 ± 0.6
Clay (%)	17.1 ± 0.8	15.9 ± 0.8	13.8 ± 0.5	11.4 ± 0.4
Soil moisture (%)	25.6 ± 0.3	23.9 ± 0.3	17.8 ± 0.4	16.8 ± 0.3
Water holding capacity (%)	47.0 ± 0.8	39.0 ± 1.0	40.4 ± 0.7	37.2 ± 0.9
Bulk density (g cm^{-3})	1.28 ± 0.1	1.45 ± 0	1.34 ± 0	1.48 ± 0
Soil pH (1: 2.5 w/v H_2O)	5.6 ± 0.1	5.8 ± 0.1	6.1 ± 0.1	6.3 ± 0.1
Soil organic carbon (%)	3.07 ± 0.1	1.34 ± 0.1	1.8 ± 0.1	1.04 ± 0.1
Carbon stock in soil (Mg C ha^{-1} soil)	58.9 ± 2.64	29.2 ± 2.07	36.2 ± 2.01	23.1 ± 1.60
Total nitrogen (%)	0.24 ± .01	0.12 ± 0	0.14 ± 0	0.08 ± 0
Total phosphorus (µg g^{-1})	626.6 ± 0.3	621.6 ± 0.4	618.3 ± 0.6	613.5 ± 0.2
C:N ratio	12.8	11.2	12.8	13.0
C:N:P ratio	50:4:1	–	29:2:1	–
Exchangeable potassium (µg g^{-1})	346.3 ± 4.0	291.3 ± 2.2	268.1 ± 1.7	245.8 ± 2.0
Soil organic matter (%)	5.3 ± 0.3	2.3 ± 0.1	3.1 ± 0.1	1.8 ± 0.1

Soil organic C, C stock in soil, total N, potassium, and phosphorus decreased depth wise in both forest stands. Soil organic C was 3.07% in upper depth of UF while it decreased to 1.8% for same depth in DF. Same was the trend for total soil N. The total C stock in the soil (0–30 cm depth) was fairly higher (88.1 Mg C ha^{-1}) in UF than DF (59.3 Mg C ha^{-1}). Moreover, 61–67% carbon stock was estimated in upper soil depth in both forest stands. The soil organic matter was higher (5.3%) in the upper layer of UF and lower (3.1%) in DF.

The effects of forest stands and soil depths on soil variables are given in Table 2. Soil moisture, WHC, SOC, total N, total P and potassium were significantly higher in UF than in DF. Moreover, they were also significantly higher in upper soil depth (0-15 cm) as compared to lower depth (15-30 cm). Soil organic carbon showed positive relationship with total N in both depths and forest types (Figure 6; Tables 5 & 6).

Table 2. F values of the effects of forest type (FT) and soil depth (SD) on sand, silt, clay, soil moisture, water holding capacity (WHC), bulk density (BD), pH, soil organic carbon (SOC), total nitrogen (TotN), total phosphorus (TotP) and exchangeable potassium (Pot) as obtained by analysis of variance.

Factors	Sand	Silt	Clay	Soil moisture	WHC	BD	pH	SOC	TotN	TotP	Pot
FT	14.01***	6.13**	34.67***	641.24***	23.58***	23.17***	51.61***	66.70***	127.05***	383.45***	547.76***
SD	35.56***	8.20**	7.06**	23.26***	42.21***	286.49***	7.08**	183.87***	181.68***	136.31***	213.90***
FT × SD	16.55***	22.25***	0.84^{NS}	1.33 ^{NS}	7.87**	4.08**	0.61^{NS}	24.03***	25.13***	0.09^{NS}	38.41***

Significance level: NS not significant, P > 0.05; * P < 0.05; ** P < 0.01; *** P < 0.001

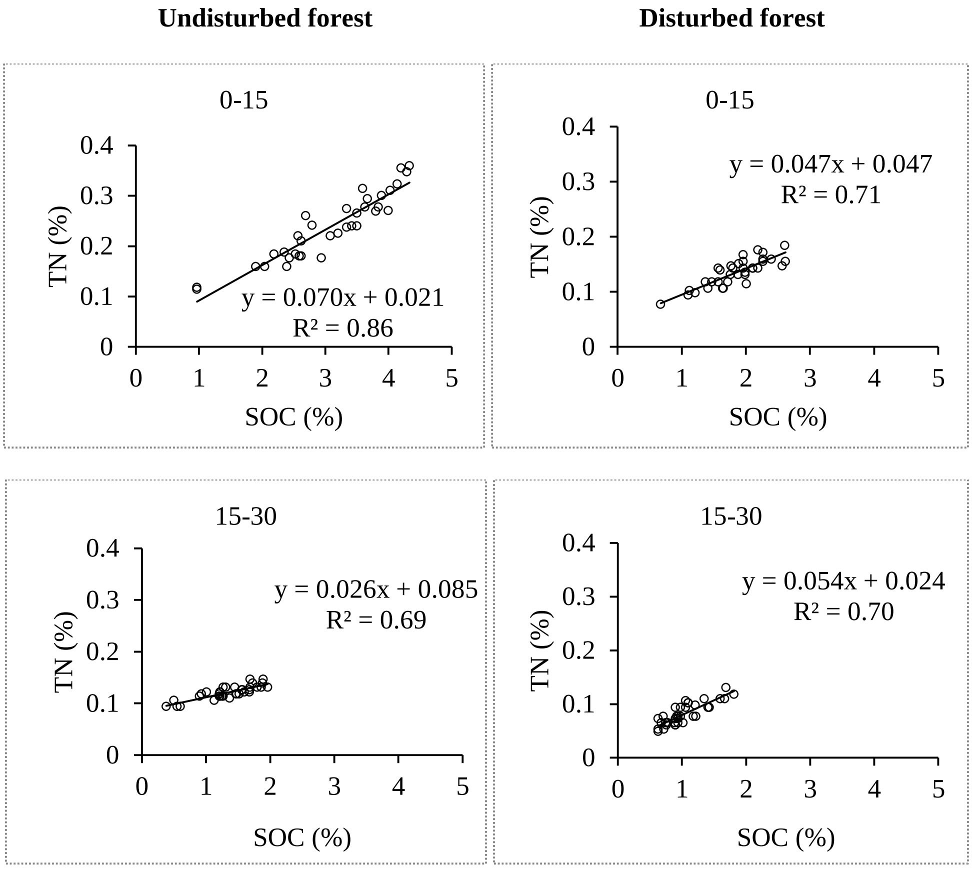

Figure 6. Relationships between soil organic carbon (SOC) and total nitrogen (TN) ($P < 0.05$) in 0–15 and 15–30 cm soil depths in undisturbed forest (UF) and disturbed forest (DF) of moist tropical forest in Sunsari district, eastern Nepal.

3.4.2 Spatial and seasonal variation in soil microbial biomass

Soil microbial biomass C, N, and P values were significantly higher in UF as compared to DF (Tables 3 & 4). They decreased by about 21% from UF to DF. The microbial biomass C:N:P ratio was surprisingly same (45:4:1) in both the forest stands. The C:N, C:P and N:P ratios were 11, 46, and 4.2, respectively in UF while they were 11, 45.1, and 4.1, respectively in DF.

Table 3. F values of the effects of forest type (FT) and season on microbial biomass carbon (MB-C), nitrogen (MB-N) and phosphorus (MB-P) as obtained by analysis of variance.

Factors	MB-C	MB-N	MB-P
FT	178.37**	158.93**	104.04**
Season	178.5**	72.96**	142.93**
FT × Season	7.47**	4.42*	14.62**

Significance level: * $P < 0.01$; ** $P < 0.001$

Table 4. Soil microbial biomass carbon (C), nitrogen (N) and phosphorus (P) with their ratios in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal (mean ± SE).

Forest type	Season	Microbial biomass (µg g^{-1})			C:N	C:P	N:P
		C	N	P			
Undisturbed	Summer	676.6 ± 8.7	59.0 ± 1.5	16.1 ± 2.9	11.5	42.0	3.7
	Rainy	432.7 ± 7.8	43.4 ± 1.0	9.2 ± 1.8	10.0	47.0	4.7
	Winter	565.9 ± 8.5	49.8 ± 0.8	11.6 ± 1.0	11.4	48.8	4.3
	Mean	**558.4 ± 7.6**	**50.7 ± 1.1**	**12.3 ± 0.2**	**11.0**	**45.9**	**4.2**
Disturbed	Summer	533.3 ± 17.5	45.2 ± 1.0	11.6 ± 1.9	11.8	46.0	3.9
	Rainy	361.8 ± 11.7	35.8 ± 1.0	8.1 ± 1.4	10.1	44.7	4.4
	Winter	420.2 ± 8.7	38.7 ± 0.7	9.4 ± 1.6	10.9	44.7	4.1
	Mean	**438.5 ± 11.8**	**39.9 ± 0.8**	**9.7 ± 0.2**	**11.0**	**45.1**	**4.1**

The microbial C:N, C:P, and N:P ratio was almost similar in the soils of both undisturbed and disturbed forest stands. The microbial biomass C, N, and P contributed 1.8, 2.1, and 2.0% to total soil organic C, total N, and P in UF and 2.4, 2.9, and 1.6% in DF (Table 5).

Table 5. Soil microbial biomass C, N and P as percentages of soil organic C, total N and total P respectively in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Forest type	Microbial biomass as % of		
	Organic C	Total N	Total P
Undisturbed	1.8	2.1	2.0
Disturbed	2.4	2.9	1.6

Statistically significant ($P < 0.001$) seasonality was observed in the distribution of microbial biomass in both forest stands (Table 3). Microbial biomass C, N, and P were maximum in rainy season, followed by winter, and minimum in summer season in both stands (Table 4). Microbial biomass C, N, and P declined from rainy to summer season by 36, 26 and 43% respectively in UF and by 32, 21, and 30% respectively in DF. It indicates that the trend of seasonality was almost same in both forest stands.

3.4.3 Relationship between the microbial biomass and soil properties

Both soil organic C and total N showed positive significant correlations ($P < 0.01$) with MB-C and MB-N in both the forest stands (Tables 6 & 7; Figures 7 & 8). Total P exhibited significant positive relationships with MB-C ($P < 0.05$) and MB-P ($P < 0.01$) in UF, whereas it showed positive correlation only with MB-P in DF ($P < 0.01$). Moreover, MB-C showed significant positive correlation with MB-N in both forest stands ($P < 0.01$). Potassium showed both negative, and positive but non-significant correlations with microbial biomass. Relatively weak positive relationships were observed between soil pH and microbial biomass in both forest stands except MB-P in UF (Tables 6 & 7).

Table 6. Correlation between soil microbial biomass and other soil chemical properties (0–15 cm depth) in undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

	pH	SOC	TN	TP	K	MB-C	MB-N
SOC	.257						
TN	.419*	.930**					
P	-.017	.390*	.294				
K	-.191	-.258	-.220	-.039			
MB-C	.332	.894**	.911**	.348*	-.139		
MB-N	.487**	.762**	.899**	.236	-.089	.884**	
MB-P	-.108	.201	.121	.720**	.048	.133	.044

. Correlation is significant at the 0.01 level (2-tailed) and *** at the 0.05 level (2-tailed).

Table 7. Correlation between soil microbial biomass and other soil chemical properties (0–15 cm depth) in disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

	pH	SOC	TN	TP	K	MB-C	MB-N
SOC	.154						
TN	.225	.843**					
P	-.006	.044	.012				
K	.422*	.006	.173	.194			
MB-C	.253	.857**	.788**	.037	.129		
MB-N	.334	.839**	.896**	.013	.225	.879**	
MB-P	.025	-.107	-.156	.842**	.170	.000	-.084

**. Correlation is significant at the 0.01 level (2-tailed) and * at the 0.05 level (2-tailed).

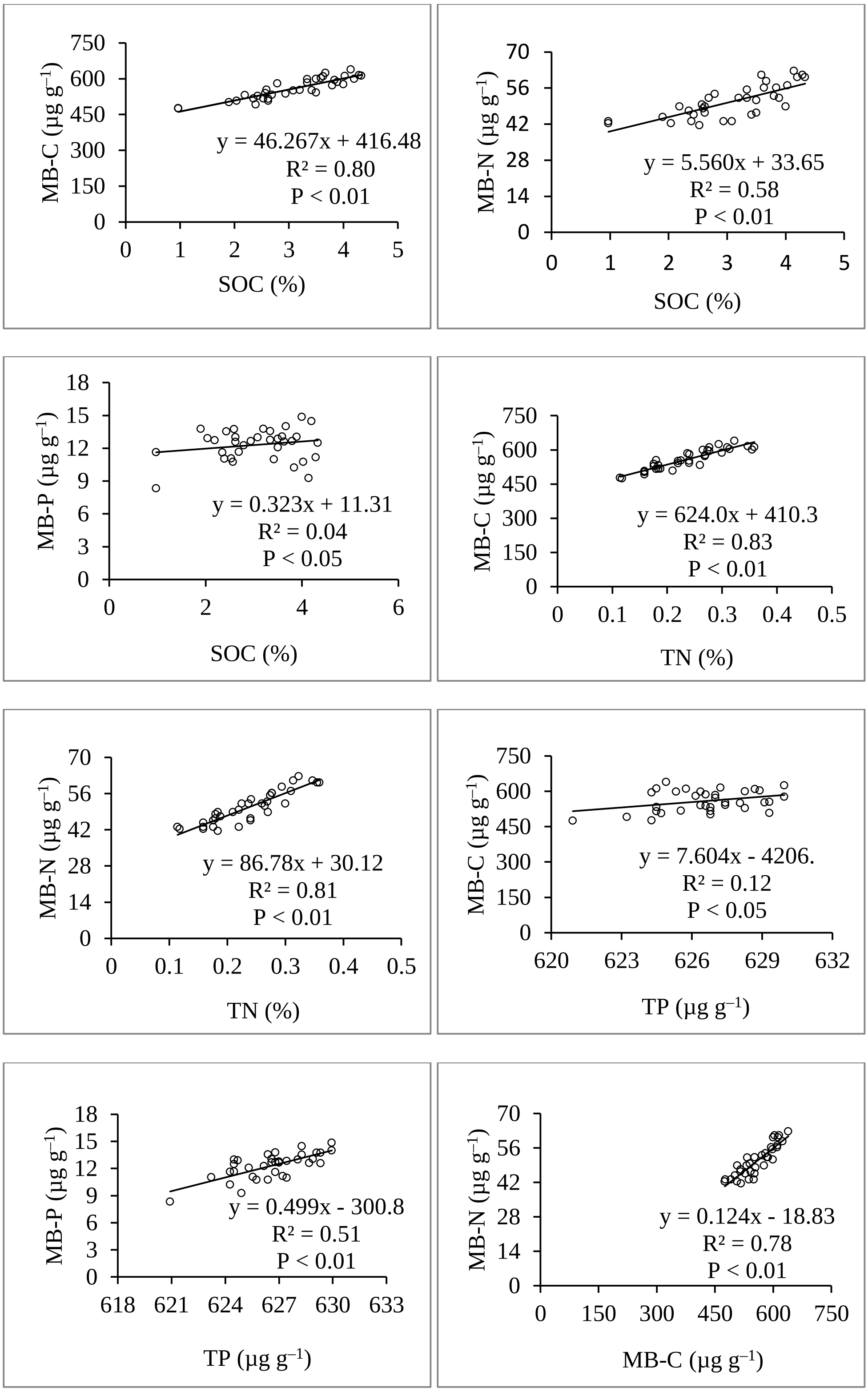

Figure 7. Relationships between soil properties (SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus) and soil microbial biomass (MB-C: carbon; MB-N: nitrogen; MB-P: phosphorus) ($P < 0.05$) in 0–15 cm soil depth of undisturbed stand of moist tropical forest in Sunsari district, eastern Nepal.

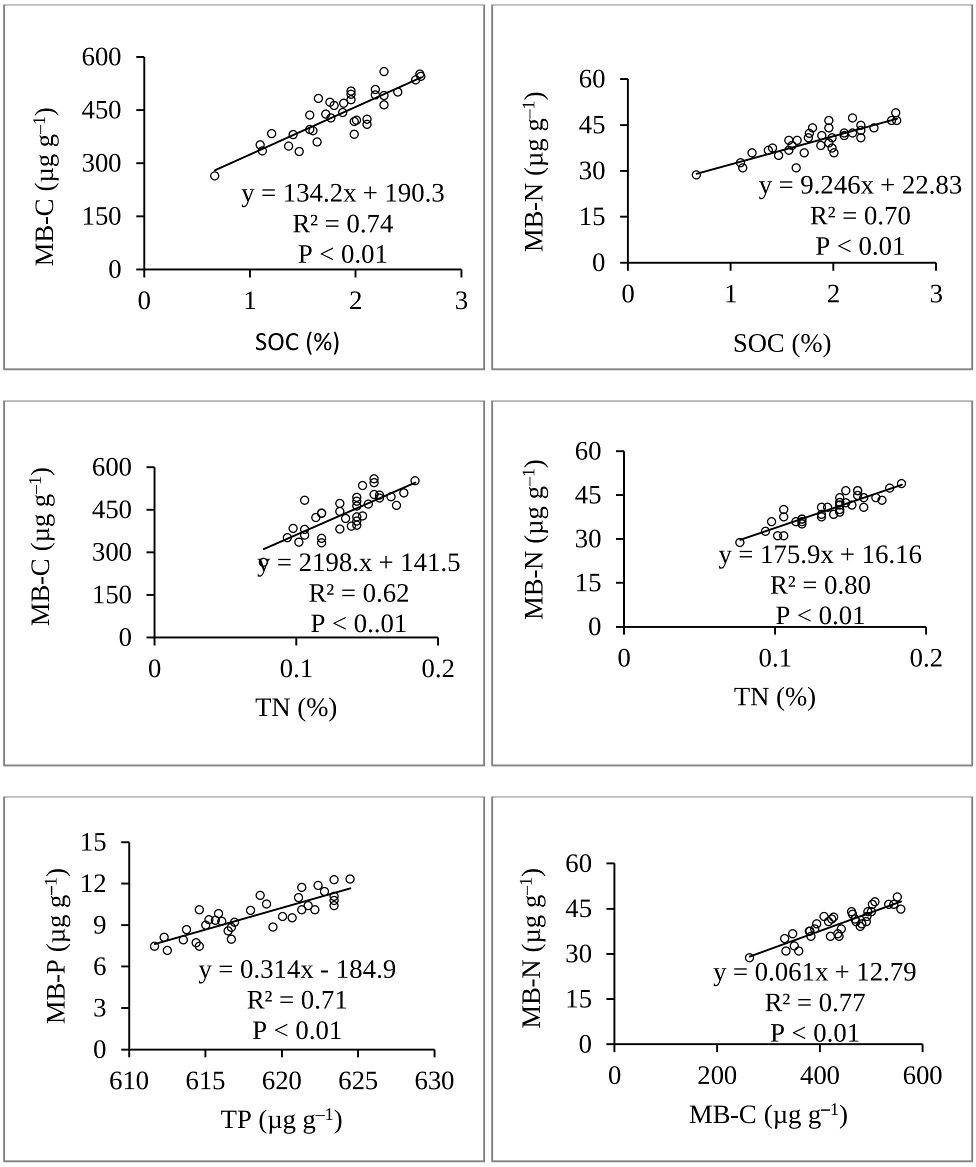

Figure 8. Relationships between soil properties (SOC: soil organic carbon; TN: total nitrogen; TP: total phosphorus) and soil microbial biomass (MB-C: carbon; MB-N: nitrogen; MB-P: phosphorus) ($P < 0.05$) in 0–15 cm soil depth of disturbed stand of moist tropical forest in Sunsari district, eastern Nepal.

3.5 DISCUSSION

3.5.1 Soil physicochemical characteristics

Soil texture plays an important role in the vegetation development and nutrient cycling because of its main role in supply of air, water and nutrients required for root development. Soil texture in the study area was loamy type which has been considered suitable for good Sal growth and high quality trees. There is no great variation in bulk density of soil in UF and DF. In the present case the disturbance is of moderate scale. Moderate disturbance destroys the forest structure but the soil is not so degraded (Jordan, 1985).

Soil pH affects a wide range of soil chemical and biological properties (Brady & Weil, 2013). The pH value in the present study (5.6‒6.3) was similar as reported by Sigdel (1994) for Royal Chitwan National Park (5.90‒6.42). Acidification of forest soil might be due to the formation of weak organic acid by dissolving the carbon dioxide in soil water which is produced during root respiration and decomposition of soil organic matter by micro-organisms.

The upper layer of the soil showed more acidic nature which may be due to the formation of organic acids from the higher amount of partially decomposed organic matter on the forest floor. The lower pH value in the soil of UF than that of DF may be due to the higher nitrification of NH_4^+ and subsequent production of H^+ ions which increase the soil acidity. Moreover, relatively higher soil pH along the soil depth may be due to the decreasing trend of soil organic matter, and leaching of alkaline cations (such as Ca, Na, K, Mg) from upper to lower layer.

Soil organic C is the main terrestrial C pool which increases the ion exchange capacity, WHC and availability of nutrients. The chemical characteristics of soil differed markedly with the increasing depths. The higher value of organic matter on the surface layer is due to greater inputs of organic matter through the above ground litter which may decompose at higher rate. Higher rate of litter decomposition may be due to microbial activities releasing more C in upper layers of soil. It is also evident from the high level of soil microbial biomass C in the upper soil depth. The lesser SOC in DF indicated that the forest area was severely affected by degradation due to various need-based forestry practices and anthropogenic disturbances.

The total N, total P, and K were higher in UF as compared to DF. Moreover, they decreased with increasing soil depth in both forest stands. Similar results were also reported by Barbhuiya *et al.* (2008) in tropical rainforest of Assam, India. The higher total N in UF may be due to the higher number of legumes which fix atmospheric nitrogen in root nodule. Further, their N rich leaf litter and dead fine roots are also the source of N in the soil. Total P in the soils of both forest stands (613–626.6 $\mu g\ g^{-1}$)

was comparable with the values (557 µg g^{-1}) reported in forest soils by Achat *et al.* (2009).

3.5.2 Spatial variation in microbial biomass

In the present study, soil microbial biomass decreased with forest disturbances. Similar trend of microbial biomass was observed by Mohanty and Panda (2011) in tropical forest of Orissa, India; and in a tropical rainforest of Northeastern India (Barbhuiya *et al.*, 2008). Soil microbial biomass and its activities may be dependent on the quality, quantity and turnover of decomposing organic matter present in the forest floor.

Relatively dense vegetation, greater accumulation of litter, higher fine root necromass, and higher amount of soil nutrients in UF of the present forest favored the growth of micro-organisms and accumulation of more C, N, and P in them. It is also evident from the positive correlations of microbial biomass with soil nutrients and soil organic C (Figures 7 & 8). Previous workers argued that the soil microbial biomass depends on soil organic matter and nutrient availability of soil (Changhui *et al.*, 2014).

On the other hand, several activities like logging, lopping, litter removal, forest fire, and grazing might have lowered the organic matter in the soil of DF, which decreased the soil moisture leading to lower value of microbial biomass. Wang *et al.* (2012) studied the effect of fire on microbial biomass and found that the fire decreased soil organic C and microbial biomass C. In the present study, microbial biomass C, N, and P decreased with soil depth as were also reported by past workers (Yang *et al.*, 2010; Xu *et al.*, 2013).

Soil MB-C (558.4 µg g^{-1}) in the undisturbed forest stand of present study was comparable with the MB-C (778 µg g^{-1} soil) reported by Mandal (1999) for moist tropical Sal forest of Nepal, and 312-653 µg g^{-1} in dry tropical soils of Vindhyan Plateau, India (Singh *et al.*, 2010). However, MB-C in the present forest stand was considerably lower than in temperate forest soils (400 to 2000 µg g^{-1} soil) (Vance *et al.*, 1987 a). The MB-N and MB-P value of UF is slightly lower than the value (32.2 to 75.7 and 18.9 to 30.8 µg g^{-1}, respectively) for dry tropical soils of Vindhyan Plateau, India (Singh *et al.*, 2010).

The microbial C:N:P ratio of present study was higher than the ratio reported for grassland (15:2:1) and agro ecosystem (14:2:1) in subtropical systems of India (Singh & Yadava, 2006). Relatively higher proportion of C in the studied forest as compared to other systems may be due to the addition of higher amount from below-ground as well as from above-ground fractions of the biomass. The C:N ratio of 11 in the both stands of the studied forest is the indication of fungal dominance in microbial population of soil.

The values obtained for microbial biomass (C and N) as percentage of SOC and total N in the present study (Table 3) is comparable with the values (2.8 and 2.0%, respectively) reported by Salamanca *et al.* (2002) for tropical forest of Philippines. Moreover, Xu *et al.* (2013) analyzed the 3422 global data and found that the fractions of soil C, N and P in soil microbial biomass were 1.2, 2.6 and 8.0%, respectively. The contribution of microbial biomass C and N to soil organic C and total N was higher in DF. It indicates that the microorganisms accumulate and immobilize more soil nutrient like N in nutrient deficient soil as in DF. In the present study, the proportion of microbial P to total P is higher in UF. These results imply that the microorganisms are more sensitive to C and N as compared to P along the disturbance regime. Nearly same microbial C:N, C:P, and N:P ratio between the soils of both studied forest stands may be due to the identical microbial biomass turnover and mineralization of organic matter. The microbial C:N:P ratios of present study (45:4:1) was almost same with the ratios of 42:6:1 for global levels (Xu *et al.*, 2013).

3.5.3 Seasonal variation in microbial biomass

Seasonality had significant effect on the microbial biomass C, N, and P ($P < 0.001$). It was maximum in summer season and minimum in rainy season in both forest stands. During the summer season microbial biomass accumulates in the soil when plant growth and nutrient demand are minimum. Microbial biomass conserves and immobilizes the nutrients in biologically active forms during the dry period, when the plant demand is low but the decomposition of belowground plant residues is continuously adding nutrients.

On the other hand, soil microbial biomass exhibited lower values in the rainy season which may be due to fast turnover of microbes (Singh *et al.*, 1989), optimum utilization of nutrients by the plants when growth and development remains at the peak, and anaerobic environment of wet soil which allows the growth of only anaerobic microbes. Similar trend of seasonal variation in microbial biomass was observed by Mandal (1999) in moist tropical Sal forest of eastern Nepal, Singh *et al*. (2010) for dry tropical forest of Vindhyan Plateau India, and Yang *et al.* (2010) in China.

3.5.4 Relationship between the microbial biomass and soil properties

Relationship between soil chemical properties and soil microbial biomass was significant ($P < 0.01$) in both forest stands which indicate that soil microbial biomass is highly sensitive to soil organic C, total N, and total P. Such relationship was also reported by previous workers (Singh & Yadava, 2006; Zhao *et al.*, 2013) in different types of ecosystems. Hu *et al.* (2014) reported that soil variables mainly SOC was the main positive predictor of microbial biomass while Liu *et al.* (2012) opined that P availability is one of the limiting factors for microbial growth. Turner *et al.* (2013) found that soil microbes contained 68–78% of the total biomass phosphorus (i.e. plant plus microbial) and concluded that, soil microbes are the major biological P pool during long-term ecosystem development.

CHAPTER– 4

4. COMPOSITION AND STRUCTURE OF FOREST

4.1 INTRODUCTION

Forests play a major role in nutrient cycling and energy flux in terrestrial ecosystems. Currently, forests cover about 4 billion hectares area with an average net annual loss of 5.2 million hectares between 2000 and 2010 (FAO, 2010). Tropical forests that comprise 52% of total forests contain about two thirds of the plant species in the world. In Nepal, tropical forests are confined to the Terai and Siwaliks. Disturbances in forest ecosystems often lead to disruption of ecosystem structure and functioning reflected by changes in species composition, density, stand biomass and productivity.

Loss of biological diversity is the most important consequence of the degradation of tropical forests as it influences all ecological services and the livelihood of forest dwellers (Sagar & Singh, 2006). Diversity of tropical forests is being reduced due to natural and anthropogenic disturbances. At local level, the causes behind the forest disturbances include fire, floods, lopping, grazing, tree felling, firewood collection, invasion by non-indigenous species etc. Anthropogenic disturbances are the root cause of habitat fragmentation which leads to spatial and temporal variations in species richness, composition, and productivity at local and regional levels (Anbarashan & Parthasarathy, 2013). The consequences of deforestation and habitat loss often lead to extinction of tropical forest species (Wright & Muller-Landau, 2006).

In order to protect the tropical biodiversity, a better knowledge of human-modified landscapes and their relationships with species diversity and composition is needed (Galanes & Thomlinson, 2009). A lot of works have been done regarding the composition and structure of tropical forests, globally (Raghubansi & Tripathi, 2009; Pragasan & Parthasarathy, 2010; Rahman *et al.*, 2010; Chaturvedi *et al.*, 2012; Gunaga *et al.*, 2013), as well as in Nepal (Shrestha *et al.*, 2000; Gautam & Deove, 2006; Timilsina *et al.*, 2007; Panta *et al.*, 2008; Sapkota *et al.*, 2010; Rijal & Meilby, 2012).

It has been suggested that the best way to conserve species in tropical forests is to ensure that ecosystems continue to have the same structure and function (Walker, 1995). To maintain this, a basic knowledge of forest ecosystem is crucial. Therefore, present study is designed in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district of eastern Nepal with following specific objectives: 1) to analyze the species richness, family richness and their diversity; 2) to estimate the stand density, basal area and girth classes 3) to understand the dispersion pattern of plants and phenology of some dominant tree species; and 4) to assess the effect of disturbance on the diversity and population characteristics of herb, shrub and tree species.

4.2 LITERATURE REVIEW

4.2.1 Works done outside Nepal

Tilman *et al.* (2014) reviewed the literature regarding the biodiversity and ecosystem functioning and concluded that the species diversity is a major determinant of ecosystem productivity, stability, invasibility, and nutrient dynamics. They added that the diversity loss has an effect as great as, or greater than, the effects of herbivory, fire, drought, nitrogen addition, elevated CO_2, and other drivers of environmental change.

Nitrogen-tracer experiments were performed in a young tree plantation to know whether the species richness promotes the acquisition and retention of nitrogen (N) compared with the monocultures (Lang *et al.*, 2014). This study provided evidence that mixed afforestation promoted N retention. To improve ecosystem services, authors strongly suggested the use of mixtures of native tree species instead of monocultures.

Tree diversity of single-and mixed species-dominated tropical dry forests (TDF) on the Coromandel coast of India were analyzed and compared with other monodominant forests of the tropics (Anbarashan & Parthasarathy, 2013). Tree species richness ranged from 18 to 27 species ha^{-1} .Tree density ranged from 771 to 1285 trees ha^{-1}. The monodominant forests across the tropics revealed that a single tree species could account for 50 to 100% of stand density in Asian, 58 to 100% in African and 51 to 91% in neotropical forests. The monodominant tree species mostly belong to Caesalpiniaceae in Africa and neotropics, and Dipterocarpaceae and Lauraceae in Asia.

Tree diversity of community-protected Kaan forests and state-managed reserve forests influenced by the level of disturbance was assessed by transect method in Karnataka, India (Gunaga *et al.*, 2013). Kaan forests possessed higher species richness, basal area and tree density than the reserve forests. The total number of species was negatively correlated with the level of disturbance. Further, with increased disturbance, the number of endemic, rare, endangered and threatened species decreased.

Structure and composition of tree species were studied in a dry semi-deciduous forest in Afram plain, Ghana (Appiah, 2013). On an average, 21 trees ha^{-1} were recorded of which 17 had DBH ≤30 cm. Trees with DBH ≥70 cm were less than one tree ha^{-1} (mean 0.8 ha^{-1}). The values of Simpson and Shannon (4.52) diversity indices were 0.06 and 4.52, respectively.

Baithalu *et al.* (2013) re-studied twice (2002 and 2012) a 1-ha permanent plot established in 1992, in a tropical dry evergreen forest on the Coromandel Coast of peninsular India, The plot was subdivided into one-hundred 10 m x 10 m quadrats for systematic enumeration of all trees ≥10 cm DBH. Overall in twenty years, one species was added and the number of genera and families remained unchanged but there was a heavy reduction in stand basal area (by 33%) and density (by 57%), indicating heavy anthropogenic activities.

The effects of different intensities of disturbance on the species and functional diversity were evaluated in Bolivian tropical forests (Carreño-Rocabado *et al.*, 2012). A large-scale field experiment in which the dynamics of 15000 stems >10 cm in diameter was monitored for 8 years in 44 one-ha forest plots. Moderate levels of disturbance (logging) neither affected species diversity nor functional diversity after logging. However, disturbance increased the primary productivity, and nutrient and carbon cycling of fast-growing species.

Katovai *et al.* (2012) examined understory plant species and functional diversity in the degraded wet tropical forests of Solomon Islands from four forest land use types (two types of primary forest, secondary forest and abandoned tree plantations) and two common human-maintained land use types (coconut plantations and grazed pastures). Species richness declined with increasing elevation across all land use types. Functional diversity was similar between primary and secondary forests (high richness, high evenness and unaltered dispersion) and lowest in coconut plantations and grazed pastures.

Islam and Sato (2012) analyzed the causes of deforestation in Sal forests of Bangladesh on the basis of surveys, formal and informal discussions with local people, expert interviews and literature reviews. Their findings showed that illegal logging and forest land conversion were the ultimate causes of deforestation in Bangladesh.

Chaturvedi *et al.* (2012) investigated the effect of grazing and harvesting on diversity, mortality, recruitment and C accumulation of juvenile trees in a tropical dry forest (TDF) of Mirzapur district of Uttar Pradesh, India. Carbon density ranged from 271 to 966 kg ha^{-1} and C accumulation from 10 to 210 g cm^{-2} yr^{-1}. Species richness, C density and C accumulation were negatively related with annual mortality index and positively with annual recruitment index.

Zhang *et al.* (2011) analyzed species-environment associations in a 24 ha subtropical broadleaved forest in China. Their results showed that not only soil properties influence the distribution of tree species, but also tree species tend to affect properties of the soil around them. The soil factors most strongly influencing species distributions were total C, total N and total P, K, Mg, Si, soil moisture, and bulk density.

Nitrogen, phosphorus, and potassium addition experiment was performed for 11 years in a humid lowland tropical forest in Panama to evaluate nutrient limitation of tree growth rates (Wright *et al.*, 2011). The addition of K and N together was associated with significant increases in growth rates of saplings and poles (<10 cm DBH).

Plant–soil relationships were tested in 100 contiguous 25 m^2 plots located in a cerrado site, Brazil. All woody individuals and several soil features were measured (Dantas & Batalha, 2011). They found weak relationships between soil and floristic composition, richness, and total abundance.

Nirmal Kumar *et al.* (2011) examined structure, species composition, and soil properties of a TDF in Western India. The forest stands contained an average of 995 stems ha^{-1} (≥ 3.0 cm DBH). The total basal area was 46.35 m^2 ha^{-1}. The mean tree species diversity indices for the plots were 1.08 for Shannon diversity index (H'), 0.71

for equitability index (J') and 5.57 for species richness index (S'). Regression analysis showed that stem density was significantly correlated with soil pH. There was a significant positive relationship between species diversity index and soil available P and a negative relationship with N, C, C:N and C:P ratio.

Structure of tropical evergreen forests of Western Ghats, India was studied by quadrat method (Swamy *et al.*, 2010). The stand density ranged from 257 to 644 individuals ha^{-1} and basal area between 29 and 42 m^2 ha^{-1}. Shannon and Simpson's indices ranged from 1.5 to 3.7 and 0.1 to 0.16 respectively, and with beta diversity of 2.01.

Rahman *et al.* (2010) reviewed the present threats to tropical moist deciduous Sal forest ecosystem of central Bangladesh including destructive anthropogenic activities (harvest for construction works, fuel wood, timbers, tannins, pillars, and furniture making) as well as natural impacts, and rapidly expanding agriculture in the forest land. Moreover, expansions of commercial fuel-wood plantations were identified as the major threats. They recommended some points to conserve the Sal forest ecosystem. These were adoption of a sustainable forest management strategy, the requirement of further scientific research for better understanding of the Sal forest ecosystem, and involvement of all relevant stakeholders in the policy formulation process.

Mangan *et al.* (2010) carried out shade-house and field experiments to know the causes of tree-species abundance in tropical forests. They found that negative plant–soil feedback was an important mechanism that can maintain species diversity and explain patterns of tree-species relative abundance in tropical forests.

A large-scale, landscape-level vegetation study was conducted in six major tropical hill forests of southern Eastern Ghats, India (Pragasan & Parthasarathy, 2010). The southern Eastern Ghats was divided into smaller grids of 6.25 km×6.25 km, totaling to 120 grids. Within each grid, a belt transect of 0.5 ha (5 m×1000 m) area was laid and all trees ≥30 cm GBH were enumerated. A total of 272 tree species (≥30 cm GBH) that belonged to 181genera and 62 families were recorded in the total 60 ha area. Diversity indices such as Shannon, Simpson and Fisher's alpha indices were 2.44, 0.03 and 42.1, respectively, for the whole 60 ha area. The total stand density and basal area for the total 60 ha area were 27,412 stems (457 stems ha^{-1}) and 1012.12 m^2 (16.9 m^2 ha^{-1}), respectively. The stand density and basal area for the six sites ranged from 290 to 527 sems ha^{-1}, respectively.

Effect of disturbance, habitat fragmentation on plant diversity was documented for the dry deciduous forests of India's Vindhyan highlands (Raghubansi & Tripathi, 2009). Fragments of smaller size had lesser number of plant communities compared to larger fragments. Generally large size fragments were species rich and more diverse as compared to smaller fragments. The study indicated that species rich communities of the dry tropical forests are being reduced in area and becoming species poor and less diverse due to rapid deforestation and forest fragmentation.

Kobayashi (2007) discussed three methods for the biodiversity conservation through the rehabilitation of degraded tropical forests at the landscape level. They include (1) development of rehabilitation technology for biodiversity enhancement, (2) site management for the rehabilitation of degraded land and monoculture plantations, (3) involvement of local communities in rehabilitation technologies thereby increasing their socio-economic options.

The influence of the loss of tropical tree species on C storage was assessed by simulating 18 possible extinction scenarios within 50-hectare tropical forest plot in Panama (Bunker *et al.*, 2005). Among extinction scenarios, aboveground C stocks varied by more than 600%. These results indicated that future C storage in tropical forests will be influenced strongly by future species composition.

4.2.2 Works done in Nepal

Effects of human activities on density, diversity and regeneration in Sal (*Shorea robusta*) and mixed broadleaved forests in the central, lower mid-hills of Nepal was studied by Rijal and Meilby (2012). The results indicated significant human impact on the forest vegetation, both with respect to species diversity, density, distribution, and composition.

Sapkota *et al.* (2010) studied changes in tree species diversity and dominance across a disturbance gradient in five Nepalese Sal forests. Altogether, they reported 67 tree species; of which 41 were present in least disturbed and 10 species in heavily disturbed forest. Alpha diversity measures declined along a disturbance gradient while dominance increased. They concluded that diversity of Sal forests decline with increasing magnitude of disturbances, which favor a higher dominance of Sal. Moreover, the continuous removal of commonly used species leads to single species dominance in the forest.

How resource extraction by two Buffer Zone villages in Nepal's Bardia National Park affects forest structure and diversity was studied in 108 plots (Thapa & Chapman, 2010). Forest subjected to resource extraction had a lower density of trees, smaller DBH and lower species richness and diversity. Forest disturbance declined with distance from the villages.

Species composition and regeneration status of Sal and *Terminalia tomentosa* (Saj) in 4 buffer zone community forests of Bardia National Park in Nepal was investigated by Acharya *et al.* (2009). The results revealed that both Sal and Saj constituted a large proportion of species diversity but their regeneration from seedlings to establish stages were low.

Sapkota *et al.* (2009b) investigated the distribution, advanced regeneration and stand structure of five Sal dominated forests subjected to disturbances of different intensities. They found that moderately disturbed forests contained the highest advanced regeneration (sapling/pole densities). No significant difference was observed in stem basal area among forests. They concluded that moderate disturbance intensity not only ensures high stand density, but also enhances the advanced regeneration of tree species.

Sapkota and Meilby (2009) developed distance-independent diameter growth models for Sal in Kankali community forest, Chitwan, Nepal. Models were developed on the basis of growth ring counting and other supplementary data and were used to convert growth ring measurements into diameter increment at breast height. The mean diameter increment for Sal was 0.87 cm yr^{-1} ($n = 1514$).

Panta *et al.* (2008) analyzed forest degradation and deforestation trends in Chitwan district in Nepal. An artificial neural network was used to predict forest canopy density in five classes using Landsat images of the year 2001. Except riverine forest, area of all other forest types was reduced. Terai Sal forest, showed a loss of 23% between 1976 and 1989 and an overall loss of 15% forest cover between the year 1976 and 2001.

Environmental and anthropogenic factors determining the forest structure were studied in the four Sal forests of western Terai of Nepal (Timilsina *et al.,* 2007). The mean density across all plots was 220 trees ha^{-1} and average basal area 13.2 $m^2\,ha^{-1}$. Three different associations of Sal forest were identified by cluster analysis. Rainfall and past disturbances were chiefly responsible for Sal communities as none of the environmental variables (pH, organic matter, total N, available P and K, and soil texture) explained the structure of plots.

Gautam and Deove (2006) reviewed ecology and productivity plus anthropogenic niches of Sal forests and concluded that the information on edaphic factors, phenology and stand development processes (regeneration, growth characteristics, soil nutrient requirement, growth allocation, nutrient cycling, stand structure and successional stages) is important for designing scientific forest management of Sal forest; likewise, knowledge of anthropogenic factors associated with use of Sal forest is also required for effective implementation of the recently paradigmed management efforts. They also mentioned that Sal has ability to resprout aggressively from root suckers after short duration of disturbances.

Shrestha *et al.* (2000) analyzed the status and trends of species loss in degraded, natural and regenerating forests in the Siwalik region of central Nepal. Total number of species ranged from 10–39, density from 23–1326 plants ha^{-1}, total basal area from 11.4–59.6 m^{-2} ha^{-1}, litterfall (March to Dec) from 238–848 kg ha^{-1}, and tree biomass from 160–807 t ha^{-1}. All the values except plant density and herb biomass were higher in natural forest site. The degraded forest had lost 78.2% species, 90.9% plant density, 80.0% basal area, 71.7% tree volume and 80.1% tree biomass compared to natural forest.

Shrestha *et al.* (2000) analyzed the vegetation distribution in Shivpuri Watershed, Nepal and reported that *Alnus nepalensis* had highest frequency and Importance Value Index (IVI, 50.3), and *Schima wallichi* had the highest density among the trees.

Mandal (1999) studied the effects of landslides of varying ages on the vegetation pattern of Plateau Sal forest in Nepal Himalaya. Both species content and density of herb, shrub and tree species increased with the increasing age of landslides. Diversity parameters revealed that the Shannon-Wiener index, the species richness and equitability increased while concentration of dominance decreased with the age of successional communities. Indices of similarity for species composition showed 85.7% similarity in herb, 95.2% in shrub and 91.7% similarity in tree species composition with that of the mature Sal forest.

Dhungana (1997) analyzed the vegetation and natural regeneration status in two Sal dominated hill forests (natural plus community and plantation) in Kavrepalanchok, Nepal. In both sites, Sal occupied highest IVI ranging from 155 in natural and 234 in plantation forests.

4.3 MATERIALS AND METHODS

4.3.1 Sampling and vegetation analysis

Central part of the forest was treated as undisturbed forest (UF), and ii) peripheral part as disturbed forest (DF). Study was conducted in UF and DF while the buffer area between two forest stands was not considered for the study. For vegetation analysis the size and number of quadrats were determined following Kershaw (1973) and Misra (1968). Altogether, seventy permanent experimental plots, thirty five each in UF and DF were randomly established. In the present study stem of tree-species having ≥ 10 cm girth at breast height (GBH) were considered as trees (Lalfakawma, 2009). For the analysis of trees, sampling plot of 20 m x 20 m was used while for shrubs nested quadrat of 5 m x 5 m and for herbs nested quadrat of 1m x 1m was established in the forest. Plant species recorded in all plots were identified with the help standard literatures and herbarium specimens deposited at Tribhuvan University Regional Herbarium, Post Graduate Campus, Biratnagar, Nepal.

The height and GBH of stems of each individual were measured in all plots and they were grouped into three height classes (canopy trees ≥ 15 m, middle story trees 8-15 m and understory trees < 8 m), and twelve girth classes (A = 10‒60, B = 60‒110, C = 110‒160, D = 160‒210, E = 210‒260, F = 260‒310, G = 310‒360, H = 360‒410, I = 410‒460, J = 460‒510, K = 510‒560, L = 560‒610, and M > 610 cm).

Frequency, density and dominance of species within plots were determined. Dominance was expressed in terms of biomass in herbs and as basal area in woody species. The importance value index (IVI) of different species was calculated as the sum of its relative density, relative frequency and relative dominance. Inter-site comparisons of vegetation composition were made through Sorensen’s similarity index (ISs) as described by Mueller‒Dombois & Ellenberg (1974). Species diversity parameters like species richness (Margalef, 1958), Shannon-Wiener index (Shannon & Weaver, 1963), equitability (evenness) (Pielou, 1966) and Simpson index (Simpson, 1949) were determined.

The distribution pattern of species was calculated according to Curtis and Cottam (1956). According to them, the ratio of abundance to frequency below 0.025 indicates regular distribution, between 0.025 and 0.05 indicates random distribution and when exceeds 0.05, indicates contagious distribution.

4.3.2 Ordination and cluster analysis

Samples by tree species and samples by their soil environmental data from both undisturbed and disturbed forest stands were analyzed through ordination and cluster analysis methods. Order of plots created automatically after entering as sequence how these were sampled in the field.

4.3.2.1 Ordination

This study utilized detrended correspondence analysis (DCA) (Hill & Gauch Jr., 1980) technique to samples by species data matrix first for both undisturbed and disturbed forests data separately to explore the general pattern existing in the dataset. Ordination was done by an application of the *vegan* package (Oksanen *et al.*, 2015) under R (R Core Team, 2015). Environmental variables were fitted to samples by species biplot in order to observe where there were some relations existing among them. Species abundances from both undisturbed as well as disturbed forest plots showed strong tendencies towards unimodal relation along their main gradient (axis length value ≥ 2.5 in DCA). Thus, Canonical Correspondence Analysis (CCA) (ter Braak, 1986) was the right choice of ordination analysis for this dataset.

4.3.2.2 Cluster analysis

Clustering was done to maximize similarity within the group and dissimilarity between the groups. Species and samples were classified into different clusters based on abundances of each species among different sample plots. Thus, a hierarchial clustering method was applied since it does not allow predefined number of clusters. Plant species sample plots were clustered through an application of the package "*pvclust*" (Suzuki & Shimodaira, 2014) in R (R Core Team, 2015). This package accesses uncertainty among clusters with *p*-values via multi scale bootstrapping re-sampling method (Suzuki & Shimodaira, 2014). Two kinds of *p*-values: approximately unbiased (AU) and bootstrap probability (BP) within each cluster or edge number computed after 1000 times multi scale bootstrap re-sampling that presented with standard error value. Each edge or clusters with own p-values makes easy to distinguish cluster to each other. Higher the AU and BP values, i.e., ≥ 95%, better or significant are the cluster.

4.4 RESULTS

4.4.1 Herb layer

The species number of herbs increased with forest disturbance. Among the total 47 species, 26 species were present in both undisturbed and disturbed forests, while 30 species were enumerated from UF and 43 species from DF (Table 8). It showed 71% similarity in the vegetation of two stands. So, 29% dissimilarity in the vegetation occurred due to the effect of disturbance. The four species present only in UF were *Piper*, *Hygrophilla*, *Curculigo* and *Lygodium*. Both, undisturbed and disturbed forests were dominated by *Chromolaena odorata* with IVI of 76.3 and 63.8, respectively. Other dominant species in UF were *Oplismenus compositus* and *Piper longum*, while in DF *Paspalum scrobiculatum* and *Oplismenus compositus* occupied the second and third ranks, respectively with respect to IVI. Density of herbs increased with the forest disturbance (Table 8). The density values ranged between 20 and 38 shoot m^{-2} in UF and DF, respectively. Herbaceous diversity (Shannon-Weiner index) and species richness were lower (Table 16) at UF (2.84 and 9.65, respectively). These parameters increased with forest disturbance and reached to 3.2 and 11.52, respectively when the concentration of dominance was conversely minimum (0.05).

Table 8. Density (D; individual ha^{-1}), biomass (B; Mg ha^{-1}) and Importance Value Index (IVI) of herb species in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Scientific names	Undisturbed stand			Disturbed stand		
	D	B	IVI	D	B	IVI
Chromolaena odorata (L.) R.M.King & H.Rob.	2.26	0.72	76.34	1.60	0.64	63.81
Oplismenus compositus (L.) P.Beauv.	3.89	0.05	34.58	3.20	0.04	17.92
Piper longum L.	2.26	0.08	25.72	–	–	–
Commelina benghalensis L.	1.54	0.02	18.42	0.77	0.01	6.01
Hedychium ellipticum Buch.-Ham. ex Sm.	0.43	0.09	14.04	0.09	0.03	3.21
Chrysopogon aciculatus (Retz.) Trin.	1.46	0.02	11.8	1.66	0.02	8.41
Sonchus asper (L.) Hill	0.06	0.12	10.29	0.69	0.01	3.18
Sida rhombifolia L.	0.8	0.02	9.61	2.06	0.05	17.37
Senna tora (L.) Roxb.	0.26	0.05	8.91	0.06	0.002	0.74
Eclipta prostrata (L.) L.	1.03	0.01	7.59	0.03	0.001	0.54
Desmodium triflorum (L.) DC.	0.49	0.01	7.55	1.31	0.02	7.47
Kyllinga brevifolia Rottb.	0.83	0.001	7.13	0.86	0.01	4.45
Blumea lacera (Burm. f.) DC.	0.51	0.01	7.02	0.74	0.01	6.18
Paspalum scrobiculatum L.	0.63	0.02	6.54	3.46	0.06	19.35
Bidens bipinnata L.	0.09	0.05	5.73	0.43	0.01	3.95
Achyranthes aspera L.	0.40	0.02	5.65	0.26	0.01	4.12
Abutilon indicum (L.) Sweet	0.26	0.01	5.48	1.06	0.03	10.46
Hygrophila auriculata (Schumach.) Heine	0.37	0.004	5.10	–	–	–
Veronica javanica Bl.	0.34	0.002	4.87	0.63	0.01	5.89
Evolvulus nummularius (L.) L.	0.37	0.003	4.31	1.69	0.01	9.36
Cyperus rotundus L.	0.43	0.01	4.19	2.49	0.02	12.67
Oxalis corniculata L.	0.37	0.004	3.63	1.14	0.01	6.14
Hemigraphis hirta (Vahl) T. Anderson	0.17	0.002	3.27	0.14	0.001	0.96
Cynodon dactylon (L.) Pers.	0.43	0.003	3.15	3.20	0.03	14.05
Curculigo orchioides Gaertn.	0.09	0.01	2.58	–	–	–
Ageratum conyzoides L.	0.14	0.003	1.72	1.69	0.03	11.3

(Contd.)

Table 8 (Contd.)

Youngia japonica (L.) DC.	0.11	0.001	1.38	0.17	0.002	1.50
Tridax procumbens L.	0.09	0.001	1.27	0.11	0.002	0.94
Centella asiatica (L.) Urb.	0.09	0.001	1.22	0.31	0.003	2.35
Lygodium flexuosum (L.) Sm.	0.03	0.001	0.91	–	–	–
Imperata cylindrica (L.) Raeusch.	–	–	–	3.83	0.03	15.98
Mikania micrantha Kunth	–	–	–	0.60	0.03	7.90
Mimosa pudica L.	–	–	–	0.49	0.01	5.77
Eragrostis tenella (L.) P. Beauv. ex Roem. & Schult.	–	–	–	0.94	0.01	5.25
Digitaria ciliaris (Retz.) Koeler	–	–	–	0.94	0.02	5.12
Paederia scandens (Lour.) Merr.	–	–	–	0.09	0.01	2.49
Scoparia dulcis L.	–	–	–	0.20	0.004	2.16
Boerhavia diffusa L.	–	–	–	0.23	0.01	1.88
Hedyotis corymbosa (L.) Lam.	–	–	–	0.20	0.003	1.67
Chamaesyce hirta (L.) Millsp.	–	–	–	0.20	0.003	1.63
Caesulia axillaris Roxb.	–	–	–	0.29	0.01	1.60
Alysicarpus vaginalis (L.) DC.	–	–	–	0.11	0.004	1.49
Solanum americanum Mill	–	–	–	0.11	0.003	1.41
Hemarthria compressa (L. f.) R. Br.	–	–	–	0.14	0.004	1.14
Helminthostachis zeylanica L. (Hook.)	–	–	–	0.06	0.004	0.93
Ophioglossum sp.	–	–	–	0.06	0.001	0.66
Laphangium luteoalbum (L.) Tzvelev	–	–	–	0.03	0.001	0.60
Total	20.2	1.35	300	38.4	1.23	300

4.4.2 Shrub layer

Altogether, 16 species were recorded in the forest. Among them, 12 species were found in UF and 15 in DF and 11 species were common to both forests (Table 9). It showed 81% similarity between UF and DF. So, 19% dissimilarity between two forests occurred due to effect of disturbance (Table 13).

Table 9. Density (D; individual ha^{-1}), basal area (BA; m^2 ha^{-1}) and Importance Value Index (IVI) of shrub species in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Scientific names	Undisturbed stand			Disturbed stand		
	D	BA	IVI	D	BA	IVI
Murraya koenigii (L.) Spreng.	1668.57	0.08	64.75	251.43	0.03	15.37
Phyllanthus reticulatus Poir.	1291.43	0.02	40.86	251.43	0.01	10.87
Osbeckia chinensis L.	1200	0.01	40.03	342.86	0.01	9.87
Lantana camara L.	1028.57	0.01	33.95	960	0.18	59.39
Clerodendrum infortunatum L.	445.71	0.05	28.24	1302.86	0.04	43.04
Pogostemon benghalensis (Burm f.) Kuntze	297.14	0.06	26.61	1245.71	0.06	44.34
Leea aequata L.	45.71	0.09	23.24	1108.57	0.08	43.16
Colebrookea oppositifolia Sm.	34.29	0.06	16.01	308.57	0.04	18.85
Vitex negundo L.	11.43	0.04	10.31	114.29	0.01	4.87
Jasminum sp.	182.86	0.01	8.98	–	–	–
Rauvolfia serpentina (L.) Benth. ex Kurz	91.43	0.002	3.74	22.86	0.001	1.50
Desmodium confertum DC.	80.00	0.001	3.27	800.00	0.002	15.73
Calotropis procera (Aiton) Dryand.	–	–	–	251.43	0.06	19.99
Jatropha curcas L.	–	–	–	11.43	0.03	6.55
Solanum torvum Sw.	–	–	–	34.29	0.02	4.15
Callicarpa macrophylla Vahl	–	–	–	34.29	0.005	2.30
Total	6377	0.43	300	7040	0.58	300

A single species recorded only in UF was *Jasminum* sp., while 4 species like *Calotropis*, *Jatropha*, *Solanum* and *Callicarpa* were present only in DF. At UF, the dominant shrubs were *Murraya koenigii*, *Phyllanthus reticulatus* and *Osbeckia chinensis*. The DF exhibited the dominance of *Lantana camara*, *Pogostemon benghalensis* and *Clerodendrum infortunatum*. Density of shrubs increased with forest disturbance from 6377 to 7040 individual ha^{-1} (Table 9). Total basal area ranged from 0.43 m^2 ha^{-1} at UF to 0.58 m^2 ha^{-1} at the DF. Both species diversity and species richness increased in DF as compared to UF, while the Index of dominance decreased in DF (Table 12).

4.4.3 Tree layer

4.4.3.1 Species content

In the present study, 981 individuals of trees were recorded which belonged to 60 species, 51 genera, and 32 families (Table 10). Out of these, 57 species were present in UF, 38 in DF and 35 were common to both forest stands. The number of species found only in UF was 22, whereas that in DF was 3. It showed 74% similarity between UF and DF as per the Sorenson's similarity index. So, 26% dissimilarity between two stands reflects the consequence of disturbance (Table 13).

Table 10. Enumeration of tree species found in undisturbed forest stand (UF) and disturbed stand (DF) in moist tropical forest of Sunsari district, eastern Nepal.

Scientific names	Local name/s	Families	Present stand
Acacia catechu (L.f.) Willd.	Khayer	Mimosaceae	Both
Acacia ferruginea DC.	Khaur	Mimosaceae	UF
Acer oblongum Wall. ex DC.	Phirphire	Aceraceae	UF
Aegle marmelos (L.) Correa	Bel	Rutaceae	Both
Alangium salviifolium (L.f.) Wangerin	Asare	Alangiaceae	Both
Albizia julibrissin Durazz.	Rato Siris	Mimosaceae	Both
Albizia lebbeck (L.) Benth.	Padke Siris	Mimosaceae	Both
Albizia procera (Roxb.) Benth.	Thakar	Mimosaceae	Both
Alstonia scholaris (L.) R. Br.	Chhatiwan	Apocynaceae	Both
Anogeissus latifolius (Roxb. ex DC.) Bedd.	Paani Sahaj, Banjhi	Combrataceae	UF
Baliospermum solanifolium (Burm.) Suresh	Aaulea	Euphorbiaceae	Both
Bauhinia malabarica Roxb.	Amiltanki	Caesalpiniaceae	UF
Bombax ceiba L.	Simal	Bombacaceae	Both
Bridelia retusa (L.) A.Juss.	Gayo	Euphorbiaceae	Both
Careya arborea Roxb.	Kumbhi	Myrtaceae	Both
Cassia fistula L.	Raajbriksha	Caesalpiniaceae	Both
Cassia sp.		Caesalpiniaceae	UF
Cordia dichotoma G.Forst.	Bohori	Cordiaceae	UF
Cornus oblonga Wall.	Lati kath	Cornaceae	UF
Dalbergia latifolia Roxb.	Satisal	Papilionaceae	UF
Desmodium oojeinense (Roxb.) H.Ohashi	Sandan	Fabaceae	UF
Dillenia pentagyna Roxb.	Tantary	Dillaniaceae	Both
Diospyros chloroxylon Roxb.	Kalikath	Ebenaceae	UF
Diploknema butyracea (Roxb.) H.J.Lam.	Chiuri	Sapotaceae	Both

Ehretia laevis Roxb.	Datrungo	Cordiaceae	Both
Elaeagnus latifolia L.	Guyelo	Elaeagnaceae	UF
Falconeria insignis Royle	Khirro	Euphorbiaceae	Both
Ficus lacor Buch.-Ham.	Kavro	Moraceae	Both
Ficus racemosa L.	Dumri	Moraceae	Both
Ficus rumphii Blume	Sami	Moraceae	UF
Ficus semicordata Buch.-Ham ex Sm.	Khaniu	Moraceae	UF
Garuga pinnata Roxb.	Dabdabe	Burseraceae	Both
Gmelina arborea Roxb.	Khamari	Verbanaceae	UF
Grewia optiva J.R. Drumm. ex Burret	Syalphusro	Tiliaceae	Both
Haldina cordifolia (Roxb.) Ridsdale	Karma	Rubiaceae	Both
Heynea trijuga Roxb. ex Sims	Aankha taruwa	Meliaceae	UF
Holarrhena pubescens Wall. ex G.Don	Musabar	Apocynaceae	Both
Holoptelia integrifolia Planch.	Pipari	Ulmaceae	Both
Lagerstroemia parviflora Roxb.	Botdhayero	Lythraceae	Both
Lannea coromandelica (Houtt.) Merr.	Hallude	Anacardiaceae	Both
Mallotus pallidus (Airy Shaw) Airy Shaw	Sindure	Euphorbiaceae	UF
Mallotus repandus (Willd.) Mull.Arg.	Pithari	Euphorbiaceae	Both
Neolamarckia cadamba (Roxb.) Bosser	Kadam	Rubiaceae	DF
Oroxylum indicum L. Kurz	Totalo	Bignoniaceae	DF
Phyllanthus emblica L.	Amala	Euphorbiaceae	UF
Premna mollissima Roth	Gineri	Verbenaceae	UF
Schleichera oleosa (Lour.) Merr.	Kusum	Sapindaceae	Both
Semecarpus anacardium L.f.	Bhalayo	Anacardiaceae	Both
Shorea robusta Gaertn.	Sal, Saakhuwa	Dipterocarpaceae	Both
Spondias pinnata (L.f.) Kurz	Amaro	Anacardiaceae	UF
Sterculia villosa Roxb.	Odal	Sterculiaceae	UF
Stereospermum tetragonum DC.	Padari	Bignoniaceae	UF
Syzygium cumini (L.) Skeels	Jamun	Myrtaceae	Both
Syzygium nervosum A.Cunn. ex DC.	Kyamuna	Myrtaceae	Both
Tamarindus indica L.	Titri	Caesalpiniaceae	DF
Terminalia bellirica (Gaertn.) Roxb.	Barro	Combretaceae	Both
Terminalia chebula Retz.	Harro	Combretaceae	Both
Terminalia tomentosa Wight. & Arn.	Saj, Asna	Combretaceae	Both
Trema orientalis (L.) Blume.	Kunyel	Ulmaceae	Both
Ziziphus mauritiana Lam.	Bayer	Rhamnaceae	UF

4.4.3.2 Species diversity

In the present forest, 6–10 tree species were observed in most of the quadrats (20 in UF and 15 in DF) (Figure 9). In the same way, 11–15 species were found only in 10 quadrats of UF. This also indicates the contagious dispersion pattern of species.

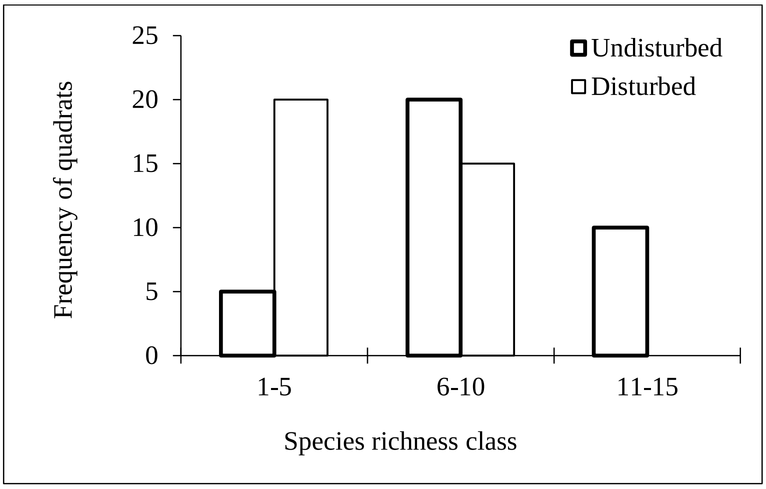

Figure 9. Spatial distribution of species richness in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

The proportions of family to species and genera to species were higher in UF whereas the proportion of family to genera was same in both forests (Table 11).

Table 11. Ratio of species, genus and family in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Forest types	Family: Species	Genus: Species	Family: Genus
Undisturbed	1.78	1.19	1.50
Disturbed	1.73	1.15	1.50

Diversity parameters for trees are presented in Table 12. Diversity parameters revealed that the species richness and the Shannon–Wiener index (*H'*) for tree species were higher in UF, while the Simpson’s index was higher in DF. It showed that concentration of dominance was higher in DF which was inversely related to Shanon–Wiener index. On the other hand, reverse case was found for shrubs and herbs where species richness and Shannon–Wiener index were higher but index of dominance was lower in DF. Changes in species diversity pattern reflect the effect of disturbance.

Table 12. Diversity parameters of trees, shrubs and herbs components in undisturbed and disturbed forest stands of moist tropical forest of Sunsari district, eastern Nepal.

Parameters	Forest stands	
	Undisturbed	Disturbed
Species richness (*d*)		
Trees	9.11	6.78
Shrubs	1.26	1.81
Herbs	9.65	11.52
Shanon-Wiener index (*H'*)		
Trees	3.08	2.80
Shrubs	1.90	2.22
Herbs	2.84	3.20
Equitability (*e*)		
Trees	0.76	0.77
Shrubs	0.77	0.78
Herbs	0.84	0.85
Index of dominance (*c*)		
Trees	0.08	0.11
Shrubs	0.18	0.13
Herbs	0.08	0.05

Table 13. Sorenson's similarity indices in different growth forms of vegetation between undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal.

Growth forms	Similarity (%)	Dissimilarity (%)
Trees	74	26
Shrubs	81	19
Herbs	71	29

4.4.3.3. Family diversity

Altogether, 32 families were present in UF but only 22 families (69% of UF) were represented in DF (Tables 14 & 15). Based on number of individuals, the dominant families in both forest stands were Dipterocarpaceae (with 140 trees in UF and 90 trees in DF) and Euphorbiaceae (95 trees in UF and 41 trees in DF). Based on species, the largest families were Euphorbiaceae (with 6 species) in UF and Euphorbiaceae and Mimosaceae (each with 4 species) in DF. On the basis of basal area, Dipterocarpaceae (33.9 m^2 ha^{-1}), Rubiaceae (23.9 m^2 ha^{-1}) and Lythraceae (14.4 m^2 ha^{-1}) were dominant families in UF, whereas Rubiaceae (14.1 m^2 ha^{-1}), Dipterocarpaceae (12.5 m^2 ha^{-1}) and Combretaceae (6.7 m^2 ha^{-1}) were dominant in DF. In terms of family importance value (FIV), Dipterocarpaceae occupied the top rank (scoring of 53.6 in UF and 53.9 in DF) followed by Rubiaceae (31.6 in UF and 41.7 in DF) and Euphorbiaceae in UF (28.4) and Combretaceae in DF (32.3).

Table 14. Family composition and Importance Value (FIV) in undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

SN	Family	Basal area ($m^2 ha^{-1}$)	Relative density	Relative diversity	Relative basal area	FIV
1	Dipterocarpaceae	33.87	21.44	1.75	30.36	53.55
2	Rubiaceae	23.86	8.42	1.75	21.38	31.56
3	Euphorbiaceae	3.65	14.55	10.53	3.27	28.35
4	Lythraceae	14.36	11.18	1.75	12.87	25.8
5	Combretaceae	11.97	7.2	7.02	10.72	24.94
6	Myrtaceae	4.56	3.83	5.26	4.08	13.18
7	Mimosaceae	1.86	2.6	8.77	1.67	13.04
8	Anacardiaceae	2.49	2.6	5.26	2.23	10.1
9	Moraceae	0.48	0.92	7.02	0.43	8.36
10	Alangiaceae	1.19	5.51	1.75	1.07	8.34
11	Sapindaceae	3.75	2.6	1.75	3.36	7.72
12	Apocynaceae	0.91	3.37	3.51	0.82	7.7
13	Caesalpiniaceae	0.32	1.84	5.26	0.28	7.38
14	Dillaniaceae	2.81	2.91	1.75	2.52	7.18
15	Papilionaceae	0.6	2.3	3.51	0.54	6.35
16	Ebenaceae	0.72	2.91	1.75	0.65	5.31
17	Bombacaceae	3.03	0.77	1.75	2.72	5.24
18	Verbanaceae	0.05	0.46	3.51	0.05	4.02
19	Ulmaceae	0.02	0.46	3.51	0.02	3.99
20	Burseraceae	0.28	0.61	1.75	0.26	2.62
21	Ehretiaceae	0.25	0.61	1.75	0.22	2.59
22	Tiliaceae	0.07	0.46	1.75	0.06	2.27
23	Sterculiaceae	0.03	0.46	1.75	0.02	2.24
24	Meliaceae	0.07	0.31	1.75	0.06	2.12
25	Cordiaceae	0.04	0.31	1.75	0.04	2.1
26	Aceraceae	0.03	0.31	1.75	0.03	2.09
27	Cornaceae	0.01	0.31	1.75	0.01	2.07
28	Sapotaceae	0.09	0.15	1.75	0.08	1.99
29	Elaeagnaceae	0.08	0.15	1.75	0.07	1.98
30	Rutaceae	0.08	0.15	1.75	0.07	1.98
31	Bignoniaceae	0.02	0.15	1.75	0.02	1.92
32	Rhamnaceae	0.02	0.15	1.75	0.01	1.92
	Total	111.6	100	100	100	300

Table 15. Family composition and Importance Value (FIV) in disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

SN	Family	Basal area (m^2 ha^{-1})	Relative density	Relative diversity	Relative basal area	FIV
1	Dipterocarpaceae	12.47	27.44	2.63	23.85	53.92
2	Rubiaceae	14.12	9.45	5.26	26.99	41.70
3	Combretaceae	6.69	11.59	7.89	12.80	32.28
4	Euphorbiaceae	1.99	12.50	10.53	3.80	26.83
5	Sapindaceae	5.19	5.18	2.63	9.92	17.74
6	Mimosaceae	1.86	3.66	10.53	3.55	17.73
7	Myrtaceae	1.62	3.35	7.89	3.10	14.35
8	Alangiaceae	0.66	8.23	2.63	1.26	12.13
9	Dillaniaceae	2.03	3.05	2.63	3.88	9.56
10	Caesalpiniaceae	0.81	2.44	5.26	1.55	9.25
11	Anacardiaceae	0.74	1.22	5.26	1.41	7.90
12	Bombacaceae	1.89	1.52	2.63	3.61	7.76
13	Rutaceae	0.46	3.35	2.63	0.88	6.87
14	Apocynaceae	0.16	1.22	5.26	0.30	6.78
15	Moraceae	0.28	0.91	5.26	0.53	6.71
16	Ulmaceae	0.04	0.61	5.26	0.07	5.94
17	Lythraceae	0.62	1.52	2.63	1.19	5.35
18	Sapotaceae	0.43	0.61	2.63	0.83	4.07
19	Bignoniaceae	0.12	0.91	2.63	0.22	3.77
20	Ehretiaceae	0.01	0.61	2.63	0.02	3.26
21	Burseraceae	0.11	0.30	2.63	0.20	3.14
22	Tiliaceae	0.02	0.30	2.63	0.03	2.97
	Total	52.3	100	100	100	300

4.4.3.4 Stand density

Plant community structure in terms of density, basal area, species richness, pattern of dispersion and stratification has been compared between undisturbed and disturbed forests. Density of tree species in UF and DF are summarized in Table 16 and Figures 10–12.

Table 16. Density (D; individual ha^{-1}), basal area (BA; m^2 ha^{-1}) and Importance Value Index (IVI) of tree species (> 10 cm GBH) in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Scientific names	Undisturbed stand			Disturbed stand		
	D	BA	IVI	D	BA	IVI
Shorea robusta	100.00	33.87	60.43	64.29	12.47	60.99
Haldina cordifolia	39.29	23.86	37.77	21.43	13.24	43.31
Lagerstroemia parviflora	52.14	14.36	33.66	3.57	0.62	3.81
Baliospermum solanifolium	39.29	1.36	16.26	6.43	0.12	6.30
Terminalia tomentosa	16.43	7.47	14.20	15.00	3.58	19.33
Alangium salviifolium	25.71	1.19	12.21	19.29	0.66	19.48
Schleichera oleosa	12.14	3.75	9.94	12.14	5.19	22.89
Dillenia pentagyna	13.57	2.81	9.74	7.14	2.03	11.38
Terminalia bellirica	12.86	3.03	8.78	10.71	2.9	16.23
Syzygium cuminii	9.29	3.42	8.04	2.86	0.56	3.97
Mallotus pallidus	16.43	1.00	7.73	–	–	–
Diospyros chloroxylon	13.57	0.72	6.87	–	–	–
Lannea coromandelica	7.86	1.77	5.92	1.43	0.26	1.65
Holarrhena pubescens	10.71	0.32	5.57	0.71	0.02	0.89
Bombax ceiba	3.57	3.03	4.81	3.57	1.89	7.92
Dalbergia latifolia	7.86	0.19	4.17	–	–	–
Alstonia scholaris	5.00	0.59	3.25	2.14	0.14	2.85
Mallotus repandus	5.00	0.34	3.03	15.00	1.14	14.1
Falconeria insignis	4.29	0.85	3.01	7.14	0.69	7.14
Semecarpus anacardium	3.57	0.62	2.98	1.43	0.48	2.09
Cassia fistula	5.00	0.15	2.86	4.29	0.28	5.14
Careya arborea	4.29	0.60	2.79	4.29	0.90	6.89
Albizia lebbeck	7.14	0.43	2.58	5.71	1.58	9.36
Syzygium nervosum	4.29	0.53	2.39	0.71	0.16	1.16
Terminalia chebula	2.86	0.60	2.14	1.43	0.22	2.14
Desmodium oojeinense	2.86	0.41	1.97	–	–	–
Garuga pinnata	2.86	0.28	1.86	0.71	0.11	1.07
Ehretia laevis	2.86	0.25	1.50	1.43	0.01	1.75
Sterculia villosa	2.14	0.03	1.48	–	–	–
Anogeissus latifolius	1.43	0.87	1.41	–	–	–
Bridelia retusa	2.14	0.09	1.21	0.71	0.04	0.94
Albizia procera	0.71	0.79	1.19	1.43	0.13	1.41
Grewia optiva	2.14	0.07	1.18	0.71	0.02	0.89

Cassia sp.	2.14	0.02	1.14	–	–	–
Ficus lacor	1.43	0.17	1.12	0.71	0.16	1.17
Bauhinia malabarica	1.43	0.15	1.10	–	–	–
Heynea trijuga	1.43	0.07	1.03	–	–	–
Acer oblongum	1.43	0.03	1.00	–	–	–
Acacia ferruginea	1.43	0.38	0.98	–	–	–
Ficus rumphii	1.43	0.27	0.88	–	–	–
Acacia catechu	2.14	0.04	0.83	0.71	0.06	0.98
Albizia julibrissin	0.71	0.22	0.68	0.71	0.08	1.02
Cordia dichotoma	1.43	0.04	0.68	–	–	–
Premna mollissima	1.43	0.05	0.68	–	–	–
Cornus oblonga	1.43	0.01	0.65	–	–	–
Trema orientalis	1.43	0.01	0.65	0.71	0.02	0.91
Spondias pinnata	0.71	0.10	0.57	–	–	–
Aegle marmelos	0.71	0.08	0.56	7.86	0.46	8.50
Diploknema butyracea	0.71	0.09	0.56	1.43	0.43	2.55
Elaeagnus latifolia	0.71	0.08	0.56	–	–	–
Ficus racemosa	0.71	0.02	0.51	1.43	0.11	1.38
Ficus semicordata	0.71	0.01	0.50	–	–	–
Stereospermum tetragonum	0.71	0.02	0.50	–	–	–
Ziziphus mauritiana	0.71	0.02	0.50	–	–	–
Gmelina arborea	0.71	0.01	0.49	–	–	–
Holoptelia integrifolia	0.71	0.01	0.49	0.71	0.01	0.88
Phyllanthus emblica	0.71	0.01	0.49	–	–	–
Neolamarckia cadamba	–	–	–	0.71	0.88	2.54
Oroxylum indicum	–	–	–	2.14	0.12	2.25
Tamarindus indica	–	–	–	1.43	0.53	2.74
Total	466.4	111.6	300	234.3	52.3	300

The UF had higher density of trees (466 trees ha^{-1}) as compared to DF (234 trees ha^{-1}). The density of trees varied greatly in both forests ranging from 0.7–100 trees ha^{-1}. In UF, the density ranged from less than one (0.7 trees ha^{-1}) each for thirteen species (22.8% species) to 100 trees ha^{-1} for *Shorea robusta* (1.8% species) (Figure 10).

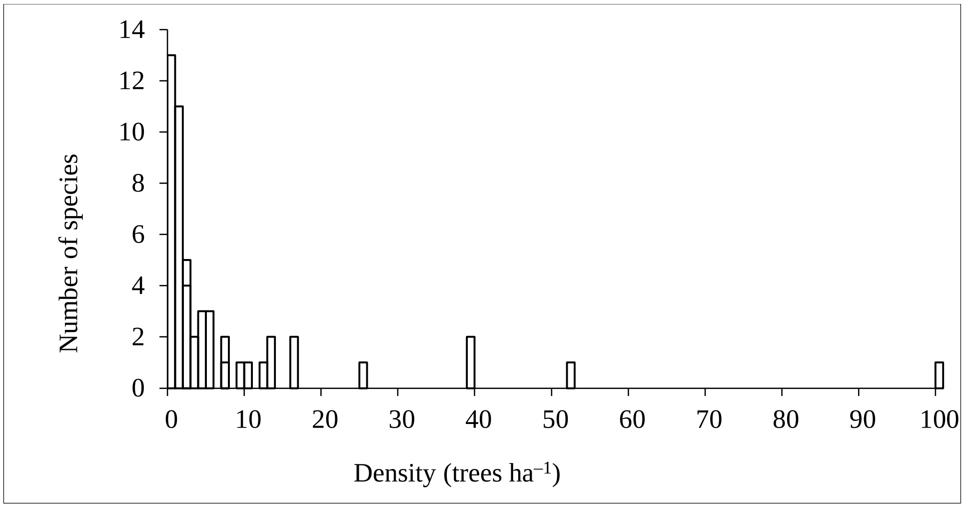

Figure 10. Species individual relationship of tree species in undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

The density value for disturbed forest was 0.7 trees ha^{-1}, each for eleven species (28.9%) and 64 for *Shorea robusta* (2.6% species) (Figure 11). Based on density value, the second dominant species was *Haldina cordifolia* with 39 trees ha^{-1} in UF and 21 trees ha^{-1} in DF.

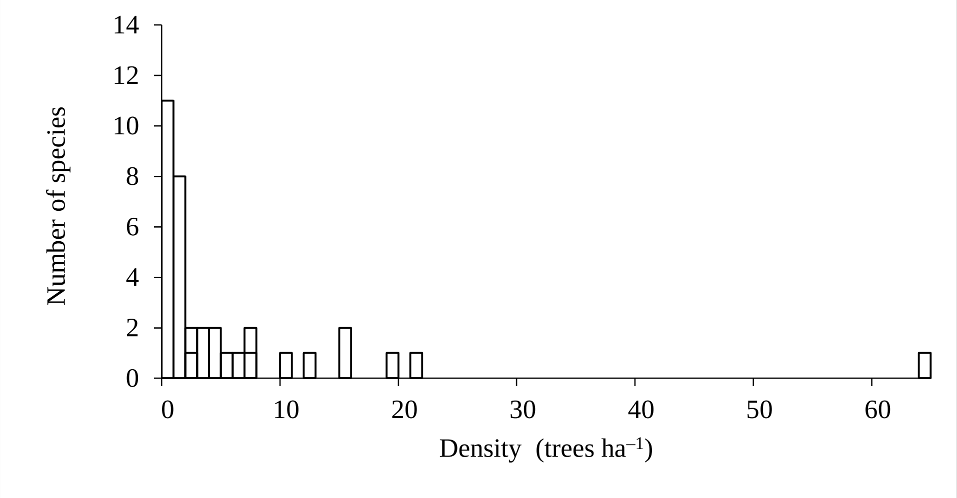

Figure 11. Species individual relationship of tree species in disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

4.4.3.5 Basal area

The basal areas of trees in the UF and DF were 111.6 and 52.3 m^2 ha^{-1} respectively (Table 16). The highest basal area in UF was of *Shorea robusta* with 33.9 m^2 ha^{-1} which contributed 30.4% to the total basal area but in DF, it was occupied by Hal*dina cordifolia* with 13.2 m^2 ha^{-1} contributing 25.3% to the total basal area. Based on basal area, the dominant families in UF were Dipterocarpaceae with 33.9 m^2 ha^{-1} (30.4%), Rubiaceae with 23.9 m^2 ha^{-1} (21.4%) and Lythraceae with 14.4 m^2 ha^{-1} (12.9%) values. However, the dominant families in DF were Rubiaceae with 14.1 m^2 ha^{-1} (26.9%) followed by Dipterocarpaceae with 12.5 m^2 ha^{-1} (23.8%) and Combretaceae with 6.7 m^2 ha^{-1} (12.8%).

4.4.3.6 Species IVI

Based on species IVI, *Shorea robusta* occupied the top rank with 60.4 (20.1% of total IVI) in UF and 60.9 (20.3%) in DF (Table 16). The second dominant species in both forests was Hal*dina cordifolia*, with IVI of 37.7 (12.5%) in UF and 43.3 (14.4%) in DF. The species IVI showed a sharp decrease up to *Baliospermum solanifolium* (4th rank) in UF and *Schleichera oleosa* (3rd rank) in DF (Figures 12 & 13). Then, the IVI in both stands decreased gradually. This indicates the dominance of only few species in both the forests.

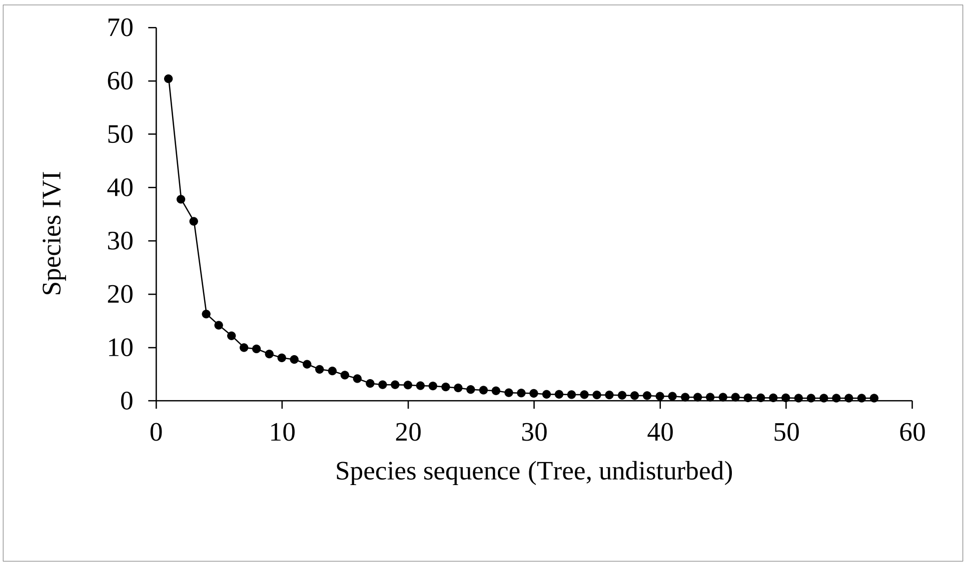

Figure 12. Importance Value Index for trees and their sequence in undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal (Sequence of top ten species in terms of IVI: 1. *S. robusta*, 2. *H. cordifolia*, 3. *L parviflora* , 4. B.. *solanifolium*, 5. *T. tomentosa*, 6. *A.salviifolium* , 7. *S. oleosa*, 8. *D. pentagyna*, 9. *T. bellirica*, 10. *S. cuminii*).

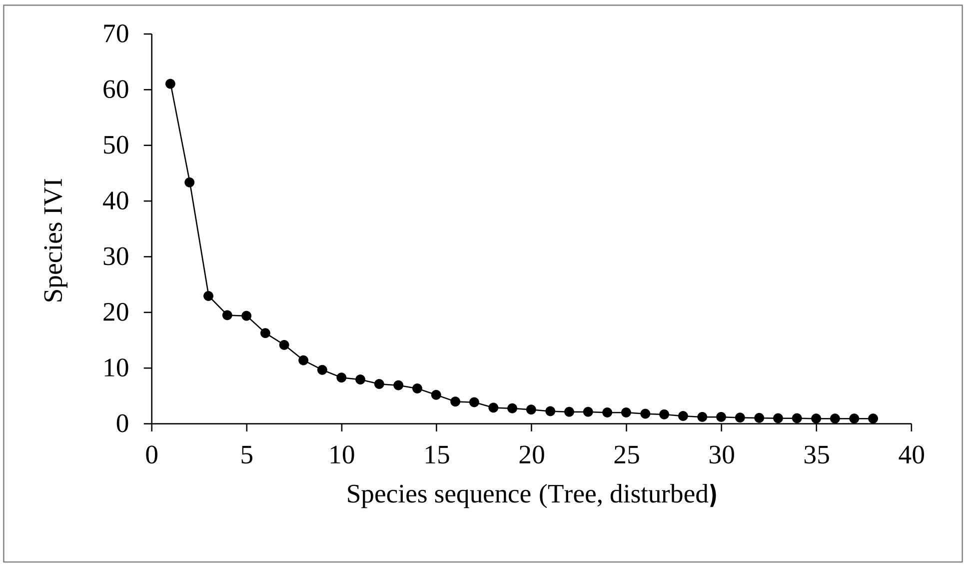

Figure 13. Importance Value Index for trees and their sequence in disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal (Sequence of top ten species in terms of IVI: 1. *S. robusta*, 2. *H. cordifolia*, 3. *S. oleosa*, 4. *A. salviifolium*, 5. *T. tomentosa*, 6. *T. bellirica*, 7. *M. rependus* 8. *D. pentagyna*, 9. *A. lebbek*, 10. *A.marmelos*).

4.4.3.7 Girth class

The distribution pattern of tree species, density and basal area in different girth classes are presented in Figure 14. The distinct difference in girth class distribution was observed in UF and DF. The large diameter trees (J–M girth classes) were present only in UF. The species richness was high in B girth class, which sharply declined up to F girth class in UF whereas it was high in A girth class and gradually decreased up to D class in DF. Overall, the density of trees decreased with increasing diameter except for the D girth class in UF, whereas density of trees showed irregular trend with girth class in DF. The basal area of trees in all girth classes except I was more in UF than DF. This indicates that the species of all girth classes were cut and removed from the DF. The higher values of basal areas in middle (D, E, F, G and H) and upper (L and M) girth classes in UF may be related to less biotic removal and high capacity of biomass accumulation in moist tropical forest.

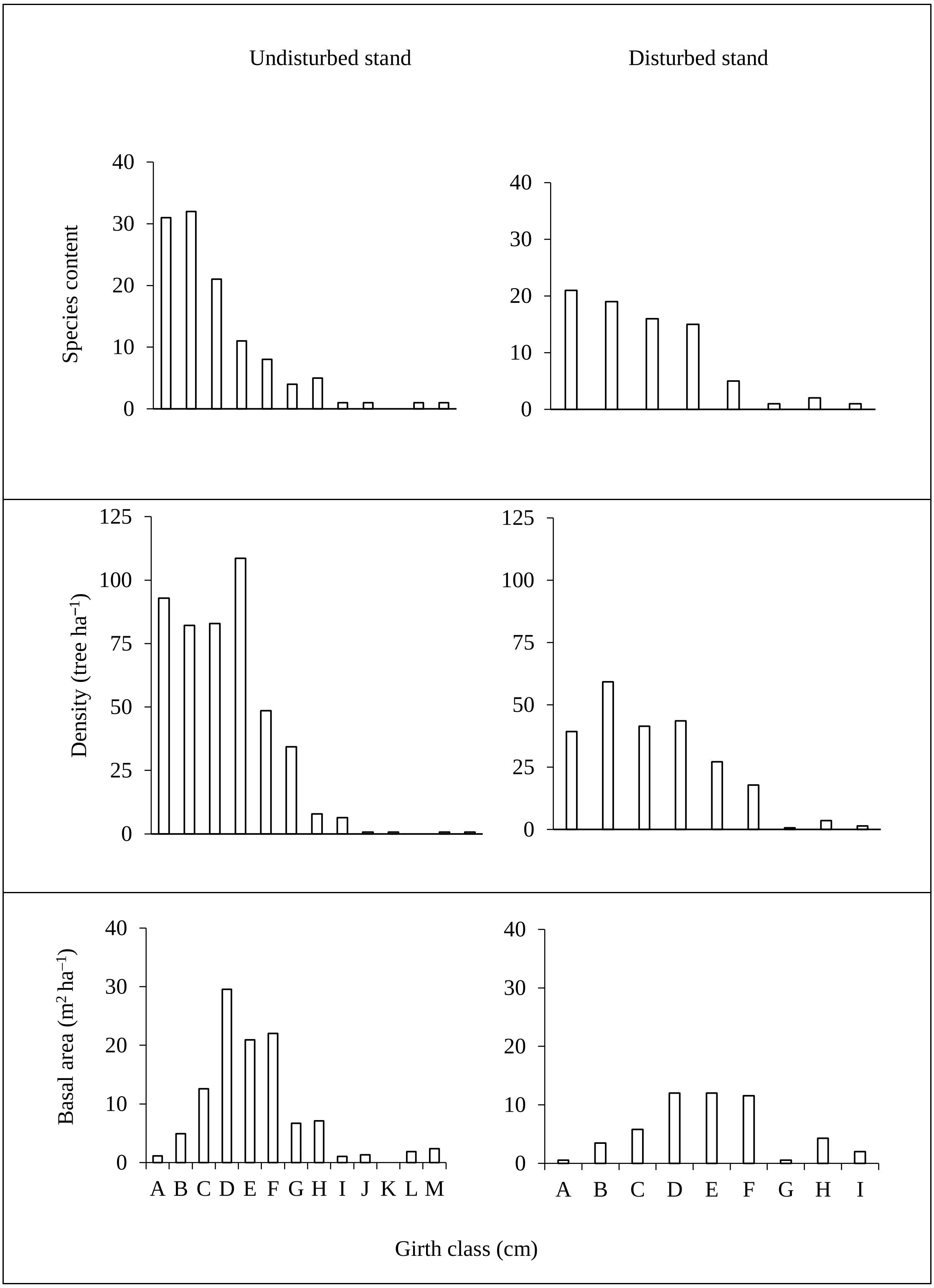

Figure 14. Distribution of species content, density and basal area of trees in different girth classes in the undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal. Girth classes (cm) are: A = 10–60, B = 60–110, C = 110–160, D = 160–210, E = 210–260, F = 260–310, G = 310–360, H = 360–410, I = 410–460, J = 460–510, K = 510–560, L = 560–610 and M > 610.

4.4.3.8 Stratification (Species distribution pattern)

Out of the 60 tree species (≥ 10 cm GBH) enumerated in the forest, 11 species (18%) were canopy trees (≥ 15 m height), 22 species (37%) were middle storey trees (8–15 m height), and the rest 27 species (45%) were understorey trees (< 8 m height) (Table 17). The canopy species in both stands were dominated by *Shorea robusta* and Hal*dina cordifolia*. The canopy trees restrict the light availability to the other species of middle storey, understory, and ground vegetation mainly in the UF.

Table 17. Distribution of tree species richness according to their height in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Growth form	Undisturbed	Disturbed	Overall
Canopy trees (≥ 15 m height)	11	10	11
Sub-canopy trees (8–15 m height)	19	15	22
Understorey trees (< 8 m height)	27	13	27
Total	57	38	60

4.4.3.9 Phenology of some dominant tree species

Phenological behaviour of 13 dominant species is presented in Table 18. Leaf initiation, leaf fall and reproduction are the periodic activity and differ with species composition. In most of the species (7 species) leaf initiation began in April while leaf fall started from March (10 species) and continued up to May. Flowering started from February and continued till July with a peak in March to May. Fruiting behavior of studied species was not uniform in the present forest. In some species (3 species) fruiting started in winter season while in others it started with the beginning of rainy season.

Table 18. Phenological behavior of some dominant tree species in undisturbed forest stand of moist tropical forest in Sunsari district of eastern Nepal.

S.N.	Plant names	Leaf fall	Leaf initiation	Flowering	Fruiting
1	*Shorea robusta*	Mar. -Apr.	April	Feb.-Mar.	Apr.-May
2	*Haldina cordifolia*	Apr. - May	Mar.- Apr.	Jun.-Jul.	July
3	*Lagerstroemia parviflora*	Mar. -Apr.	April	Apr. - May	Dec.-Jan.
4	*Terminalia tomentosa*	Mar. -Apr.	May-Jun.	Jun.-Jul.	Feb.-Apr.
5	*Schleichera oleosa*	Feb.-Mar.	Mar. -Apr.	Mar. -Apr.	May-Jun.
6	*Dillenia pentagyna*	March	April	Mar. -Apr.	May-Jun.
7	*Terminalia bellirica*	March	April	Apr. - May	May
8	*Syzygium cuminii*	Feb.-Mar.	March	Mar.-May	Jun.-Aug.
9	*Diospyros tomentosa*	March	April	May-Jun.	Apr. -May
10	*Lannea coromandelica*	March	Apr.-Jun.	March	Apr.-Jun.
11	*Holorrhena pubescens*	Mar. -Apr.	April	May-Jun.	Jun.-Jul.
12	*Semecarpus anacardium*	Mar. -Apr.	May	May-Jun.	Nov.-Jan.
13	*Cassia fistula*	Mar. -Apr.	May-Jun.	May-Jun.	Jun.-Jul.

4.4.3.10 Pattern of dispersion

None of the 57 species in UF and 38 species in DF showed the uniform dispersion pattern. Only 5 species (8.3% of total species) including *Lagerstroemia parviflora*, *Haldina cordifolia*, *Dillenia pentagyna*, *Schleichera oleosa* and *Alangium salvifolium* in UF exhibited random distribution. Rest of all species in both forest stands showed contagious distribution.

4.4.3.11 Ordination and cluster analysis

4.4.3.11.1 Ordination

Both datasets showed much stronger as due to the greater value of axis lengths (axis lengths ≥ 2.5 *Standard Deviation Units)* (Table 19). The variance governed by the DCA first axis is slightly less (40%) in case of the plots sampled from undisturbed forest than samples from disturbed forest (greater than 50%) (Table 19). Variances decreased as DCA axes increased in both forest stands. Forest plots from disturbed field had much better or stronger heterogeneity than plots from undisturbed forest.

Table 19. DCA result for samples by species datasets from undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal.

Undisturbed stand	Axes	1	2	3	4
	Eigen-values	0.4	0.4	0.3	0.2
	Decorana values	0.4	0.4	0.2	0.2
	Axis lengths	3.5	2.8	2.2	2.3
Disturbed stand	Axes	1	2	3	4
	Eigen-values	0.5	0.4	0.3	0.3
	Decorana values	0.6	0.5	0.3	0.2
	Axis lengths	5.0	3.3	2.5	2.4

Correlations among environmental variables with two major DCA axes found almost less relation (Table 20). Only one environmental variable i.e., MB-N from disturbed forest stand showed significant correlation with DCA first and second axes (Table 20). Other variables were found non-significant.

The direct gradient analysis method, CCA showed that both plots from undisturbed and disturbed datasets explain exactly the same in term of variance explained by total number of environmental variables (Table 21). Total environmental variables have explained 30% variance out of the total that applied same to the disturbed forest dataset too (Table 21).

Table 20. DCA with over fitting of environmental variables for undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal.

Undisturbed stand	Soil variables	DCA 1	DCA 2	r^2	Pr (> r)
	Soil mois	0.65	0.76	0.03	0.64
	WHC	-0.70	0.72	0.05	0.55
	BD	0.42	-0.91	0.01	0.88
	pH	0.24	0.97	0.16	0.09
	SOC	0.31	0.95	0.08	0.31
	TotN	0.42	0.91	0.07	0.34
	TotP	0.44	-0.90	0.02	0.80
	MBC	0.81	0.59	0.04	0.55
	MBN	0.80	0.60	0.05	0.53
	MBP	-0.85	0.53	0.00	0.99
Disturbed stand	Soil variables	DCA 1	DCA 2	r^2	Pr (> r)
	Soil mois	-0.48	0.88	0.04	0.49
	WHC	0.44	0.90	0.11	0.15
	BD	-0.49	0.87	0.05	0.49
	pH	-0.07	1.00	0.02	0.75
	SOC	0.25	-0.97	0.11	0.15
	TotN	0.16	-0.99	0.15	0.08
	TotP	0.10	0.99	0.09	0.21
	MBC	-0.06	-1.00	0.09	0.21
	MBN	0.36	-0.93	0.19	0.03
	MBP	-0.86	0.51	0.02	0.74

Table 21. CCA summary for the datasets from undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal.

Undisturbed stand		Inertia	Proportion	Rank
	Total	5.2	1.0	
	Constrained	1.6	0.3	10
	Unconstrained	3.6	0.7	24
Disturbed stand		Inertia	Proportion	Rank
	Total	5.9	1.0	
	Constrained	1.7	0.3	10
	Unconstrained	4.2	0.7	24

Each environmental variable represented CCA axes differently. During CCA the soil moisture variables represented by the CCA second axis was much significant for undisturbed forest dataset whereas CCA fourth axis in the data from disturbed forest (Table 22). In table 22, environmental axes of all variables are given.

Table 22. CCA environmental variable by axes for undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal. Bold entries represented the significant axes.

Soil variables	**Undisturbed stand**				**Disturbed stand**			
	CCA 1	CCA 2	CCA 3	CCA 4	CCA 1	CCA 2	CCA 3	CCA 4
Soil mois	0.23	**0.70**	-0.29	0.34	0.0	-0.04	-0.10	**0.50**
WHC	0.16	-0.10	**0.33**	-0.27	0.40	**-0.50**	-0.10	-0.20
BD	0.10	**-0.36**	-0.14	0.40	0.10	**-0.40**	-0.20	0.30
pH	**0.74**	-0.39	0.19	0.07	0.20	**-0.30**	0.0	-0.30
SOC	0.25	-0.15	0.08	**-0.37**	0.0	**0.70**	0.30	0.0
TotN	**0.34**	-0.29	0.17	-0.18	0.10	**0.90**	-0.20	-0.20
TotP	0.01	**-0.74**	0.02	0.10	-0.10	**-0.50**	-0.20	0.0
MBC	0.07	**-0.29**	0.24	-0.19	0.10	**0.50**	0.20	0.0
MBN	0.26	**-0.44**	0.21	0.02	-0.20	**0.80**	-0.10	0.0
MBP	0.16	-0.08	**0.63**	0.11	0.20	**-0.40**	-0.20	0.0

The highest abundance of species like *Ziziphus mauritiana*, *Bauhinia malabarica* and *Gmelina arborea* has been explained significantly by the soil moisture in case of undisturbed forest (Figure 15). High pH loving species were *Elaeagnus latifolia* and *Ehretia laevis*, which was significantly denoted by CCA first axis. But pH indicated along the second axis in disturbed forest sites (Figure 16).

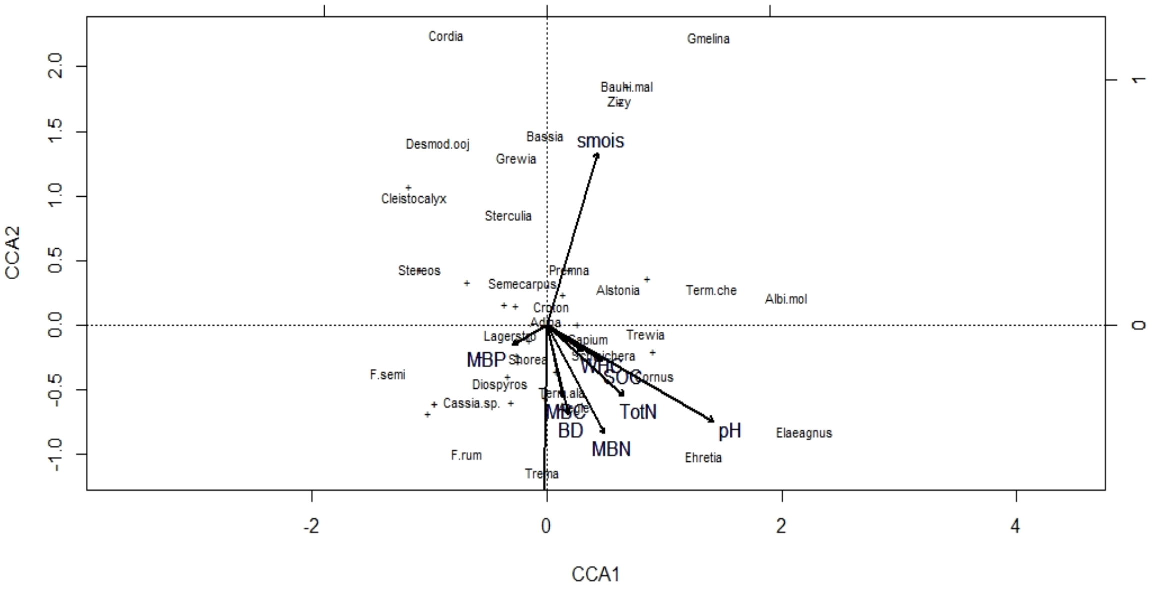

Figure 15. CCA biplot for undisturbed forest dataset. Full form of species and environmental variables are given in appendix.

Significant abundances of species *Ehretia laevis*, *Neolamarckia cadamba* and *Lagerstroemia parviflora* along negative end of CCA first axis explained by total P and MB-N (Figure 16).

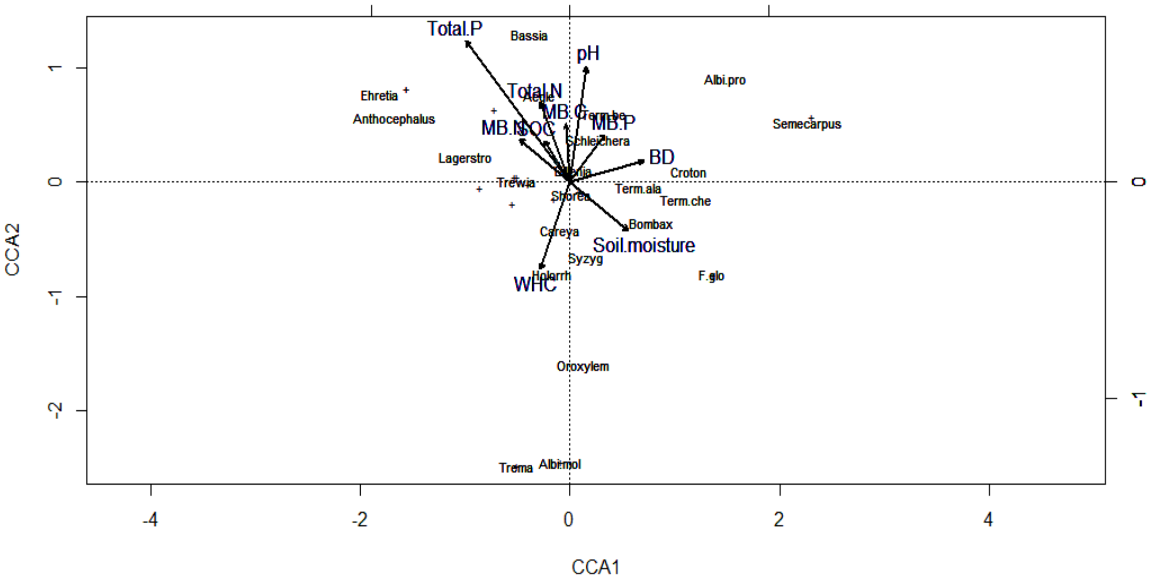

Figure 16. CCA biplot for disturbed forest dataset. Full form of species and environmental variables are given in appendix.

Abundance of *Holarrhena pubescens* was significantly explained towards the highest WHC of soil. Although total variance explained and residuals left were almost similar to both forest types, composition patterns and significance of environmental variables to CCA axes were different. Thus samples and species had a great contribution between both studied forest stands. This could be further investigated after clustering them separately.

4.4.3.11.2 Species and plots clustering

A total of 56 clusters formed after cluster analysis of the species dataset from undisturbed forest and 37 by disturbed forest species. These clusters represented in full by the figures (Figures 17 & 18). Among these species, 14 from undisturbed and 13 from disturbed forest formed significant clusters. Species such as *Garuga pinnata* and *Trema orientalis* at edge number 4 having AU/BP % value 99 and 56 respectively formed significant cluster (Figure 18). Likewise, *Bridelia retusa* and *Ficus glomerata* at edge number 3 formed significant cluster.

Likewise, sample plots from both undisturbed and disturbed forests formed 34 clusters each (Figures 19 & 20), but with different number of significant clusters. Plots 1, 12 and 15, 30 (Figure 20) formed significant clusters from disturbed forest sites.

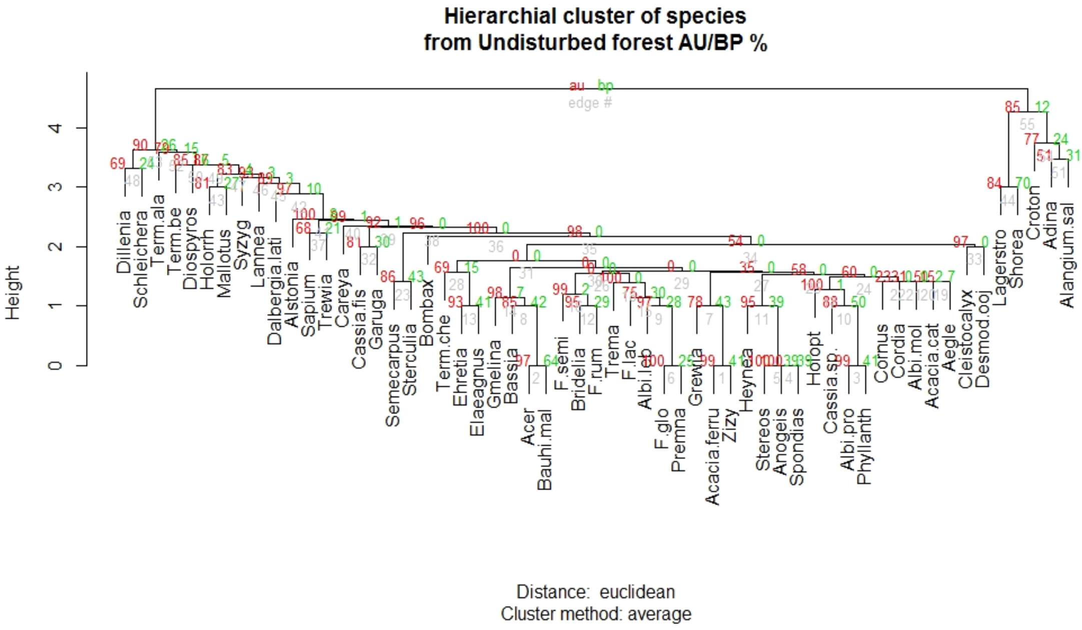

Figure 17. Hierarchical clustering of species from undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

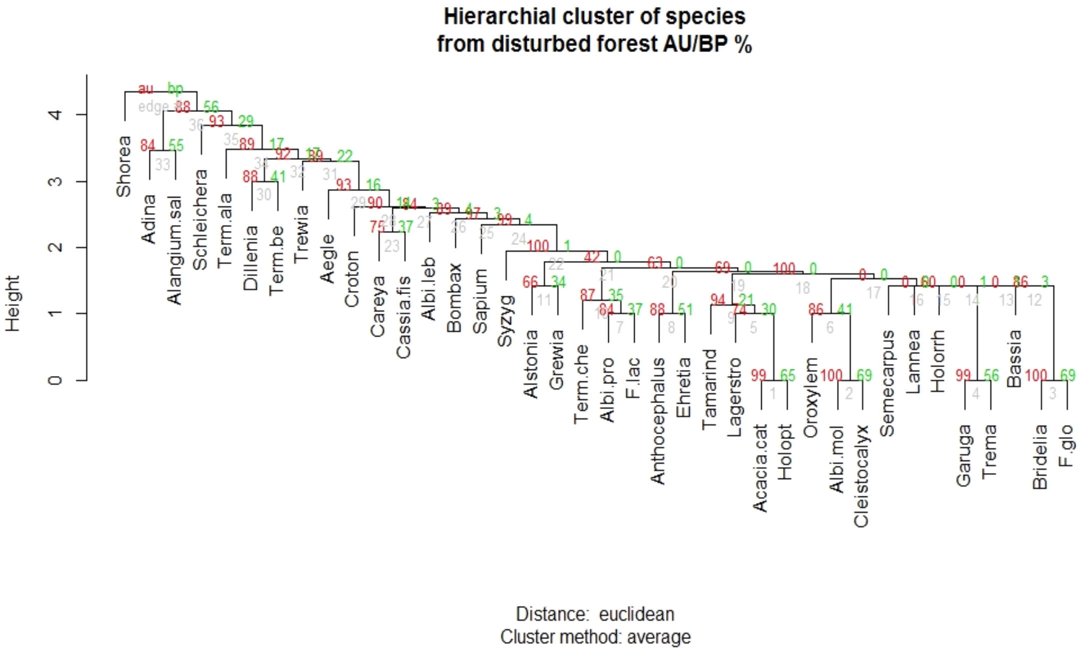

Figure 18. Hierarchical clustering of species from disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

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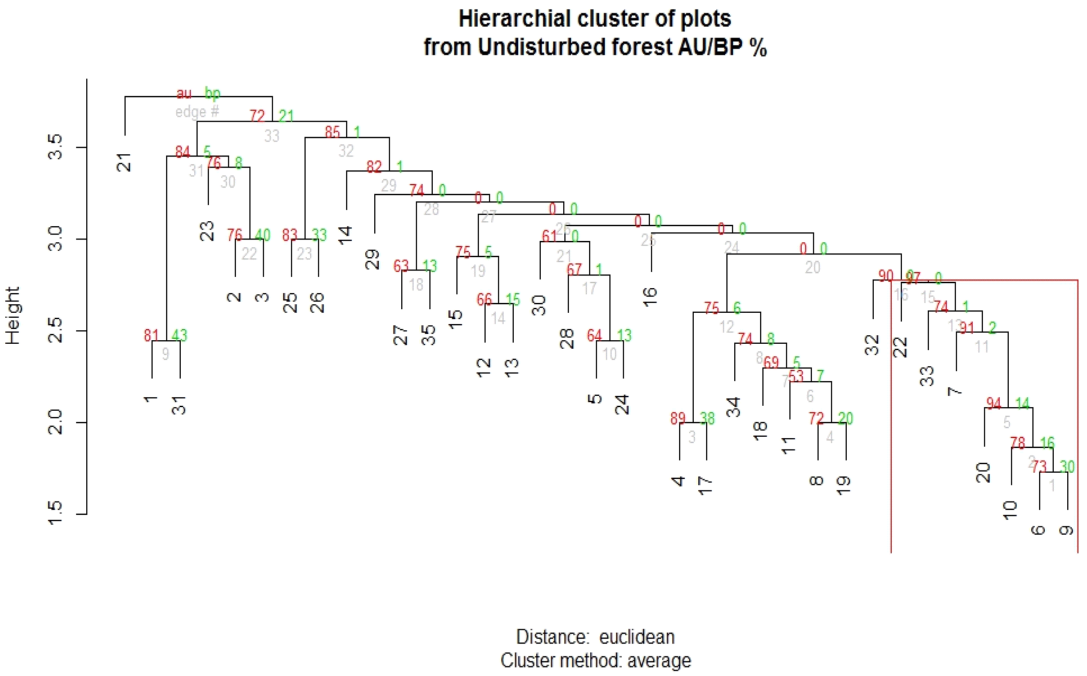

Figure 19. Hierarchical clustering for plots from undisturbed forest stand. The heights towards the vertical axis represented Euclidean distance between clusters.

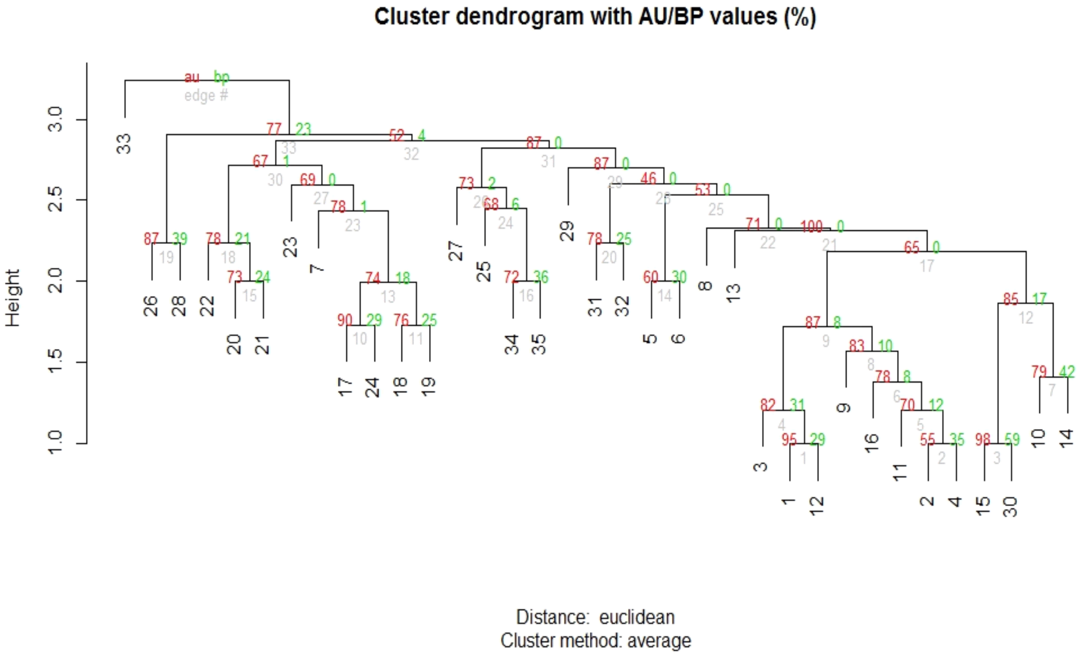

Figure 20. Hierarchical clustering for plots from disturbed forest stand. The heights towards the vertical axis represented Euclidean distance between clusters.

4.5 DISCUSSION

4.5.1 Herb and Shrub layer

Forest disturbances resulted in the formation of fragmented, exposed, and nutrient poor sites, awaiting recolonization. Colonization on disturbed site by successional species generally occurs through stump, root and rhizome sprouts and through seeds. Both herb and shrub species were higher in DF which may be due to edge effect and open canopy favoring light loving plants. On the other hand, lower number of species in UF could be attributed to the dense canopy of trees which tended to suppress the undergrowth from obtaining sufficient sunlight required for germination, growth and development in light loving species. So far Sorenson's similarity is concerned herbs and shrubs in DF showed 19–29% dissimilarity with the UF, which reflects the consequence of disturbance.

Among the total species, 26 herb and 11 shrub species were present in both forest stands. High species overlap between UF and DF can be explained in part by their intactness, similarity in structure and their position on the landscape, and similar geography.

Chromolaena odorata, an annual forb of family Asteraceae dominated both forest stands. It may be due to its light weight seeds easily dispersed by wind, a character which makes Asteraceae a most successful family. The early colonizers usually have their growth and reproductive strategies so that they could invade and attain dominance in the disturbed sites (Pandey & Singh, 1985). The growth of *Chromolaena odorata* in the DF is suppressed by the proliferation of a dominant shrub, *Lantana camara* resulting in its lower IVI. Ferns are reported to colonize disturbed sites and increase soil stability, soil moisture, and soil nutrients in the tropics.

Forest disturbances resulted in an increase in herb and shrub species diversities. Shannon-Wiener index of herbaceous species increased to 3.20 in DF Vs 2.84 in UF. Generally, the species diversity increases with the development of secondary communities (Odum, 1969). Herb and shrub species content, density, species richness and species diversity increased in DF. It is in accordance with the "Intermediate Disturbance Hypothesis" which stated that under intermediate levels of disturbance diversity is highest (van der Marrel, 1993).

4.5.2 Tree layer

4.5.2.1 Species content

Knowledge of tree species content is elementary to total forest biodiversity as it provides resources and habitats for almost all other forest species. In DF, 19 species (33%) were eliminated as compared to UF. The eliminated species were represented by few individuals in UF. Among them, 7 species were represented by 1 individual each, 9 species by 2 individuals each, 2 species by 3 individuals each and 1 species by 19 individuals. It means that they are more prone to local extinction as compared to the heavily exploited species with relatively high population. The reduction in the density of some important species like *Shorea robusta* (by 35.7%) and *Haldina cordifolia* (by 45.4%) suggests the selective felling by local people because of their high demand in construction works, timber and other purposes. However, the convincing (existing) population of locally high demanded species in DF suggests their high regeneration capacity.

The occurrence of 13 species (22.8%) with single individual in UF of present study is in range with the report of Sagar *et al.* (2003) for Indian dry forest species (18–30% species of > 30 cm GBH). Upadhaya *et al.* (2004) reported 42–53% of the total species represented by one or two individuals in sub-tropical humid forest of Meghalaya, India. The occurrence of many species with single individual in less disturbed forests might be due to unfavorable regeneration conditions, lack of appropriate habitat or both. In spite of this, species composition in the undisturbed and disturbed stands of present forest is more or less similar, which may be attributed to the similar topography, soil and climatic conditions and to the sufficient movement of propagules and pollens through the landscape.

4.5.2.2 Species diversity

Diversity indices reflect the manner in which abundance is distributed among the different species constituting the community. Species diversity is a major determinant of ecosystem productivity, stability, invasibility, and nutrient dynamics (Tilman *et al.*, 2014). Species diversity is often correlated with rainfall, nutrient status and disturbance level.

The equitability or evenness refers to the degree of relative dominance of each species in that area. The equitability of trees in the present forest (0.76 in UF and 0.77 in DF) is higher to matured Sal forest of eastern Siwaliks, Nepal (0.69; Mandal, 1999) and sub-tropical humid forests of Meghalaya, India (0.53 in UF and 0.61 in DF, Upadhaya *et al.*, 2004); while it is lower to the tropical wet evergreen forests of Western Ghats, India (1.3–2.4, Swamy *et al.*, 2010).

In the present study, Simpson's index (index of dominance or concentration of dominance) of trees was higher in DF (0.11) than in UF (0.08). It happens due to sharing of large portion of resources by few species only (Singh & Singh, 1991a; Swamy *et al.*, 2010) or related to the dominance of disturbance tolerance species like Sal in the forest. Moreover, it may be attributed to the restrictions imposed by policy on cutting important timber species.

Sal has ability to re-sprout aggressively from root suckers after short duration of disturbances (Gautam & Devoe, 2006; Sapkota *et al.*, 2009a). It has proved to be more aggressive than its competitors with its resistance to forest fires and other external factors through the die- back mechanism (Champion & Seth, 1968). It may be attributed to high light demanding character of Sal; disturbance mediated light availability favors its seedling recruitment process (Sapkota *et al.*, 2009b). On the other hand, repeated removal of fodder and fuel-wood species lead to single species dominance in the forest (Sapkota *et al.*, 2010).

Moreover, some co-dominant species like *Haldina cordifolia*, *Schleichera oleosa* and *Alangium salvifolium* also occur in the DF. It may be due to their ability to compete with dominant species for space and resources and also the result of less preference given by the local people for their exploitation (Sapkota *et al.*, 2010). The Simpson's index in this study is lower as compared to tropical dry evergreen forest of Coromandel Coast of India (0.14–0.53; Anbarashan & Parthasarathy, 2013), whereas it is nearly equal to the tropical wet forests of Western Ghat, India (0.1; Swamy *et al.*, 2010) but quite higher to the sub-tropical humid forests of Meghalaya, India (0.034 in DF and 0.067 in UF; Upadhaya *et al.*, 2004).

The Shannon-Wiener index is used as a diversity index because it combines the variety and equitability components. However this may obscure the individual behavior of two components since an increase in the equitability may counteract a decrease in number of species. This index increased with an increase in number of species. The higher *H'* index compared to the Simpson's index indicates an inverse relationship between these two indices. The higher *H'* index in UF of present study may be due to the microclimatic and soil nutrient availability which have direct impact on the spatial diversity of vegetation. The Shannon-Wiener index (*H'*) for the tree species in the present forest is comparable to the several tropical and subtropical forests of Asia (Table 23).

Table 23. Shannon-Wiener index (*H'*) for the tree species in tropical and subtropical forests of Asia.

Forests and localities	*H'* index	References
Tropical Plateau Sal, eastern Nepal	1.66	Mandal (1999)
Tropical dry evergreen, India	1.24–2.2	Anbarashan & Parthasarathy (2013)
Subtropical, Meghalaya, India	3.42–3.87	Upadhaya *et al.* (2004)
Tropical wet, Bangladesh	3.37	Feroz *et al.* (2013)
Tropical wet, western Ghats, India	2.01–3.7	Swamy *et al.* (2010)
Tropical moist, eastern Nepal	3.08	Present study

Species richness or variety index (*d*) is the mean number of species per unit area. The tree species richness of the present forest (6.78 in DF– 9.11 in UF) is lower to the tropical wet evergreen forests of Western Ghat, India (7.9–12.7, Swamy *et al.*, 2010). The number of tree species reduced by 33.3% in DF as compared to UF. The higher species richness in UF may be due to higher soil moisture and nutrients. On the other hand, less number of species in DF is attributed to frequent and fluctuating disturbances and also to the responses of species to such disturbances. The species richness of present forest is quite higher to the matured Plateau Sal forest of eastern Siwaliks, Nepal (1.57; Mandal, 1999). Higher species richness in the present forest as compared to dry forests might be due to higher value of annual precipitation. The degree of natural disturbance has often been considered as a critical factor in determining tropical forest species diversity. Anthropogenic disturbances, such as burning, grazing, and wood collection, may have significantly lowered plant species richness in DF.

4.5.2.3 Stand density

The variation in the composition of dominant tree species and forest stand density in tropical forests of world is mainly due to variation in biogeography and habitat disturbance (Mani & Parthasarathy, 2009). In the present study, the reduced density in DF was largely attributed to a low proportion of young trees belonging to smaller girth classes. The lower tree density could be a result of higher edge to area ratio and a subsequent increase in exposure to the physical environment. It may also be attributed to the selective cutting of straight boles of tree for use as poles by local people. The stand density of the present forest is lower, higher or comparable to some tropical forests of Nepal and India (Table 24).

Table 24. Stand density of tree species in tropical forests of Nepal and India.

Forests and localities	Density (trees ha^{-1})	References
Tropical Plateau Sal, eastern Nepal	580	Mandal (1999)
Sal, Bhabar-Terai, Nepal	152–264	Rautiainen (1999)
Tropical, Bardia, Nepal	348	Shrestha & Jha (1997)
Sal, western Terai, Nepal	220	Timilsina *et al.* (2007)
Tropical dry evergreen, India	771–1285	Anbarashan & Parthasarathy (2013)
Tropical moist, eastern Nepal	234–466	Present study

4.5.2.4 Basal area

Basal area reflects stand volume or biomass. The basal area of trees in DF was reduced by 53.1%. This reflects the removal of large and old trees. The high density and basal area of *Shorea robusta* in the forest suggests the dominancy of it. The basal area of trees in the UF of present forest (111.6 $m^2 ha^{-1}$) is higher to the tropical forests of Nepal and India (Table 25).

Table 25. Basal area of trees in some tropical forests of Nepal.

Forests and localities	Basal area (m^2 ha^{-1})	References
Tropical Plateau Sal, eastern Nepal	67.1	Mandal (1999)
Tropical, Bardia, Nepal	36	Shrestha & Jha (1997)
Sal, Western Terai, Nepal	13	Timilsina *et al.* (2007)
Tropical moist, eastern Nepal	52.3–111.6	Present study

The high basal area resulted from very high stocking of the middle-size class (160–210 cm GBH) and also due to the availability of very larger size-classes (up to 610 cm GBH) older trees in fair number. It might be due to the presence of nutrient-rich, porous and loamy soil in the forest (Gautam & Mandal, 2013).

4.5.2.5 Species IVI

The high scoring of IVI by *Shorea robusta* even in DF might be due to the high disturbance tolerant capacity of it. Sapkota *et al.* (2010) opined that diversity in Sal forests declines with increasing magnitude of disturbances, which in turn favors a higher dominance of Sal.

4.5.2.6 Phenology of some dominant tree species

Phenology is the study of relationship between climatic factors and periodic phenomena in plants. Phenological studies are significant for the conservation of plant genetic resources, forestry management, a better understanding of the ecological adaptations of plant species and community level interactions, and plant-animal interactions in the community. Leaf fall is a major vector of nutrient cycling between plants and soil. The phenology usually depends on species composition, plant communities, climatic conditions and edaphic factors.

A strong seasonality was observed with respect to vegetative and reproductive phenology of dominant tree species in moist tropical forest ecosystems. In most of the dominant species leaf fall showed distinct seasonality, with a peak during the dry season (March and April) which is also supported by the maximum litterfall in the studied forest during March and April. The high rate of leaf litterfall during the dry season is interpreted as a way to evade water stress through reducing leaf area. The results of this study revealed that leaf flushing and flowering were simultaneous in most of the species exhibiting major peak in March-April while fruiting behavior was extended up to cool and dry winter.

4.5.2.7 Pattern of dispersion

Most of the tree species in UF (52) and all species in DF showed the contagious (Clumping or aggregation) pattern of distribution. Similar result was reported by Tripathi and Singh (2009) for moist tropical deciduous forests of north India.

According to Odum (1971), contagious distribution is the commonest pattern of plant distribution in nature. It is common in tropical forests due to the low seed availability, restricted mode of seed dispersal (dispersal limitation) or due to the large gap formation resulted by natural or anthropogenic disturbances (Odum, 1971). The random dispersion of species in the forest may be associated with frequent and large-scale fire.

CHAPTER– 5

5. BIOMASS AND NET PRIMARY PRODUCTION

5.1 INTRODUCTION

Biomass and production are important parameters for characterizing a forest ecosystem. The status of carbon in a forest reflects environmental conditions such as climate, soil, structure, nutrient availability and disturbance (Chave *et al.*, 2001). Forest disturbances often lead to the changes in species composition, density, stand biomass and productivity. Tropical forests contain about 55% of global forest C (Pan *et al.*, 2011) and account for 34% of terrestrial gross primary production (Beer *et al.*, 2010). Tropical forests and savannas account for over 60% of global terrestrial photosynthesis, and play a significant role in the global C cycle (Malhi *et al.*, 2014). Therefore, a small disruption in this biome could result in a significant change in the global C cycle. Biomass or C content of tropical forests has changed constantly over time as a result of past disturbances by people and natural catastrophes (Pan *et al.*, 2013). Hence a complete knowledge of biomass, productivity and C cycling of tropical forests is inevitable.

Generally, the destruction of forest results in loss of biodiversity, degradation in forest structure, decrease in forest biomass and production. Studies on biomass help to assess the effect of disturbances on productivity, nutrient cycling and stability of forest stands. Primary production is generally influenced by the availability of nutrients which in turn depends on the amount of organic matter present in the soil, and its rate of decomposition and mineralization. Shed fine roots together with litter from aerial parts of plants provide the materials for the decomposition. Changes in these fundamental components of ecosystem, due to forest disturbances, prompted this study.

Fine root is one of the dynamic components of below-ground biomass. It comprises about 30% of the aboveground biomass (Noordwijik *et al.*, 1996), while as far the production is concerned it contributes between 40–85% of the net primary production (Hendricks *et al.*, 2006; Hoffmann & Usoltsev, 2001), which reflects how vital it is for forest ecosystem.

Fine roots absorb water and nutrients from the soil. They influence the soil organic matter and nutrient cycling in the terrestrial ecosystems (Hendricks *et al.*, 2006). They contribute significantly to forest soil C flux and help in the reduction of elevated carbon dioxide concentration in the atmosphere. The contribution of fine roots in the carbon and nutrients input to soil is equivalent or even higher to that from leaf litter in moist tropical forests (Roderstein *et al.*, 2005).

Fine root dynamics and their governing factors are not well studied in moist tropical forests (Kochsiek *et al.*, 2013). They are influenced by various factors like soil nutrients, soil water and species composition. They show quick response to changes in water and nutrient availability (Espeleta & Clark, 2007). There exist two views regarding the effect of nitrogen on fine root production. According to some studies, nitrogen fertilization increases the fine root production and turnover (Pei *et al.*, 2012; Yuan & Chen, 2012b) whereas other studies indicate uncertain and opposite results (Maycock & Congdon, 2000; Nadelhoffer, 2000).

Most of the researches in tropical forests are confined to aboveground systems (Chave *et al.*, 2008; Hertel *et al.*, 2009; Aragão *et al.*, 2009; Chave *et al.*, 2010; Swamy *et al.*, 2010; Djomo *et al.*, 2011; Cleveland *et al.*, 2011; Malhi *et al.*, 2011; Ngo *et al.*, 2013; Doughty *et al.*, 2013; Banin *et al.*, 2014; Raich *et al.*, 2014; Malhi *et al.*, 2014; Girardin *et al.*, 2014). Only few studies are concerned to the belowground aspect of tropical forests (Ibrahima *et al.*, 2010; Powers & Peréz-Aviles, 2013; Noguchi *et al.*, 2014). In order to quantify the forest biomass and production, and C stock accurately, both aboveground and belowground aspects should be estimated carefully.

In Nepal, only few studies have been made regarding the biomass, production, and C sequestration in tropical (Mandal, 1999; Baral *et al.*, 2009) and temperate (Limbu *et al.*, 2013) forests. Further, what is the effect of disturbance on the biomass production and carbon dynamics in moist tropical forest is insufficiently known. As the biomass production is reduced due to disturbance the C stocks and sequestration will also be reduced which can help to assess the C emission. Therefore, the present study was designed with the following specific objectives: 1) to estimate the biomass of herb, shrub and tree species in undisturbed and disturbed forest stands; 2) to estimate the level of litterfall and litter mass in both stands; 3) to assess the net primary production (NPP) of the forest; 4) to understand the fine root dynamics (biomass, production, turnover, and seasonality) in the forest; 5) to find out the effect of disturbance on biomass, production and carbon sequestration capacity of the forest.

5.2 LITERATURE REVIEW

5.2.1 Biomass, production and carbon dynamics

Thapa-Magar & Shrestha (2015) analyzed the carbon stock in the living biomass of nine community managed Sal forests in mid hills of central Nepal. The carbon stock of forests ranged from 70-183 Mg ha^{-1}. The carbon stock increased with increasing soil organic carbon (SOC) and management duration but did not vary with species richness and litter cover.

Pandey *et al.* (2014) estimated aboveground (AG) and belowground (BG) C stocks in 105 community forests of Nepal. Average AG and BG biomass C (Mg C ha^{-1}) in dense and sparse *Shorea robusta* forests were 129.9 and 89.2 Mg C ha^{-1}, respectively (total 121.2 Mg C ha^{-1}) whereas the biomass C for dense and sparse mixed broadleaved forest was 118.0 and 69.5 Mg C ha^{-1}, respectively (total 110.3 Mg C ha^{-1}). Similarly, change in biomass C/year in dense and sparse *Shorea robusta* forests was 5.6 and 2.9 Mg C ha^{-1} yr^{-1}, respectively (total 5.0 Mg C ha^{-1}) whereas that for dense and sparse mixed broadleaved forest was 5.6 and 2.9 Mg C ha^{-1} yr^{-1}, respectively (total 5.8 Mg C ha^{-1}). *Shorea robusta* forests were analyzed in Chitawan and Gorkha districts while mixed broadleaved forests was studied in Chitawan district.

Girardin *et al* (2014) measured the productivity and C allocation in two 1-ha plots in a tropical montane cloud forest in the Peruvian Andes. Net primary production (NPP) ranged between 7.05 ± 0.39 and 8.04 ± 0.47 Mg C ha^{-1} yr^{-1}, and gross primary production (GPP) between 22.33 ± 2.23 and 26.82 ± 2.97 Mg C ha^{-1} yr^{-1}. Strong seasonality was found in NPP, suggesting that forest NPP is driven by changes in photosynthesis due to variation in solar radiation. Trees invest more in biomass production in the cooler season with lower solar radiation and more in maintenance during the warmer and high solar radiation period.

Malhi *et al.* (2014) presented the C budget of two forest plots in south-eastern Peru, western Amazonia. The NPP for the two plots was 15.1 ± 0.8 and 14.2 ± 1.0 Mg C ha^{-1} yr^{-1}, the GPP was 35.5 ± 3.6 and 34.5 ± 3.5 Mg C ha^{-1} yr^{-1}, and the carbon use efficiency (CUE) was 0.42 ± 0.05 and 0.41 ± 0.05. Net primary production and CUE showed a large degree of seasonality.

Raich *et al.* (2014) compared mature humid tropical forest and nearby tree plantations (15–20 year old) in Costa Rica to evaluate differences in allocation of C to AG production and root systems. The tree plantations, which had fully developed closed canopies, allocated more C belowground than did mature forest. This increase in BG carbon allocation correlated significantly with AG tree growth but not with canopy production (i.e., leaf fall or fine litter production). Enhanced allocation of C to root systems can enhance plant nutrient uptake, providing nutrients beyond those required for the production of short-lived tissues such as leaves and fine roots, and thus enabling biomass accumulation.

Banin *et al.* (2014) sampled aboveground wood production (AGWP) in Amazon (17 long-term forest plots) and Borneo (11 plots). Plot-level AGWP was positively associated with soil fertility and 49% greater in Borneo than in Amazonia (9.73 ± 0.56 vs. 6.53 ± 0.34 Mg ha^{-1} yr^{-1}, respectively).

Doughty *et al.* (2013) determined total NPP for fine roots, wood, and canopy from two 1-ha plots on contrasting soils in eastern Amazonia. Total NPP (15.77 ± 1.13 vs. 13.57 ± 0.60 Mg C ha^{-1} yr^{-1}) and rates of fine root production (6.41 ± 1.08 vs. 3.68 ± 0.52 Mg C ha^{-1} yr^{-1}) were greater at *terra preta* (dark earth) plots vs. infertile plot.

Limbu *et al.* (2013) studied C stock on vegetation at three rangelands: Milke (3,000 m), Gorujure (3,500 m) and Jaljale (4,000 m) in eastern Nepal. The estimated total vegetation C was 22.68, 29.79 and 42.54 t ha^{-1} at Milke, Gorujure and Jaljale, respectively. They concluded that the highest elevation site with least external disturbance (Jaljale area) had high storage of C.

Aboveground NPP and total below-ground carbon flux (TBCF) for the Bornean tropical rainforest were quantified (Katayama *et al.*, 2013). Gross primary production (30.61 Mg C ha^{-1} yr^{-1}) and aboveground NPP (6.76 Mg C ha^{-1} yr^{-1}) were comparable to, and TBCF (19.63 Mg C ha^{-1} yr^{-1}) was higher than, their respective values for Amazonian rainforests.

Alvarez-Clare *et al.* (2013) studied the effect of N or P on net primary productivity in lowland tropical forests of Costa Rica. They found no community-level responses to N or P additions on basal area increase, litterfall productivity, or root growth.

Ngo *et al.* (2013) estimated C stocks in primary and secondary forests in Singapore. Total C stock in the primary forest (80–115 m elevation) was 337 Mg C ha^{-1}, of which 50% was in aboveground biomass (AGB), 33% in soil (3 m depth), 12% in coarse roots, 4.6% in coarse woody debris, and 0.8% in fine roots (3 m depth). In the secondary forest (50–85 m elevation), the total C stock was 274 Mg C ha^{-1} with 38% in AGB, 52% in soil, 6.9% in coarse roots, 1.5% in coarse woody debris, and 1.3% in fine roots.

Unger *et al.* (2012) examined the impact of soil chemistry on AGB and production in mature tropical forest stands of the equatorial Andes, spanning from 500 to 2000 m elevation, in Ecuador. The AGB remained invariant (344 ± 17 Mg ha^{-1}) with elevation while stem wood production decreased from 4.5 to 3.2 Mg ha^{-1} yr^{-1}, indicating a higher biomass turnover at lower elevations. They concluded that both N and P availability significantly influenced productivity, indirectly through alterations in wood specific gravity and stem density.

Becknell *et al.* (2012) reviewed 44 published and unpublished studies that estimated AGB in seasonally dry tropical forests (SDTFs) around the world. AGB in mature SDTF ranged from 39 to 334 Mg ha^{-1}. A single climatic variable, mean annual precipitation, explained over 50% of the variation in AGB.

Malhi *et al.* (2011) analyzed a global dataset of NPP allocation between canopy, woody tissue and fine roots in tropical forests. On average, the data suggested an equal partitioning of resources between all three main components (mean 34± 6% canopy, 39 ± 10% wood, 27 ± 11% fine roots. They added that where all main components of NPP cannot be measured, litterfall is a good predictor of overall NPP ($r^2 = 0.83$).

Cleveland *et al.* (2011) conducted a meta-analysis of C-nutrient-climate relationships in 113 sites across the tropical forest biome. The analyses showed that mean annual temperature was the strongest predictor of aboveground NPP across all tropical forests. But within lowland tropical forests (< 1000 m), P availability regulates NPP and other ecosystem processes.

Based on forest inventory data and long-term ecosystem C studies, Pan *et al.* (2011) estimated a total forest sink of 2.4 ± 0.4 Pg C yr^{-1} globally for 1990 to 2007. They also estimated a source of 1.3 ± 0.7 Pg C yr^{-1} from tropical land-use change, consisting of a gross tropical deforestation emission of 2.9 ± 0.5 Pg C yr^{-1} partially compensated by a C sink in tropical forest regrowth of 1.6 ± 0.5 Pg C yr^{-1}. Together, the fluxes comprise a net global forest sink of 1.1 ± 0.8 Pg C yr^{-1}.

Fonseca *et al.* (2011) estimated biomass and C accumulation in humid tropical secondary forests of Costa Rica. Average C content was 4.1% in soil, and 82.2 Mg ha^{-1} in plant biomass. The mean annual increment for C in the biomass was 4.2 Mg ha^{-1} yr^{-1}. About 65.2% of total biomass was found in the aboveground parts, while 14.2% was found in structural roots and the rest in the herbaceous vegetation and necromass.

Djomo *et al.* (2011) collected biomass data from different vegetation types and land uses in a moist evergreen tropical forest in Cameroon. The average C biomass (aboveground C, root C and SOC down to 30 cm depth) was 264 ± 48 Mg ha^{-1}. This value varied from 283 ± 51 Mg ha^{-1} of C in managed forests to 278 ± 56 Mg ha^{-1} of C in national park.

Forest structure and live AGB variation along an elevation gradient (0–1100 m) of Atlantic Forest in SE Brazil was studied (Alves *et al.*, 2010). Live AGB ranged from 166.3 Mg ha^{-1} to 283.2 Mg ha^{-1} and increased with elevation. Across all elevations, the largest proportion of the live AGB (68–85%) was stored in stems.

The functions of tropical evergreen forests of Western Ghats, India were studied by Swamy *et al.* (2010). Total stand biomass averaged from 440 to 571 Mg ha^{-1}, of which trees contributed 90.2–92.2% and remaining 8.8–9.8% by shrubs and herbs. The standing litter ranged from 3.5 to 4.2 Mg ha^{-1} and litter production from 4.0 to 5.7 Mg ha^{-1} yr^{-1}. The average NPP was 23.7 Mg ha^{-1} yr^{-1}, of which 64.7% was contributed by trees, 13.6% by shrubs, 2.7% herbs and 19.1% by litter. Turnover rate and turnover time ranged from 0.93 to 0.95 yr^{-1} and 1.05 to 1.08 yrs respectively.

Baral *et al.* (2009) assessed the aboveground C stock in the five major forest types of varying age (18–75 years) in Nepal. The aboveground C stock varied from 34.30–97.86 Mg ha^{-1} and rate of carbon sequestration from 1.30–3.21 t ha^{-1} yr^{-1} in different forest types. Tropical riverine and *Alnus nepalensis* forest types demonstrated the highest C sequestration rates.

Above and below ground NPP of ten Amazonian forests was quantified (Aragão *et al.*, 2009). The NPP ranged between 9.3 ± 1.3 to 17.0 ± 1.4 Mg C ha^{-1} yr^{-1}, with an overall average of 12.8 ± 0.9 Mg C ha^{-1} yr^{-1}. These forests allocated 64 ± 3% and 36±3% of the total NPP to the aboveground and belowground components, respectively. Litterfall and fine root production both increased with total NPP. Total NPP slightly increased with soil P and leaf N status.

The AGB and NPP were estimated in Dipterocarpus forest of Manipur, Northeast India (Supriya Devi & Yadava, 2009). The total biomass ranged from 18.27 to 22.50 t ha^{-1}, and annual aboveground NPP varied from 8.86 to 18.27 Mg ha^{-1}.

Biomass and productivity of six tropical forest stands (ca. 1000 m elevation) on Sulawesi (Indonesia) was determined (Hertel *et al.*, 2009). The mean total biomass of the stands was 303 Mg ha^{-1} (or 128 Mg C ha^{-1}), with the largest biomass fraction in the AG components (286 Mg ha^{-1}) and 11.2 and 5.6 Mg ha^{-1} of coarse and fine root biomass (300 cm depth). The total above- and below-ground NPP was estimated as 15.2 Mg ha^{-1} yr^{-1} (or 6.7 Mg C ha^{-1} yr^{-1}) with 14% of this being invested BG and 86% representing above-ground NPP.

Baishya *et al.* (2009) compared tree AGB and C storage in different DBH classes between natural forest (NF) and sal plantation forest (PF) in humid tropical region of northeast India. The AGB was lower (323.9 Mg ha^{-1}) in NF than the PF (406.4 Mg ha^{-1}). About 49% of the AGB was present in > 60 cm DBH trees in the NF against 24% in the PF. The C storage was highest in 60-80 cm and 40-60 cm DBH classes in the NF and PF, respectively.

Carbon stock was assessed in four types of forest: dense Sal (DS), degraded forest (DF), pine mixed (PS), and *Schima-Castanopsis* (SC) in the Pokhare Khola watershed of Nepal (Shrestha & Singh, 2008). The vegetation C pool was largest in DS forest (219 ± 34 Mg ha^{-1}) and least in SC forest (36 ± 5 Mg ha^{-1}), its order among forest types was DS > DF > PS > SC.

Dynamics of tropical forest woody plants was studied at the Nouragues Field Station, central French Guiana (Chave *et al.*, 2008). AGB ranged from 356 to 398 Mg ha^{-1}. Leaf biomass was 6.47 Mg ha^{-1}. Total aboveground NPP was 8.81 Mg C ha^{-1} yr^{-1}. Litterfall contributed 4.65 Mg C ha^{-1} yr^{-1} with 3.16, 1.10, and 0.39 Mg C ha^{-1} yr^{-1} due to leaves, twigs, and to fruits and flowers, respectively.

Upadhyay *et al.* (2005) reviewed the literature to know the effect of disturbances on C sequestration in the Hindu Kush Himalayan region. The net emission of C due to land-use changes in Nepal was 6.9×10^{6} to 42.1×10^{6} Mg yr^{-1}. It indicated a high potential for enhancing the C sequestration in the Himalayas through the better management of degraded lands.

Biomass was analyzed in tropical American lowland rainforest (terra firme forest), considering the estimates of live tree AGB and total aboveground biomass by Sarmiento *et al.* (2005). Belowground biomass comprised about 20% of the aboveground part. They also added that mature forests, having high canopy, would allocate a smaller proportion of their carbon to below-ground structures.

Clark *et al.* (2001) synthesized the data from the primary literature on NPP in old-growth tropical forests. The BG production range was 0.2–1.2 X ANPP. Across this broad spectrum of tropical forests (dry to wet, lowland to montane, nutrient-rich to nutrient-poor soils), the total NPP ranged from 1.7 to 11.8 Mg C ha^{-1} y^{-1} (lower bounds) and from 3.1 to 21.7 Mg C ha^{-1} y^{-1} (upper bounds).

Mandal (1999) studied the recovery pattern in biomass and net production of plants in five landslide damaged sites of varying ages (1, 4, 15, 40 and 58 years) and a nearby mature forest in Plateau Sal forest ecosystem of Nepal Himalaya. Oven dried stand biomass increased with the age of landslides while net production increased up to 40 years and then decreased. The stand biomass in mature forest site was reported as 729 t ha^{-1} while net production was 22.1 t ha^{-1} yr^{-1}.

Karmacharya and Singh (1992a) estimated the biomass and net production of teak plantations in a dry tropical region in India. The AGB ranged from 25.7 to 76.9 Mg ha^{-1} whereas net production at the age of 30 years was reported as 12.9 Mg ha^{-1}.

Plant biomass and NPP were studied on three sites of a dry tropical forest (Singh & Singh, 1991a). Total standing crop of vegetation averaged 66.98 t ha^{-1} with 46.70 t ha^{-1} in the tree layer, 13.97 t ha^{-1} in the shrub layer, 0.35 t ha^{-1} in the herb layer, 2.83 t ha^{-1} in the litter layer and 3.13 t ha^{-1} in fine roots. Of the total annual litterfall (4.88−6.71 t ha^{-1}), 69% was accounted for by leaves and 31% by non-leaf matter. Net primary production ranged between 11.3 and 19.2 t ha^{-1} yr^{-1}, to which the contributions of trees, shrubs and herbs averaged 72, 22 and 6%, respectively. Contribution of fine roots to NPP was substantial and ranged from 2.9 to 5.3 t ha^{-1} yr^{-1}.

5.2.2 Litterfall

Xu *et al.* (2013) compiled 68 studies on litter addition or removal experiments, and concluded that litter addition or removal although significantly alter soil temperature and moisture, but not soil pH. Soil microbial biomass C, total C, total N and the C:N ratio in the soil increased with increased litter inputs.

The pattern of litterfall was studied in common banj oak and chir pine forests in Uttarakhand, India (Rawat, 2012). The mean annual litter fall was 6.25 ± 0.26 t ha^{-1}. The mean litter fall value was higher in the summer season (2.86 ± 0.39 t ha^{-1}) and minimum in winter season (1.53 ± 0.04 t ha^{-1}).

Shin *et al.* (2011) assessed litter dynamics for four years in a *Quercus mongolica* forest in Korea. The average amount of leaf litter, branch and bark, reproductive organs (flowers and nuts), and miscellaneous categories were 2.92, 1.11, 0.63 and 0.84 t ha^{-1} yr^{-1}, respectively. The average amount of litterfall was 5.49 t ha^{-1} yr^{-1}. The average amount of N, P and K returned to the forest floor via litterfall were 53.4, 3.8, 17.8, 17.2 and 5.8 kg ha^{-1} yr^{-1}, respectively.

Nitrogen, P and K addition experiment was performed for 11 years in a humid lowland forest on fertile soil in Panama (Wright *et al.*, 2011). The addition of P was associated with a marginally significant increase in fine-litter production.

Swamy *et al.* (2010) analyzed litterfall of tropical evergreen forests of Western Ghats, India. The standing litter ranged from 3.5 to 4.2 Mg ha^{-1} and litter production from 4.0 to 5.7 Mg ha^{-1} yr^{-1}. Turnover rate and turnover time ranged from 0.93 to 0.95 yr^{-1} and 1.05 to 1.08 yrs respectively.

Datasets from 81 sites were used to assess the determinants of litterfall variation across South American tropical forests (Chave *et al.*, 2010). Average litterfall in old growth and secondary tropical forests were 8.61 ± 1.91 and 8.01 ± 3.41Mg ha^{-1} yr^{-1}, respectively. Litterfall seasonality did not depend on annual rainfall or on soil type. Mean leaf fall was 71% while reproductive organs comprised 9% of total litterfall.

Matala *et al.* (2008) analyzed the global literature and found that the stand-level litter fall was significantly correlated with growth of stemwood volume, basal area, stand volume and latitude but not clearly correlated with stand age and density.

Wang *et al.* (2008) studied litter production in two forest stands of southern China. About 65% of total litterfall occurred during the cool and dry period (November–March). The mass loss of leaf litter was positively correlated with N and P content and negatively correlated with C/N ratio.

Pandey *et al.* (2007) studied the pattern of litterfall in subtropical natural oak forest and managed plantation in northeastern India. Total litterfall was 419.9 g m^{-2} yr^{-1} in plantation and 547.7 g m^{-2} yr^{-1} in natural forest.

Aboveground fine litterfall was estimated in mature forest of Indonesia (Paoli & Curran, 2007), which ranged from 5.1 to 11.0 Mg ha^{-1} yr^{-1}. Fine litterfall was weakly related to aboveground NPP but increased strongly with extractable P.

Fine litter production and standing crop of litter was estimated in two tropical dry evergreen forests in the Coromandel Coast of India (Pragasan & Parthasarathy, 2005). Fine litter production ranged between 13.51 to 13.27 t ha^{-1} yr^{-1}, while the standing crop of total forest floor litter ranged 4.11 to 4.86 t ha^{-1}. Leaves formed 67.9 to 71.4% of the total litter. Litter production peaked during summer at both the sites.

5.2.3 Fine root

Noguchi *et al.* (2014) estimated fine root biomass (FRB) in a moist tropical forest in Brazil. More than 74 and 93% of the FRB was distributed within the upper 20 and 40 cm soil layers, respectively.

A study measured live and dead fine roots of ≤ 2 mm diameter (0–10 cm depth) in regenerating tropical dry forest in Costa Rica (Powers & Peréz-Aviles, 2013). Total, live, and dead fine roots were negatively correlated with a multivariate index of soil fertility and other individual edaphic variables including pH, silt, calcium, magnesium, N, and P.

Using root cores and ingrowth cores, Kochsiek *et al.* (2013) quantified fine root in clay and sandy loam soils. The standing FRB was higher in sandy loam, the soil type that is better-drained and less fertile for most nutrients. In clay, specific root length (m/g) (total fresh length/total dry mass of fine roots in a core) was significantly greater, and turnover tended to be faster, than in sandy loam.

The dynamics of fine roots in a tropical dry mixed evergreen forest and an arboretum in the dry zone of Sri Lanka was studied (Kuruppuarachchi *et al.*, 2013). Annual mean FRB of the forest and the arboretum were 5.72 and 7.88 t ha^{-1}, respectively; with C densities of 2.69 and 3.7 t ha^{-1}, respectively.

The fine root dynamics was studied by a sequential soil coring method in the southern Xinjiang, China (Pei *et al.*, 2012). The FRB, necromass, and production significantly increased from April until it peaked in August, and then it decreased. Mean turnover rate in the 0–120 cm soil layer was 1.52 to 1.60 yr^{-1}. Fine root turnover (FRT) rate did not differed significantly among the soil layers.

Richter *et al.* (2012) studied the fine root dynamics in European beech (*Fagus sylvatica* L.) stands. The FRB, necromass, production and mortality decreased significantly with soil depth. No relationship was observed between any of the soil chemical parameters and the FRB, necromass, production and mortality. A significant negative correlation was found between soil pH and FRT.

Fine root properties were studied in undisturbed stand and disturbed stands of a tropical wet forest of India and were found to differ significantly between the stands (Barbhuiya *et al.*, 2012). In the highly disturbed stand, more than 90% of the FRB was recorded in the surface soil layer whereas in the moderately disturbed and undisturbed stands the proportion averaged 67%. Root turnover also decreased with increasing soil depth, root size and intensity of stand disturbance. In the undisturbed, moderately disturbed and highly disturbed stands the annual FRT was 3181, 1701 and 822 kg ha^{-1} yr^{-1}, respectively.

Fine root (<2 mm in diameter) dynamics was studied in a post fire chronosequence (3, 11, 29, 94, 142 and 205 years since fire) from both sequential and ingrowth cores in boreal forest (Yuan & Chen, 2012a). The FRT was faster in young stands than in old stands. Fine root dynamics were influenced by changes in species composition and soil properties.

The effect of nutrient availability on FRP was studied by synthesizing data from 410 natural habitats and from 469 N and/or P addition experiments (Yuan & Chen, 2012b). Result showed that FRP increased with the increase in soil total N up to 0.5%. Fine root production also increased with soil P up to 300 mg kg $^{-1}$, and then plateaued or even decreased at sites with high total P. With N, P and combined N + P addition, FRP increased by a global average of 27, 21 and 40%, respectively.

Finér *et al.* (2011a) compiled global data to estimate FRP and turnover for boreal, temperate and tropical forests. The FRP for all plants (trees + understorey) was 311, 428 and 596 g m^{-2} yr^{-1} in the boreal, temperate and tropical forests, respectively, and the corresponding annual FRT rates were 0.77, 1.21 and 1.44, respectively.

Finér *et al.* (2011b) updated FRB estimates for different forest biomes using a database of 512 forest stands. The FRB of the whole rooting depth was 526 g m^{-2}, 775 g m^{-2} and 776 g m^{-2} for boreal, temperate and tropical forests, respectively. The mean basal area of the forest stand explained 49% of the total FRB and 79% of the FRB of trees.

Nitrogen, P, and K addition experiment was performed for 11 years in a humid lowland tropical forest in Panama (Wright *et al.*, 2011). The addition of K, and K plus N together significantly decreased stand-level FRB.

Griscom and Ashton (2011) reviewed the restoration pattern of dry tropical forests in Central America and concluded that disturbance history, including the extent to which trees were removed; post-disturbance management, introduction of exotic species, and the proximity of intact forest or regeneration sources all affect the regeneration rate and the amount of biomass attained by secondary forests.

Fertilization experiments with N and P was done in order to know the response of fine roots in lowland tropical moist forest in Panama (Yavitt *et al.*, 2011). Fine root turnover increased with the fertilization of K, and both K and N together in the forest soil. After 2 years, added K decreased fine root biomass from 330 to 275 g m^{-2}.

A study was made in mountain rainforests (1050 and 3060 m) of South Ecuador to know the response of tree fine roots to N, P and K fertilization in ingrowth cores (Graefe *et al.*, 2010). At 1050 m, root growth was stimulated by N, P and K. In contrast, N was the only element to promote root growth at 3060 m.

Total ecosystem carbon storage in a tropical seasonal forest in SW China was investigated by Lü *et al.* (2010). Living tree carbon stocks (both above- and belowground) ranged from 163 to 258 Mg C ha^{-1}. The mineral soil C pools (top 100 cm) ranged from 84 to 102 Mg C ha^{-1} and the C in woody debris from 5.6 to 12.5 Mg C ha^{-1}, representing the second and third largest C component in this ecosystem. High percentage (70%) of C was stored in biomass and less in soil.

Effects of logging on FRP were studied in the tropical rainforests of south-western Cameroon (Ibrahima *et al.*, 2010). Total fine roots decreased from 7.43 to 1.74 t ha^{-1} in undisturbed forests. Seventy to 80% of FRB were produced in the first 10 cm of soil depth. The FRP of disturbed forest was high.

Lima *et al.* (2010) evaluated the response of fine root dynamics to altered availability of soil water and nutrients in a 20-yr-old forest in eastern Amazonia. In one experiment the dry season reduction in soil moisture was alleviated by irrigation. In the other experiment, nutrient supply was reduced by litter removal. Dry-season irrigation had no significant effect on mass and length of live and dead roots, whereas litter removal reduced mass and length of live roots. For both irrigation and litter removal experiments, root growth was significantly greater in the dry season than in the wet season.

Fine root dynamics was studied along a gradient of increasing forest disturbance in Central Sulawesi, Indonesia (Leuschner *et al.*, 2009). Fine root biomass decreased markedly with increasing forest disturbance whereas FRT was higher in the more heavily disturbed stands.

Jimenez *et al.* (2009) measured the fine root (< 2 mm) by ingrowth cores and sequential soil coring in two lowland forests with different soils in the colombian Amazon. Both mass and production of fine roots were significantly different between soil depths (0–10 and 10–20 cm) and forests. The mass of fine roots also decreased substantially in the dry period.

Xiao *et al.* (2008) studied fine root dynamics by sequential soil coring method in a 60-year-old forest in China. Fine root mass, production, and turnover rate decreased along soil depth. The mean turnover rate of the finest roots (<1 mm), very fine roots (1–2 mm) and fine roots of the two size classes were 0.63, 0.39 and 0.51 yr^{-1} respectively.

Uselman *et al.* (2007) estimated FRP by ingrowth cores method in California and found positive correlations with soil N and soil water content but negative correlation with soil P. Fine root production increased significantly with ecosystem age.

Valverde-Barrantes *et al.* (2007) studied fine root of six tropical tree species (up to 1 m depth) in 16-year-old plantations in the Costa Rica. Under all species > 60% of the total FRB was located in the uppermost 15 cm of the soil.

Harteveld *et al.* (2007) studied the effect of disturbance on the FRB and production in a tropical moist forest in Sulawesi. All FRB, necromass and FRP decreased with increasing intensity of forest use. Fine root biomass and necromass did not differ along the disturbance gradient. No seasonality was observed in fine root mass.

Green *et al.* (2005) studied the influence of rainfall on FRB in a tropical rainforest in Malaysia. Fine root (< 2 mm) biomass was 1700 kg ha^{-1}. Standing root biomass was positively correlated with preceding rainfall. Low FRB in the dry season had higher concentrations of N and lower concentrations of P and K than at other times.

Relationships among climate, edaphic conditions and below-ground carbon storage were studied along a wet tropical climate gradient (McGroddy & Silver, 2000). Total soil C and P pool were significantly related to soil moisture. Total fine root biomass was strongly and positively correlated with soil moisture content.

5.3 MATERIALS AND METHODS

5.3.1 Plant biomass estimation

Central part of the forest was treated as undisturbed forest (UF), and ii) peripheral part as disturbed forest (DF). At each forest stand, plant biomass was estimated within the thirty five randomly established sampling plots established for vegetation analysis. In the present study stem of tree-species having ≥ 10 cm GBH were considered as trees (Lalfakawma, 2009). For the estimation of tree biomass (>10 cm GBH), quadrats of 20 m x 20 m were used, while for the shrubs and herbs nested quadrats of 5 m x 5 m and 1 m x 1 m were used, respectively.

Girths of all trees at breast height (1.37 m above the soil) and shrubs (10 cm above the ground level) lying within each plot were measured. Biomass of trees in plots was estimated by using girth: biomass allometric equations (Table 26) for sub-montane Sal forest in Southern Siwaliks (available only for trees ≥ 30 cm girth) published by Singh and Singh (1992). For estimating coarse root biomass, roots: shoot ratio of 0.21 proposed by Malhi *et al.* (2009; 2014) for lowland tropical forests was used. For the estimation of biomass of Sal trees having < 30 cm GBH and of shrubs, girth: biomass regression equations developed by Mandal (1999) (Table 26) for the Sal forest of eastern Siwaliks of Nepal Himalaya was used.

Table 26. Allometric relationships between the biomass of tree and shrub components (Y, kg tree^{-1}) and circumference of tree (X, cm at 1.37 m height) and shrub (X, cm at 10 cm height) from ground.

Biomass (kg tree^{-1})	Intercept (a)	Slope (b)	r^2
Trees			
Shorea robusta			
Bole	-2.832	1.976	0.980
Branch	-2.037	1.501	0.992
Twig	-2.688	1.463	0.980
Leaf	-1.736	1.175	0.960
Total	-1.789	1.892	0.980
Mallotus philippinensis			
Bole	-2.1425	1.398	0.922
Branch	-2.2820	1.215	0.960
Twig	-2.3285	0.810	0.922
Leaf	-3.8605	1.066	0.902
Total	-1.2385	1.281	0.960
Interspecies for *Shorea* forest			
Bole	-5.0299	2.333	0.792
Branch	-5.2096	2.081	0.828
Twig	-4.6330	1.683	0.487
Leaf	-4.9546	1.679	0.420
Total	-4.3138	2.214	0.689
Shorea robusta (10–30 cm girth) class			
Bole	-4.5149	2.2173	0.9498
Branch	-6.9930	2.3647	0.9649
Twig	-8.0338	2.4048	0.9335
Leaf	-4.0232	1.3612	0.9247
Root	-4.2725	1.8340	0.9285
Total	-3.5428	2.0742	0.9456
Shrubs			
Maesa chisia			
Stem	-4.1008	1.6387	0.9405
Leaf	-3.1204	0.8399	0.7758
Root	-3.6681	1.2567	0.9735

Contd.

Contd. **Table 26**

Biomass (kg tree^{-1})	Intercept (a)	Slope (b)	r^2
Total	-2.6115	1.3016	0.9560
Murraya koenigii			
Stem	-3.5961	1.4555	0.9479
Leaf	-3.2336	0.7828	0.7701
Root	-3.2537	1.0923	0.9298
Total	-2.3899	1.2146	0.9392
Shrub species pool			
Stem	-7.1694	3.0945	0.9571
Leaf	-4.6354	1.4607	0.6621
Root	-6.9133	2.7756	0.9630
Total	-5.4841	2.6518	0.9684

The equation is $\text{LnY} = a + b \text{ Ln X}$; where Ln is natural log, a intercept of Y and b is slope or regression coefficient. Equations for *Shorea robusta*, *Mallotus philippinensis* and Interspecies for *Shorea* forest are from Singh & Singh (1992); and for *Shorea robusta* (10–30 cm girth class) and shrubs are from Mandal (1999).

The aboveground herbaceous biomass was harvested at all sites twice, in summer (May 2012) representing annual lowest biomass, and at the end of rainy season (September 2012) representing annual peak biomass. Summer and rainy season values were averaged to obtain annual mean herbaceous biomass.

Fine roots (< 5 mm diameter) were collected from seventy randomly established locations, thirty five each in UF and DF. Fine root biomass (FRB) was determined from soil monolith (10 x 10 x 30 cm^3), divided into two depth ranges (upper: 0–15 and lower: 15–30 cm) at each location in summer (May 2011), rainy (September 2011) and winter (January 2012) seasons. Soil monoliths were washed over a jet of water and any adhering materials were removed manually. All fine roots were handpicked with forceps without separating them into live and dead mass. Fine roots were divided into two size classes (smaller: 0–2 and larger: 2–5 mm diameter) for the estimation of biomass. Summer, rainy and winter season values were averaged to obtain annual mean fine root biomass.

5.3.2 Litter mass and Litterfall

Litter mass accumulated at each site was collected once every season from one 1 m x 1 m plot and separated as: (a) fresh leaf litter, (b) non-leaf litter (including reproductive parts also, i.e. flower, fruit and seed) (c) partly decayed leaf litter (including highly fragmented dark material on the soil surface) and (d) partly decayed non-leaf litter. For the estimation of litterfall one litter trap (1 m x 1 m) was fixed on the forest floor at each of the seventy sites. Litterfall was collected at monthly intervals from April 2012 to March 2013 and categorized into leaf and non-leaf components.

The turnover rate (k) of litter was calculated following Jenny *et al.* (1949) as: $k = A / (A + F)$, where A is the annual litterfall and F is the mass of litter at steady state. In the present study, the F value for leaf litter was assumed to be equal to the partly decayed leaf litter mass during the winter season, and for non leaf, equal to the non-leaf litter mass during the winter season. For total litter (leaf + non-leaf), F was assumed to be the sum of partly decayed leaf and non-leaf litter mass during the winter season. Turnover time, the reciprocal of turnover rate was expressed as: $t = 1 / k$.

5.3.3 Net production

Using the allometric equations, the aboveground biomass of different components of marked trees / shrubs in permanent sites was computed for 2011 (B_1) and 2012 (B_2) from respective girth measurements. The net changes in biomass ($\Delta B = B_2 - B_1$) of components yielded annual biomass increments which were summed to get the net aboveground biomass accretion in the trees / shrubs.

Volatile organic compound (VOC) production (a part of aboveground production) appears to be a very small component of the C cycle of tropical forests (Malhi *et al.*, 2009), and was not quantified in present study. As recommended by Singh *et al.* (1994), the annual leaf fall was added to the foliage biomass accumulation to represent leaf production and wood and miscellaneous litterfall values were added to the biomass accumulation in twigs. Aboveground herbaceous net production was estimated as the differences between maximum and minimum biomass values through the year.

Regarding the belowground production, coarse root was estimated as a fraction of stem production, following the method proposed by Malhi *et al.* (2009; 2014): NPP of coarse root = 0.21 × NPP of stem (where, 0.21is the mean ratio of belowground stocks to aboveground stocks reported across lowland tropical forests). Fine root production (FRP) (< 5 mm size class) was estimated as the differences between maximum (rainy season values) and minimum biomass values (summer season values). The fine root turnover was calculated as a ratio of its production and annual mean biomass (Srivastava *et al.*, 1986).

Root exudates and export to mycorrhizae, which are component of belowground production, were not measured in this study.

5.3.4 Carbon estimation in vegetation and litter

Samples of different tree components of all species were collected from each sampling plots from the representative individuals of all available girth classes. Samples of shrubs from different components and herbs (aboveground) were collected from each site. Composite samples of all components of trees, shrubs and herbs were oven dried at 80 ^{o}C to constant weight.

Litterfall samples (leaf litter and non-leaf litter) collected from the litter traps at monthly interval were pooled together to represent annual samples for each site. The oven dried samples of each component of plant, leaf litter and wood litter were used separately for further analyses. The fine roots of < 2 and 2‒5 mm diameter of all sampling locations were mixed separately and ground for chemical analyses.

Carbon present in plant materials was estimated by ash content method. Carbon concentrations were assumed to be approximately 50% of ash free weight (McBrayer & Cromack, 1980). In this method oven dried plant components like stem, branch, root, leaf, and litter (5g each) were burnt separately in electric furnace at 400 °C until the tissue was burned to a grayish-white ash. Ash content (inorganic elements in the form of oxides) left after burning was weighed and carbon concentration was calculated by using the following equation:

$$\% \text{ Carbon} = (\text{Initial weight} - \text{Ash weight}) \times 100/2$$

The carbon stock in vegetation was calculated by multiplying a carbon conversion factor (concentration of C) to dry weight. From the present study, a conversion factor of 0.470 was obtained to convert aboveground and coarse root biomass to carbon. To obtain carbon stock in fine roots a conversion factor of 0.430 and 0.455 was used for < 2 and 2-5 mm size class respectively. Moreover, the conversion factors of 0.453 and 0.468 were used for leaf and non-leaf litter, respectively.

5.3.5 Statistical analysis

Statistical analyses were done with MS excel 2007 and SPSS (IBM Statistics, ver. 20) packages. Before analysis, all data were tested for outliers and normality (Shapiro–Wilk test). Pearson's correlation coefficients were obtained between biomass, net production, stand density, basal area, and all soil variables. Before proceeding with correlation analysis, abnormal data of basal area in both UF and DF were log transformed.

Fine root biomass and production were correlated with soil physicochemical variables. A Pearson correlation matrix was used to correlate FRB and FRP with soil moisture, water holding capacity, bulk density, pH, soil organic C, total N, total phosphorus, potassium, organic matter, and microbial biomass: carbon, nitrogen and phosphorus from upper soil depth of undisturbed and disturbed forest stands. Regression analysis was done only between correlated variables, by considering fine root parameters as the dependent ones. Three way ANOVA was performed to know the effect of forest type, season and depth on the mean FRB. Further, Post Hoc test (LSD) was performed for season which had more than three groups (summer, winter and rainy) and had significant effect on dependent variables.

5.4 RESULTS

5.4.1 Plant biomass in the context of disturbance

Data on biomass and carbon stocks of trees, shrubs, herbs and fine roots are summarized in Tables 27–29. The total biomass estimated for the UF of the forest was 960.4 Mg ha^{-1} (equivalent to 452.06 Mg C ha^{-1}), while for DF it was 449.1 Mg ha^{-1} (equivalent to 211.33 Mg C ha^{-1}).

Table 27. Oven dried stand biomass (Mg ha^{-1} ± SE) and carbon stock (Mg C ha^{-1}) in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Components		Undisturbed forest		Disturbed forest	
		Biomass	Carbon stock	Biomass	Carbon stock
Trees					
	Bole	610.4 ± 20.0	287.5	281.5 ± 15.8	132.59
	Branch	119.4 ± 3.2	56.23	56.8 ± 3.1	26.75
	Twig	32.9 ± 1.6	15.59	14.5 ± 0.9	6.87
	Leaf	20.8 ± 0.8	9.67	9.5 ± 0.5	4.42
	Coarse root	164.5 ± 12.0	77.48	76.1 ± 11.0	35.84
	Total	948.0 ± 108.8	446.47	438.4 ± 50.1	206.47
Shrubs	Stem	2.0 ± 0.2	0.94	3.00 ± 0.4	1.41
	Leaf	1.0 ± 0.1	0.46	1.14 ± 0.1	0.52
	Root	1.4 ± 0.1	0.66	1.92 ± 0.2	0.90
	Total	4.4 ± 0.3	2.06	6.1 ± 0.5	2.83
Herbs *****		1.4 ± 0.1	0.61	1.2 ± 0.1	0.53
Total		953.8 ± 82.4	449.14	445.7 ± 37.8	209.83
Stand fine root		6.6 ± 0.1	2.92	3.4 ± 0.2	1.50
Total, Vegetation		960.4 ± 73.1	452.06	449.1 ± 33.6	211.33

*Aboveground parts

The total biomass of the tree layer was 948.0 Mg ha^{-1} in UF, which decreased to 438.4 Mg ha^{-1} in DF, due to disturbance in the forest. The tree biomass in UF and DF was significantly different ($P < 0.001$) at 95% confidence level. Of the total tree biomass, 83% was aboveground and 17% belowground (excluding fine root) in both forest stands (Table 28). The maximum contribution to tree aboveground biomass was made by bole in both stands (64% each) and minimum share belonged to foliage (2% each in both stands).

Table 28. Biomass (Mg ha^{-1} ± SE) of trees and shrubs and their distribution (%) in different components in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Components	Forest stands	
	Undisturbed forest	Disturbed forest
Trees	948.0 ± 109.0	438.4 ± 50.0
Bole (%)	64	64
Branch (%)	13	13
Twig (%)	4	3
Leaf (%)	2	2
Coarse root (%)	17	18
Shrubs	4.4 ± 0.3	6.1 ± 0.5
Stem (%)	45	49
Leaf (%)	23	19
Root (%)	32	32

Table 29. Carbon stock (Mg C ha^{-1}) estimates for undisturbed and disturbed forest stands of moist tropical forest of Sunsari district, eastern Nepal. Biomass was assumed to contain 47% carbon. Coarse woody debris (fallen and standing necromass) was not estimated.

Component	Undisturbed forest		Disturbed forest	
	Carbon stocks	% of total	Carbon stocks	% of total
Aboveground biomass	371.0	68.7	173.1	64.0
Coarse roots	78.14	14.5	36.7	13.6
Fine roots	2.92	0.5	1.5	0.5
Soil (to 30 cm depth)	88.10	16.3	59.3	21.9
Total	540.2	100	270.6	100

The biomass of shrubs increased from 4.4 Mg ha^{-1} (equivalent to 2.06 Mg C ha^{-1}) at UF to 6.1 Mg ha^{-1} (equivalent to 2.83 Mg C ha^{-1}) at DF. Contribution of shrub biomass to the total stand biomass was higher in DF (1.4%) than UF (0.5%). This happens due to loss in tree layer. The aboveground herbaceous biomass contributed 0.1% in UF and 0.3% in DF due to open area. The annual fine root biomass decreased by 49.5% due to forest disturbance (6.6 Mg ha^{-1} in UF to 3.4 Mg ha^{-1} in DF). Remarkable seasonal variation was observed in the amount of fine roots.

5.4.2 Interrelations between biomass and soil properties

Soil variables including sand, soil moisture, bulk density, pH, soil organic carbon, total nitrogen, total phosphorus, potassium, soil organic matter, and microbial biomass: carbon and nitrogen showed positive relationships with biomass of trees whereas silt, clay, water holding capacity, and microbial biomass phosphorus showed negative correlations in UF (Table 36). Moreover, almost all variables except sand and soil moisture showed non-significant negative correlations with tree biomass in DF.

5.4.3 Litterfall, litter mass and turnover

The total annual litterfall decreased by 54.2% in DF (Table 30). Leaves accounted for 69% (UF) to 76% (DF) of total litterfall while non-leaf litter formed the rest. Seasonal pattern exhibited a concentrated litterfall in summer season during March to June when more than 70% litterfall occurred in both stands (Figures 21–23).

Table 30. Annual litterfall (Mg ha^{-1} yr^{-1}) with their carbon stocks (Mg C ha^{-1} yr^{-1}) in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Litter components	Undisturbed stand			Disturbed stand		
	Litterfall	Carbon stocks	%	Litterfall	Carbon stocks	%
Leaf	8.1 ± 0.50	3.67	69	4.1 ± 0.06	1.86	76
Non-leaf	3.7 ± 0.03	1.73	31	1.3 ± 0.01	0.59	24
Total	11.8 ± 0.70	5.40	100	5.4 ± 0.13	2.45	100

The proportion of litterfall was highest during April (more than 27%) followed by March (more than 21%) in both forests. Compared to leaf fall, a greater proportion of annual non-leaf litterfall (30% in DF and 42% in UF) occurred during the rainy season.

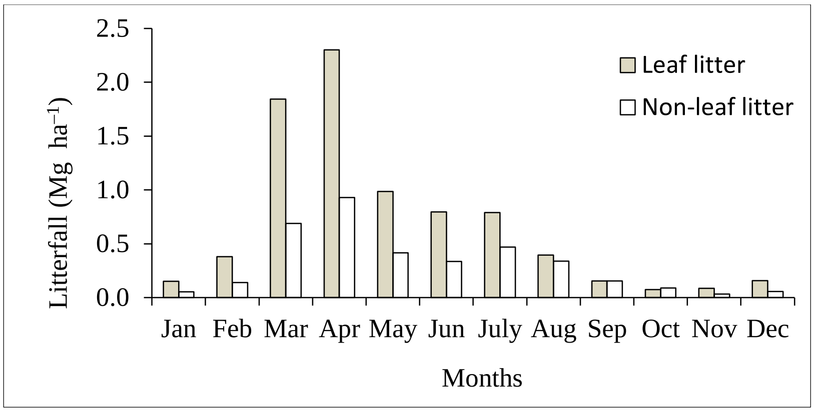

Figure 21. Monthly litterfall in undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

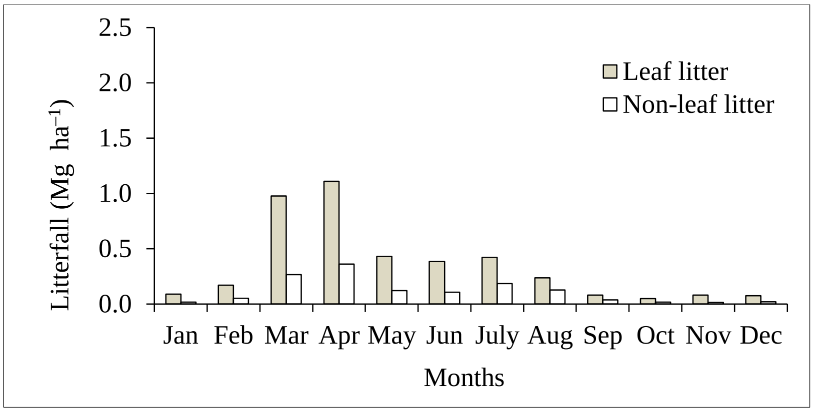

Figure 22. Monthly litterfall in disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

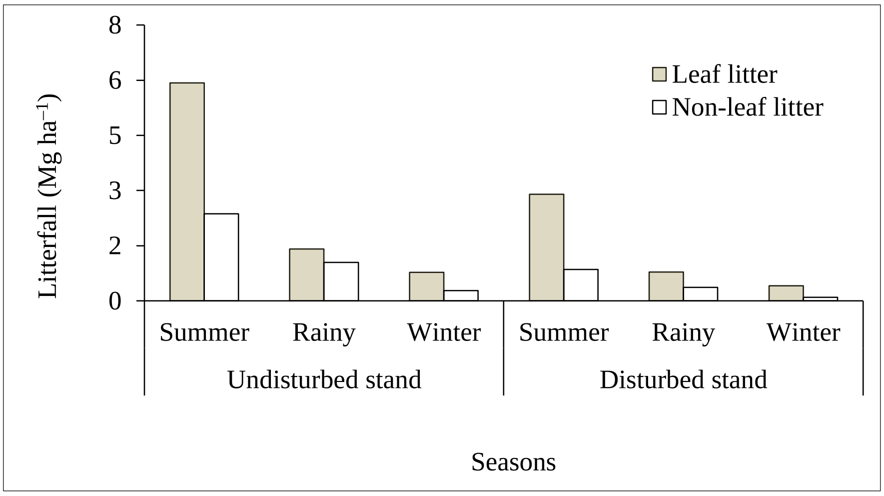

Figure 23. Seasonal variation in litterfall in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Forest floor litter mass also decreased due to forest disturbance. In litter mass, fresh litter mass accounted 64% while partly decayed litter mass comprised 36% in both stands (Table 31). The turnover rate (per yr) of the total litter ranged from 0.79 in DF to 0.83 in UF (Table 32). The turnover time (the reciprocal of turnover rate) of the total litter ranged between 1.21 and 1.26 years in UF and DF indicating 83% and 79% replacement of litter on the forest floor each year in these sites respectively.

Table 31. Forest floor litter mass (Mg ha^{-1} ± SE, average of three seasons) of undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal.

Litter mass components	Undisturbed forest		Disturbed forest	
	Litter mass	% of total	Litter mass	% of total
Fresh leaf	2.7	40	1.5	42
Non-leaf	1.6	24	0.77	22
Partly decayed leaf	1.4	21	0.83	23
Partly decayed non-leaf	1	15	0.47	13
Total	6.7 ± 0.35	100	3.6 ± 0.22	100

Table 32. Turnover (rate and time) of litter in undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal.

Turnover	Undisturbed forest			Disturbed forest		
	Leaf litter	Non-leaf litter	Total	Leaf litter	Non-leaf litter	Total
Rate (k/year)	0.85	0.77	0.83	0.82	0.73	0.79
Time (t, years)	1.17	1.3	1.21	1.22	1.38	1.26

5.4.4 Net Production in the context of disturbance

The total (above and belowground) net primary production (NPP) of vegetation comprising tree, shrub, herb (aboveground only) and fine root was 26.6 Mg ha^{-1} yr^{-1} (equivalent to an annual carbon sequestration of 12.26 Mg C ha^{-1} yr^{-1}) in UF and 14.9 Mg ha^{-1} yr^{-1} (i.e. 6.88 Mg C ha^{-1} yr^{-1}) in DF (Table 33). Among the different life forms: tree, shrub, and herb comprised 72%, 2%, and 6% of NPP in UF and 67%, 5%, and 9% in DF, respectively; while rest 20% NPP in UF and 19% in DF was contributed by stand fine root.

Table 33. Net primary production (NPP; Mg ha^{-1} yr^{-1}) and carbon allocation (Mg C ha^{-1} yr^{-1}) in different components of vegetation in undisturbed and disturbed stands of moist tropical forest of Sunsari district, eastern Nepal. No data were available for the root exudation, transfer to mycorrhizal hyphae and consumption by herbivores. Leaf litterfall was added in leaf production, whereas non-leaf litter fall was added in twig production (mean ± SE).

Components		Undisturbed forest		Disturbed forest	
		NPP	Carbon allocation	NPP	Carbon allocation
Trees					
	Bole	4.78 ± 0.25	2.25	2.96 ± 0.16	1.39
	Branch	0.91± 0.05	0.43	0.57 ± 0.03	0.27
	Twig	3.93 ± 0.02	1.86	1.45 ± 0.01	0.69
	Leaf	8.24± 0.01	3.83	4.19 ± 0.01	1.95
	Coarse root	1.27 ± 0.02	0.60	0.79 ± 0.06	0.37
	Total	19.13 ± 1.21	8.97	9.96 ± 0.75	4.67
Shrubs	Stem	0.30 ± 0.03	0.14	0.42 ± 0.04	0.20
	Leaf	0.07 ± 0.04	0.03	0.08 ± 0.01	0.04
	Root	0.18 ± 0.02	0.08	0.25 ± 0.02	0.12
	Total	0.55 ± 0.07	0.25	0.75 ± 0.10	0.36
Herbs*		1.70 ± 0.12	0.74	1.30 ± 0.09	0.57
Stand fine root		5.20± 0.21	2.30	2.90 ± 0.16	1.28
Total, Vegetation		26.58 ± 0.87	12.26	14.91 ± 0.44	6.88
**BAR		36		30	

*Aboveground parts; **Biomass accumulation ratio (biomass/annual net production)

The contribution in NPP by different components of trees was in the order leaf > bole > twig > coarse root > and branch, in both forests (Table 34). The most prominent carbon sink was found to be leaf growth that accounted for 42-43% of the total NPP. The allocation of NPP in shrub was higher in DF (0.75 Mg ha^{-1} yr^{-1}) than UF (0.55 Mg ha^{-1} yr^{-1}). For shrub, maximum contribution to NPP was made by stem in both forest stands (56% in DF and 54% in UF) and minimum share belonged to foliage (11% in DF and 13% in UF). The NPP of herbs (aboveground) ranged between 1.3 and 1.7 Mg ha^{-1} yr^{-1} in DF and UF, respectively (Table 33).

Table 34. Net production (Mg ha^{-1} yr^{-1}) of trees and shrubs and their distribution (%) in different components in undisturbed and disturbed stands of moist tropical forest in Sunsari district, eastern Nepal.

Components	Forest stands	
	Undisturbed	Disturbed
Trees	19.13 ± 1.21	9.96 ± 0.75
Bole (%)	25	30
Branch (%)	5	6
Twig (%)	20	14
Leaf (%)	43	42
Coarse root (%)	7	8
Shrubs	0.55 ± 0.07	0.75 ± 0.10
Stem (%)	54	56
Leaf (%)	13	11
Root (%)	33	33

Total aboveground net primary production (ANPP) combining tree, shrub and herb were 19.93 Mg ha^{-1} yr^{-1} in UF and 10.97 Mg ha^{-1} yr^{-1} in DF. Further, tree comprised about 90% of total ANPP (17.86 Mg ha^{-1} yr^{-1}) in UF whereas it was 84% (9.17 Mg ha^{-1} yr^{-1}) in DF. Allocation of ANPP in shrubs was about 2% (0.37 Mg ha^{-1} yr^{-1}) and 5% (0.5 Mg ha^{-1} yr^{-1}) in UF and DF, respectively. Similarly, herb contributed about 8% (1.7 Mg ha^{-1} yr^{-1}) of total ANPP in UF and 12% (1.3 Mg ha^{-1} yr^{-1}) in DF.

In belowground parts, percentage allocation of net primary production (BNPP) was up to 25% (6.65 Mg ha^{-1} yr^{-1}) of total NPP (26.58 Mg ha^{-1} yr^{-1}) in UF and 26% (3.94 Mg ha^{-1} yr^{-1}) in DF (Table 33). Of this, both tree and shrub's coarse root contributed about 21% and 26% of total BNPP in UF and DF, respectively; whereas fine root comprised nearly 79% of BNPP in UF and 74% in DF. The biomass accumulation ratio (biomass / net production) decreased to 30 due to the consequences of forest disturbance in DF, while this value was higher (36) in UF. Considering the NPP (Mg ha^{-1} yr^{-1}) of trees and shrubs, the total shoot to root ratio was 2.74 in UF and 2.45 in DF (Table 35). Moreover, the total leaf to fine root ratio also decreased with forest disturbance.

Table 35. Net primary production (NPP; Mg ha^{-1} yr^{-1}) and carbon allocation (Mg C ha^{-1} yr^{-1}) of trees and shrubs in undisturbed and disturbed forest stands in moist tropical forest of Sunsari district, eastern Nepal. Leaf litterfall was added in leaf production, whereas non-leaf litter fall was added in branches production. Production of herbs not included as there is no belowground component.

Biomass fraction	Undisturbed stand		Disturbed stand	
	NPP	Carbon allocation	NPP	Carbon allocation
Leaves	8.31	3.86	4.27	1.99
Stems and branches	9.92	4.68	5.4	2.55
Coarse root	1.45	0.68	1.04	0.49
Fine root	5.20	2.30	2.90	1.28
Total aboveground	18.23	8.54	9.67	4.54
Total belowground	6.65	2.98	3.94	1.77
Stand total	24.88	11.52	13.61	6.31
Leaf: fine root ratio	1.60	1.68	1.47	1.55
Shoot: root ratio	2.74	2.87	2.45	2.56

Net production of trees in UF showed non-significant positive correlation with sand, clay, water holding capacity, soil organic carbon, total phosphorus, soil organic matter, and microbial biomass phosphorus whereas it exhibited non-significant negative relations with rest soil variables (Table 36). Moreover, soil pH showed significant negative correlation with NPP of trees in DF while other soil parameters had no significant correlation.

Net primary production of trees was significantly higher in UF than DF ($P < 0.001$). Positive correlations were found between stand density, basal area, biomass and NPP in both stands (Table 37 & Figure 24). Moreover, the relationships between basal area and biomass, and stand density and NPP in UF ($P < 0.01$); and between stand density and NPP ($P < 0.01$); basal area, and biomass ($P < 0.01$) and NPP ($P < 0.05$); and biomass and NPP ($P < 0.01$) in DF were significant.

Table 36. Pearson's correlations between soil variables (0–15 cm depth), and biomass (BM) and net primary production (NPP) of trees in undisturbed and disturbed forest types of moist tropical forest in Sunsari district, eastern Nepal.

	Sand	silt	clay	mois	whc	bd	pH	soc	ton	top	pot	som	mbc	mbn	mbp
Undisturbed forest															
BM	.147	-.049	-.068	.234	-.034	.165	.108	.035	.001	.299	.004	.035	.009	.082	-.001
NPP	.224	-.307	.095	-.158	.085	-.093	-.274	.017	-.033	.330	-.004	.016	-.060	-.142	.245
Disturbed forest															
BM	.087	-.050	-.027	.291	-.067	-.149	-.167	-.144	-.126	-.208	-.316	-.143	-.162	-.154	-.048
NPP	-.059	.201	-.213	.259	.238	.038	-.519**	-.025	.017	-.072	-.288	-.023	-.188	-.126	-.053

**Correlation is significant at the 0.01 level (2-tailed).

Table 37. Pearson's correlations between stand density, basal area, biomass and net primary production (NPP) in undisturbed and disturbed stands of moist tropical forest in Sunsari district, eastern Nepal.

	Density	Basal area	Biomass
Undisturbed forest			
Basal area	.293		
Biomass	.251	.902**	
NPP	.725**	.210	.279
Disturbed forest			
Basal area	.116		
Biomass	.221	.926**	
NPP	.788**	.347*	.525**

**Correlation is significant at the 0.01 level and *at 0.05 level (2-tailed).

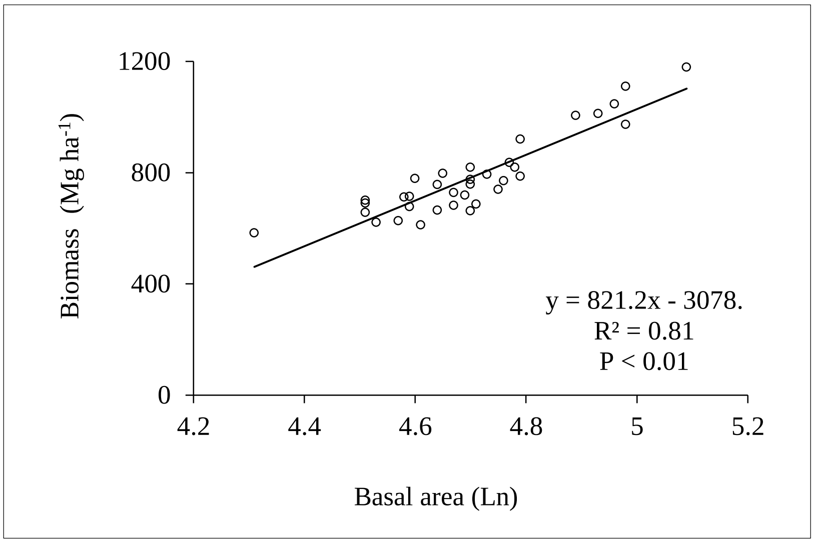

Figure 24. Regression between basal area and biomass of trees in undisturbed stand of moist tropical forest in Sunsari district, eastern Nepal.

5.4.5 Carbon budget and flux in undisturbed and disturbed forest stands

The dry matter values for standing crops, net production, litterfall etc. of both undisturbed and disturbed stands were converted to carbon and presented in Figures 25 and 26. Aboveground C storage in both stands was 82% of the total stored in vegetation and 64–69% of that stored in the stand (vegetation plus soil). The forest received a C input through NPP of 12.26 in UF and 6.88 Mg ha^{-1} yr^{-1} in DF.

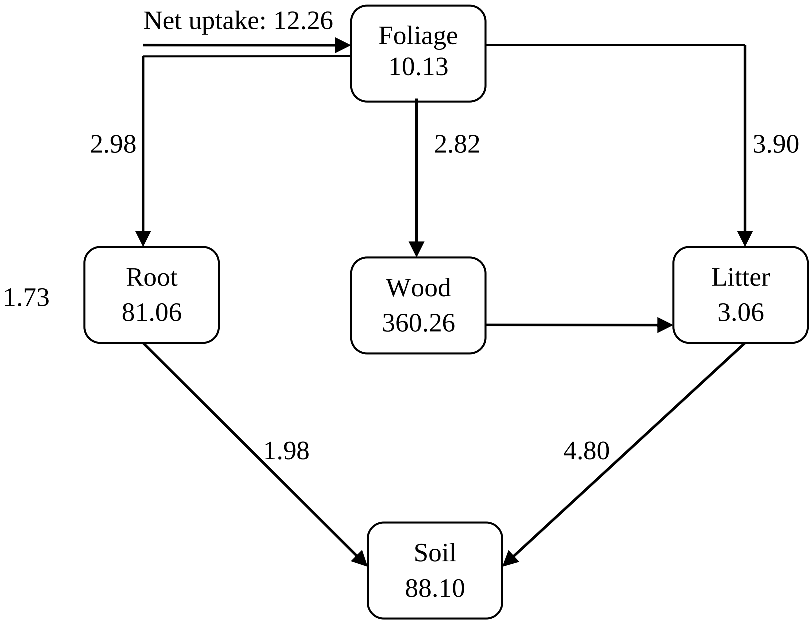

Figure 25. Compartment model showing annual carbon budget for the undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal. Values in 'tanks' represent average carbon content (Mg ha^{-1}). The foliage compartment also includes aboveground standing crop of herbs, and the root compartment includes coarse roots as well as fine roots. Net annual fluxes between the compartments are given on arrows (Mg ha^{-1} yr^{-1}).

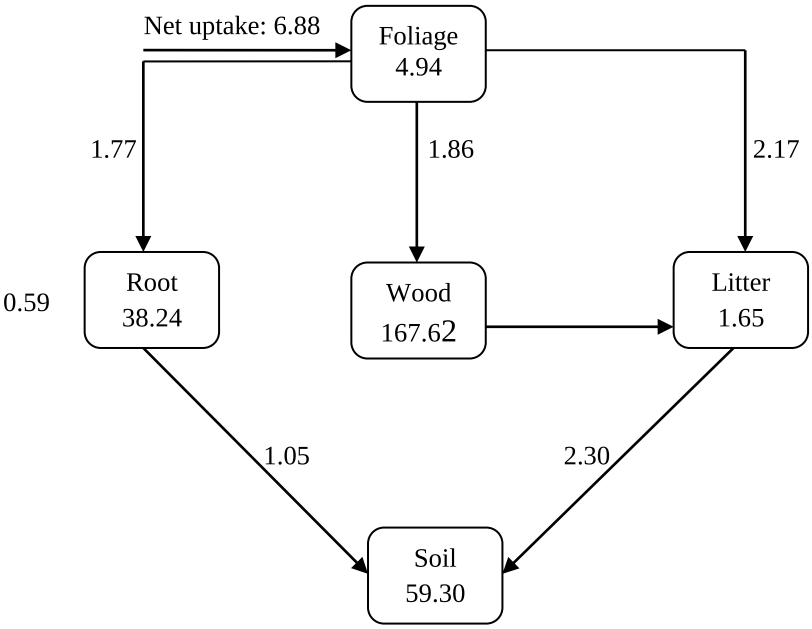

Figure 26. Compartment model showing annual carbon budget for the disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal. Values in 'tanks' represent average carbon content (Mg ha^{-1}). The foliage compartment also includes aboveground standing crop of herbs, and the root compartment includes coarse roots as well as fine roots. Net annual fluxes between the compartments are given on arrows (Mg ha^{-1} yr^{-1}).

Of this, 69% was associated with aboveground and 31% with root NPP in UF while in DF, contributions from aboveground and root parts to total NPP was 67% and 33%, respectively.

Wood (bole plus branch) and roots accounted for 47% (in UF) to 53% (in DF) of the total C input, the remaining 53% in UF and 47% in DF being utilized for the extension of the photosynthetic parts (tree and shrub foliage plus herbaceous shoots). The input from the foliage compartment to the litter compartment was 3.90 Mg ha^{-1} yr^{-1} (equivalent to 100% of herbaceous aboveground production plus 86% of foliage production) in UF while it was 2.17 Mg ha^{-1} yr^{-1} for DF. About 14% (0.51 Mg ha^{-1} yr^{-1} in UF and 0.26 Mg ha^{-1} yr^{-1} in DF) of foliage production did not find its way into leaf litterfall.

Carbon addition to the soil through the turnover of roots and aboveground litter amounted to 1.98 and 4.80 Mg ha^{-1} yr^{-1}, respectively in UF (fine root and litter turnover were 86% and 83% yr^{-1}, respectively). Similarly, C input due to the turnover of roots and aboveground litter was 1.05 and 2.30 Mg ha^{-1} yr^{-1}, respectively in DF (fine root and litter turnover were 82% and 79% yr^{-1}, respectively). Evidently, belowground plant part contribution to soil C is substantial, representing 29 and 32% of the total input in UF and DF, respectively.

5.4.6 Fine root dynamics in undisturbed and disturbed forest stands

5.4.6.1 Spatial distribution of fine root biomass (FRB)

Annual mean FRB (< 5 mm in diameter) in 0–30 cm soil depth was almost double in UF (6.64 Mg ha^{-1}) than the DF (3.35 Mg ha^{-1}) (Table 38). In both forest stands, FRB of < 2 mm size class was almost three times greater than that of 2-5 mm size class. FRB of smaller size class combining both depths was significantly higher (4.96 Mg ha^{-1}) in UF than DF (2.55 Mg ha^{-1}) ($P < 0.001$). Similarly, the biomass of larger fine roots was more than double (1.68 Mg ha^{-1}) in UF than the DF (0.80 Mg ha^{-1}). Variation in FRB due to difference in forest type was significant ($P < 0.001$) (Table 39).

Table 38. Fine root biomass (Mg ha^{-1}) in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal (mean ± SE).

Seasons	0–15 cm soil depth			15–30 cm soil depth		
	Size class (mm)			Size class (mm)		
	< 2	2–5	Total	< 2	2–5	Total
Undisturbed forest						
Rainy	4.81± 0.12	1.72 ± 0.09	6.53 ± 0.11	2.28 ± 0.08	0.67 ± 0.09	2.94 ± 0.10
Winter	2.97 ± 0.10	1.05 ± 0.09	4.02 ± 0.11	1.64 ± 0.08	0.50 ± 0.07	2.14 ± 0.09
Summer	2.0 ± 0.09	0.74 ± 0.08	2.74 ± 0.10	1.19 ± 0.05	0.35 ± 0.05	1.54 ± 0.07
Mean	**3.26 ± 0.10**	**1.17 ± 0.09**	**4.43 ± 0.10**	**1.70 ± 0.07**	**0.51 ± 0.07**	**2.21 ± 0.09**
Disturbed forest						
Rainy	2.57 ± 0.10	0.85 ± 0.07	3.42 ± 0.11	1.15 ± 0.07	0.34 ± 0.04	1.49 ± 0.08
Winter	1.65 ± 0.07	0.51 ± 0.06	2.16 ± 0.08	0.77 ± 0.04	0.18 ± 0.03	0.95 ± 0.04
Summer	1.03 ± 0.05	0.34 ± 0.02	1.37 ± 0.06	0.48 ± 0.02	0.19 ± 0.01	0.67 ± 0.02
Mean	**1.75 ± 0.08**	**0.57 ± 0.07**	**2.32 ± 0.09**	**0.8 ± 0.04**	**0.24 ± 0.02**	**1.03 ± 0.05**

Table 39. F values of the effects of forest type (FT), season and soil depth on fine root biomass (FRB), and the effects of (FT) and soil depth on fine root production (FRP) as obtained by analysis of variance.

Factors	FRB	FRP
FT	1045.49*	83.87*
Season	535.98*	
Depth	1187.60*	204.75*
FT × Season	44.57*	
FT × Depth	85.47*	20.80*
Season × Depth	109.57*	
FT × Season × Depth	12.52*	

Significance level: * P < 0.001

5.4.6.2 Vertical distribution of FRB

In the present study, 67–69% of annual mean FRB was present in upper soil depth in both forests (Table 38). Only 31–33% FRB was recorded from lower depth. In comparison to upper depth, FRB decreased in lower depth by 50% in UF and 55% in DF. The FRB of < 2 mm diameter was also higher in upper soil depth in both UF

(66%) and DF (69%) as compared to lower depth. The variation in annual mean of FRB due to depth was significant in both forest stands ($P < 0.001$) (Table 39).

5.4.6.3 Seasonality in FRB

Statistically significant ($P < 0.001$) seasonality was observed in the distribution of FRB in both forest stands. FRB of both size classes were maximum in rainy season, followed by winter, and minimum in summer season in both forests (Table 40). FRB reduced from rainy to summer season by 55% in UF and 59% in DF. Fine root size class also showed distinct seasonality in UF with 48% value in rainy, 31% in winter, and 21% in summer season. Same trend was seen in the DF also. However, seasonality did not showed effect on the vertical distribution of FRB (Table 38). It ranged between 64–70% in upper depth in all season in both stands while in lower depth the range was 30–36%.

Table 40. Seasonal variation in fine root biomass (Mg ha^{-1}) in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal (mean ± SE).

Size class (mm)		Forest types	
		Undisturbed	Disturbed
Summer	< 2	3.19 ± 0.12	1.51 ± 0.07
	2–5	1.1 ± 0.09	0.53 ± 0.03
	0–5	4.29 ± 1.04	2.04 ± 0.49
Rainy	< 2	7.09 ± 0.14	3.73 ± 0.12
	2–5	2.39 ± 0.15	1.19 ± 0.08
	0–5	9.48 ± 2.35	4.92 ± 1.27
Winter	< 2	4.61 ± 0.14	2.41 ± 0.08
	2–5	1.54 ± 0.10	0.69 ± 0.07
	0–5	6.15 ± 1.54	3.1 ± 0.86

5.4.6.4 Fine root production (FRP) and turnover

Fine root production was higher in UF (5.2 Mg ha^{-1} yr^{-1}) than DF (2.9 Mg ha^{-1} yr^{-1}) (Table 41), which was statistically significant ($P < 0.001$) (Table 39). Further, FRP in < 2 mm size class was significantly higher ($P < 0.001$) in both forests in comparison to 2–5 mm size class. Combining both size classes, FRP was higher by 71–73% in upper depth in both forests. It revealed that FRP showed less production in the lower depth.

Table 41. Fine root production (Mg ha^{-1} yr^{-1}) in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal (mean ± SE).

Soil depth (cm)	Undisturbed forest			Disturbed forest		
	< 2 mm	2–5 mm	Total	< 2 mm	2–5 mm	Total
0–15	2.81 ± 0.08	0.98 ± 0.04	3.79 ± 0.11	1.54 ± 0.07	0.51 ± 0.02	2.05 ± 0.08
15–30	1.09 ± 0.03	0.32 ± 0.02	1.41 ± 0.05	0.67 ± 0.03	0.15 ± 0.01	0.82 ± 0.05
0–30	3.90 ± 0.10	1.30 ± 0.04	5.20 ± 0.15	2.21 ± 0.07	0.66 ± 0.02	2.87 ± 0.09

Turnover rate (per yr) of fine root was faster for < 2 mm size class in both forests (Table 42). For both size classes, turnover rate was slower in UF than DF. Considering both depths, average turnover rate of smaller fine roots was 0.75 in UF and 0.86 in DF, whereas it was 0.74 and 0.76 for larger size class in UF and DF respectively. Moreover, the fine root of both size classes showed faster turnover rate in the upper soil depth as compared to lower depth in both forest stands. Turnover time was longer for the fine roots of UF as compared to that of DF for both size classes in both depths. Turnover time of smaller fine roots was shorter than that of the larger in both forests.

Table 42. Turnover rate and turnover time of fine root in undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Soil depth (cm)	Undisturbed forest			Disturbed forest		
	< 2 mm	2–5 mm	Mean	< 2 mm	2–5 mm	Mean
Turnover rate (per yr)						
0–15	0.86	0.84	0.85	0.88	0.89	0.89
15–30	0.64	0.63	0.64	0.84	0.63	0.74
Turnover time (yr)						
0–15	1.16	1.19	1.18	1.14	1.12	1.13
15–30	1.56	1.59	1.58	1.19	1.43	1.31

5.4.6.5 Environmental variables and their correlation with fine root

The test of the normality of environmental (soil) variables and fine root data showed normal distribution. The normally distributed fine root data are presented in Figure 27. The environmental variables were correlated with fine root biomass and production. In UF, mean FRB showed significant negative correlations ($P < 0.05$) with SOC, total P, MB-C and MB-N whereas, FRP showed significant positive correlations ($P < 0.05$) with them, except total P (Table 43). Regression analysis of FRP with SOC, total N, MB-C and MB-N in upper soil depth of UF was positive (Figure 28). In DF, none of the soil variables showed significant correlations with mean FRB but SOC, TN, MB-C and MB-N showed significant negative correlations ($P < 0.01$) with FRP (Table 44).

Table 43. Pearson's correlation coefficient between the soil variables, and fine root biomass and production in 0−15 cm soil depth of undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

	mois	whc	bd	pH	soc	ton	top	pot	som	mbc	mbn	mbp
Fine root biomass												
Summer	-.019	-.018	.273	-.474**	-.779**	-.831**	-.436**	.209	-.779**	-.726**	-.747**	-.208
Winter	.006	.050	-.178	-.077	-.060	.036	-.341*	-.292	-.063	-.101	-.009	-.314
Rainy	.159	.308	-.052	-.124	.049	.065	-.008	-.043	.056	.040	-.025	-.047
Mean	.049	.168	-.010	-.309	-.374*	-.332	-.387*	-.079	-.372*	-.373*	-.361*	-.293
Fine root production												
0−2 mm	.270	.169	-.336*	-.042	.374*	.398*	.231	-.077	.378*	.327	.299	-.010
2−5 mm	-.215	.075	.181	.371*	.221	.250	.058	-.122	.221	.230	.226	.157
0−5 mm	.129	.237	-.224	.231	.564**	.611**	.290	-.173	.569**	.521**	.488**	.106

*Correlation is significant at the 0.05 level (2-tailed) and **at the 0.01 level (2-tailed).

mois = soil moisture, whc = water holding capacity, bd = bulk density, soc = soil organic carbon, ton = total nitrogen, top = total phosphorus, pot = potassium, som = soil organic matter, mbc = microbial biomass carbon, mbn = microbial biomass nitrogen, mbp = microbial biomass phosphorus.

Table 44. Pearson's correlation coefficient between the soil variables, and fine root biomass and production in 0−15 cm soil depth of disturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

	mois	whc	bd	pH	soc	ton	top	pot	som	mbc	mbn	mbp
Fine root biomass												
Summer	.045	.084	.129	.110	.790**	.875**	.143	.063	.797**	.748**	.776**	.023
Winter	.323	.197	.045	.010	.023	.140	.171	.002	.041	.038	.067	.198
Rainy	.130	.108	.287	.128	-.265	-.182	.089	.116	-.261	-.260	-.197	.056
Mean	-.087	.012	-.188	.134	.117	.273	-.099	-.112	.133	.112	.185	-.153
Fine root production												
0−2 mm	-.109	.137	-.151	.073	-.447**	-.445**	-.206	-.103	-.445**	-.385*	-.357*	-.107
2−5 mm	.359*	-.101	-.275	-.003	-.308	-.256	.060	.029	-.308	-.356*	-.327	.086
0−5 mm	.126	.053	-.292	.059	-.557**	-.524**	-.135	-.068	-.556**	-.534**	-.494**	-.036

*Correlation is significant at the 0.05 level (2-tailed) and **at the 0.01 level (2-tailed).

mois = soil moisture, whc = water holding capacity, bd = bulk density, soc = soil organic carbon, ton = total nitrogen, top = total phosphorus, pot = potassium, som = soil organic matter, mbc = microbial biomass carbon, mbn = microbial biomass nitrogen, mbp = microbial biomass phosphorus.

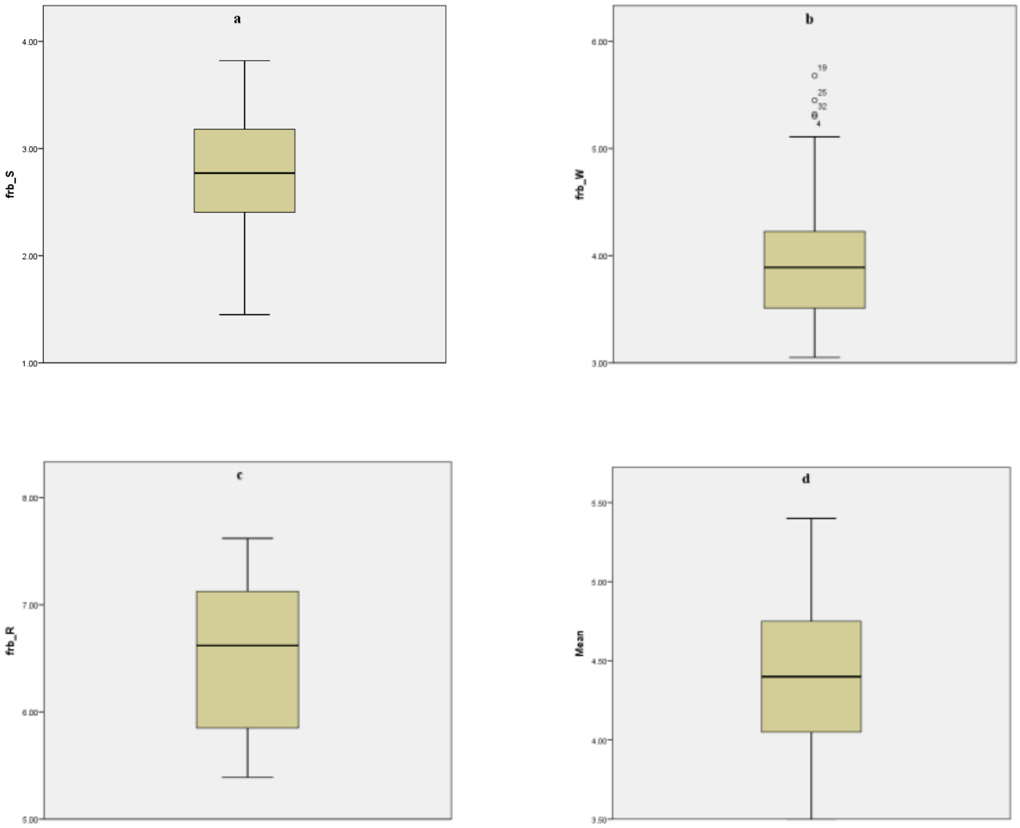

Figure 27. Box plots of fine root biomass (Mg ha^{-1}) of three seasons in moist tropical forest of Sunsari district, eastern Nepal (a-Summer, b-Winter, c-Rainy and d-Mean three seasons).

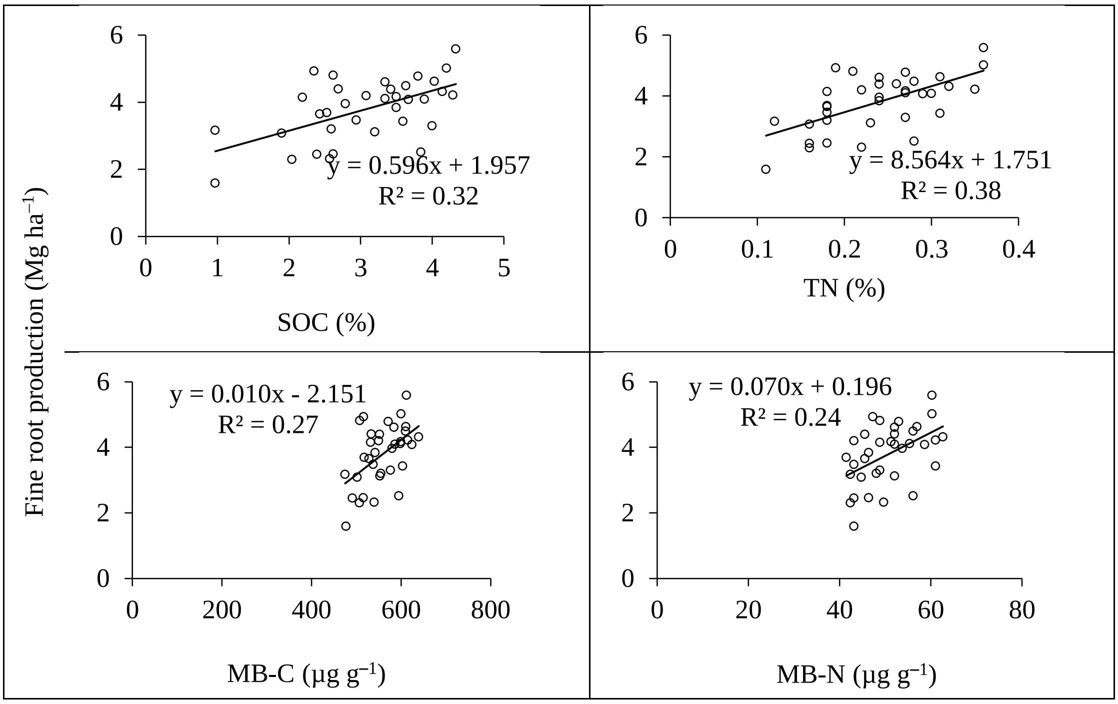

Figure 28. Regression analyses of fine root production with soil organic carbon (SOC), total nitrogen (TN), microbial biomass carbon (MB-C) and nitrogen (MB-N) ($P < 0.05$) in undisturbed forest stand of moist tropical forest in Sunsari district, eastern Nepal.

5.4.6.6 Carbon stock in fine roots

Carbon stock in the fine roots was almost double in UF than the DF (Table 45). Moreover, more than double carbon was found in the fine root of < 2 mm size class in both forest stands. Similarly, carbon stock was fairly higher in upper soil depth as compared to lower in both forests. The carbon stock in lower depth varied from 31–33% of the total carbon stock in fine roots.

Table 45. Carbon stocks (kg ha^{-1}) in fine root at undisturbed and disturbed forest stands of moist tropical forest in Sunsari district, eastern Nepal.

Diameter (mm)	Undisturbed forest			Disturbed forest		
	Soil depth (cm)			Soil depth (cm)		
	0–15	15–30	Total	0–15	15–30	Total
Carbon stock (kg ha^{-1})						
< 2	1402 ± 28.5	731 ± 21.2	2133 ± 32.7	753 + 18.1	344 ± 13.7	1097 ± 24.8
2–5	532 ± 26.6	232 ± 20.6	764 ± 34.0	259 ± 13.5	109 ± 7.6	368 ± 16.1
0–5	1934 ± 33.8	963 ± 27.6	2897 ± 44.5	1012 ± 22.3	453 ± 16.5	1465 ± 30.7

5.5 DISCUSSION

5.5.1 Biomass in the context of disturbance

The average biomass of the forest combining both undisturbed and disturbed forests (704.8 Mg ha^{-1}) is higher than the biomass of other tropical forests of the world (Table 46).

Carbon stocks of different forests of the World are given in Tables 47 and 48. As far the average biomass C is concerned, the present forest again holds the top position (211.3–452.06 Mg C ha^{-1}) among the biome-average values of tropical forests throughout the globe. The C pool in tree biomass of the studied forest (206.5 Mg C ha^{-1} in DF–446.5 Mg C ha^{-1} in UF) is quite higher than the C pool in tree biomass of eastern Amazonian forest i.e. 110.9–179.4 Mg C ha^{-1} as reported by Doughty *et al.* (2013).

Table 46. Dry biomass (Mg ha^{-1}) of different forests of the World.

Locality and forest types	Biomass (Mg ha^{-1})		References
	Aboveground	Total	
India (Humid tropical)	323.9	–	Baishya *et al.* (2009)
Global (Dry tropical)	39–334	–	Becknell *et al.* (2012)
Indonesia (Paleotropical)	286	303	Hertel *et al.* (2009)
Global (Tropical)	46–694 (mean 278)	–	Clark *et al.* (2001)
Brazil (Amazonia)	–	286.8	Nogueira *et al.* (2008)
Central French Guiana (Tropical rain)	356–398	–	Chave *et al.* (2008)
Nepal (Tropical Sal)	–	257.9*	Pandey *et al.* (2014)
Nepal (Tropical mixed)	–	234.7*	Pandey *et al.* (2014)
Central Nepal (Mid hills)	–	70–183	Thapa-Magar & Shrestha (2015)
Nepal (Moist tropical, Plateau Sal)	571.4	729 ± 82	Mandal (1999)
Nepal (Moist tropical)	367.7–787.9	449.1–960.4	Present study

*Calculated value from Pandey *et al.* (2014).

The higher biomass and C stock in the present forest as compared to other tropical forests may be due to the suitable climatic and soil condition that supported the growth of very large-sized trees in terms of both GBH and height. It is also evident by the 34% hold on the species IVI, by only two dominant species (*Shorea robusta* and Hal*dina cordifolia*).

Table 47. Biome-average tropical forest biomass carbon stock (Mg C ha^{-1}) estimates.

Forest type	Biomass Carbon stocks	References
Tropical Asia		
All forests	151	Achard *et al.* (2004)
Tropical equatorial	164	Gibbs & Brown (2007a, 2007b)
Tropical equatorial	180	IPCC (2006)
Tropical equatorial	250	DeFries *et al.* (2002)
Tropical seasonal	142	Gibbs & Brown (2007a, 2007b)
Tropical dry	120	Gibbs & Brown (2007a, 2007b)
Pan-Amazon	129	Achard *et al.* (2004)
Brazilian Amazon	186	Achard *et al.* (2004)
Latin America		
Tropical equatorial	200	DeFries *et al.* (2002)
Tropical seasonal	140	DeFries *et al.* (2002)
Tropical dry	55	DeFries *et al.* (2002)
Sub-Saharan Africa		
All forests	143	Achard *et al.* (2004)
Tropical equatorial	200	IPCC (2006)
Tropical seasonal	152	IPCC (2006)
Tropical dry	72	IPCC (2006)

Table 48. Carbon stocks (Pg) of different forests of World.

Forest type	Carbon stocks (total)	References
Global, dry tropical	8.7	Becknell *et al.* (2012)
China, total (1999-2003)	5.9	Guo *et al.* (2010)
Global, tropical	471	Pan *et al.* (2011)
Global, boreal	272	Pan *et al.* (2011)
Global, temperate	119	Pan *et al.* (2011)
Global (all forests)	861	Pan *et al.* (2011)

The total biomass in the UF was more than double of DF. The higher total biomass at UF may be related to the presence of more trees of larger girth classes. The lower biomass in DF is also evident from the almost half density of trees compared to UF. The main local cause behind it is tree felling and removing for timber. The secondary causes may include firewood collection, lopping, grazing, and selective logging of poles for the construction of houses by the surrounding people. The percent allocation of tree biomass to bole, branch and leaves is same in both stands of present forest. But the allocation to coarse root in DF is slightly higher than that in UF. It indicates that trees of DF allocate more resources to root system to optimize the nutrient and water uptake. The analysis showed that in UF, tree biomass was dependent upon most of the soil variables but in DF, the major factors determining tree biomass were sand and soil moisture.

In the present study, biomass allocated to shrub was higher for DF than the UF (Table 33). More shrub biomass associated to DF may be due to the fact that the space/resource created by disturbances is efficiently utilized by shrubs due to their smaller niche size. The higher biomass of herbs in UF as compared to DF may be due to the nutrient rich soil at this stand (Gautam & Mandal, 2013). It may be the consequence of relatively open understorey space created as a result of less number of shrubs in UF.

The different causes are put forward by different workers regarding the accumulation of biomass in the forest. Mean annual precipitation explain 55% of the variation in biomass in seasonally dry tropical forests (Becknell *et al.*, 2012). The available nutrients, soil, land use history, and species composition are also responsible for the remaining variation (Powers *et al.*, 2009). It is also determined by stand age. Disturbance history, including the extent to which trees were removed, post-disturbance management, the introduction of exotic species, and the proximity of intact forest or regeneration sources all are factors likely to impact the regeneration rate and the amount of biomass attained by secondary forests (Griscom & Ashton, 2011).

As the biomass is reduced due to disturbance activities consequently the C stock also reduced on the disturbed site. Most of the C stock in the present forest was associated with aboveground biomass (64‒69%), 14‒15% in belowground biomass and 31% in soil up to the depth of 30 cm (Table 29). Ngo *et al.* (2013) also found 33% C in top soil of 1m in primary tropical forest of Singapore. Globally, tropical forests store about 50% carbon in aboveground biomass and next 50% within 1m soil (Dixon *et al.*, 1994). The contributions of these pools to the total C stocks vary among the sites. For example, an African moist tropical forest had more than three times as much C in aboveground biomass as in soil to 1m depth (Djomo *et al.*, 2011), while a Peruvian montane forest had twice as much C in soil as in aboveground biomass (Gibbon *et al.*, 2010). Two Asian forests, a tropical seasonal forest in China (Lü *et al.*, 2010) and a lowland dipterocarp forest in Malaysia (Saner *et al.*, 2012) store twice as much C in biomass as in soil.

5.5.2 Litterfall and litter mass

Mean annual litterfall of the forest combining both UF and DF amounted to 8.6 Mg ha^{-1} yr^{-1} (equivalent to 3.93 Mg C ha^{-1} yr^{-1}). More than double litter production in the present UF compared to DF suggests that leaf litter production is susceptible to the intensity of human effects, which may, consequently, have effects on overall forest dynamics. On the DF presence of substantial amount of partly decayed litter (leaf and non-leaf) also serve as the indicator of disturbance. The total litterfall in UF is in lower range for that in tropical forests of Panama and Brazil, while it is convincingly higher than the value for tropical old-growth and secondary forests of South America, and other forests of Asia (Table 49). The NPP allocation to the annual litterfall of UF is almost equal to that of Amazonian forests which is 4.52–5.03 Mg C ha^{-1} yr^{-1} (Doughty *et al.*, 2013), 4.94–5.39 Mg C ha^{-1} yr^{-1} (Malhi *et al.*, 2014), and lowland tropical rain forest of Central French Guiana 4.65 Mg C ha^{-1} yr $^{-1}$ (Chave *et al.*, 2008).

Table 49. Litterfall (Mg ha^{-1} yr^{-1}) in different forests of the World.

Locality and forest types	Leaf litter	Total litter	References
India (Uttarakhand)	–	6.25 ± 0.26	Rawat (2012)
South America (Tropical)	–	8.61 ± 1.91	Chave *et al.* (2010)
South America (Tropical)	–	8.01 ± 3.41	Chave *et al.* (2010)
India (Sub-tropical)	–	5.47	Pandey *et al.* (2007)
India (Tropical)	–	3.9–5.2	Swamy *et al.* (2010)
Indonesia (Borneo)	5.1–11.0	–	Paoli & Curran (2007)
India (Dry tropical)	–	13.27–13. 51	Pragasan & Parthasarathy (2005)
Brazil (Tropical)	8.55–11.01	12.32–14.74	Schessl *et al.* (2008)
Nepal (Moist tropical, Plateau Sal)	7.2 ± 0.31	10.3 ± 0.61	Mandal (1999)
Nepal (Moist tropical)	4.1–8.1	5.4–11.8	Present study

The contribution of leaf litter to total litterfall ranged between 69% (at UF) to 76% (at DF). Malhi *et al.* (2014) reported almost same range of allocation in leaf fall

(72–74%) while Girardin *et al.* (2014) reported a range of 69–73%. The higher percentage of leaf litter and lower percentage of non-leaf litter in DF as compared to UF may be linked to the lopping of tree twigs for fodder which prevents the plant from flowering and fruiting, thereby reducing the quantity of non-leaf litter. On the other hand, in poor soils as in DF, forests tend to invest less into the construction of reproductive organs relative to photosynthesis but when resources are well supplied the excess in resources is made available for reproduction (Chave *et al.*, 2010).

Litter production showed distinct seasonality peaking during dry summer season. Same trend was also reported in previous studies (Pragasan & Parthasarathy, 2005; Doughty *et al.*, 2013; Malhi *et al.*, 2014). This is likely to be related to the low soil moisture level during this period resulted due to a strong and continuous solar radiation. Moreover, water stress triggers the synthesis of abscissic acid in the leaf, which in turn stimulates senescence leading to leaf fall. It may be the water conservation mechanism of plants by shedding their leaves during hot summer.

The annual litter turnover rate was faster in UF as compared to DF (Table 32). It may be associated with the higher microbial biomass and their activities in the soil of UF. Relatively faster turnover rate of leaf litter than that of the non-leaf litter in both stands of the forest may be linked to the fact that the leaves contain relatively lower amount of lignified tissues (low lignin and high nitrogen) as compared to non-leaf components. Annual litter turnover value of present forest is comparable to the wet tropical evergreen forest of India i.e. 0.92–0.96 as reported by Swamy *et al.* (2010), while quite lower than that of sub-tropical oak forest and managed plantation (2.34–2.37) in north-east India (Pandey *et al.*, 2007).

In the present study, turnover time of litter ranged between 1.21 (in UF) and 1.26 years (in DF) which is comparable to the range in several tropical and sub-tropical evergreen and deciduous forests reported by Vogt *et al.* (1986). However, these values are slightly higher than the values reported for tropical wet evergreen forests (1.04 and 1.08 years) of Western Ghats India (Swamy *et al.*, 2010).

5.5.3 Net Primary production (NPP) in the context of disturbance

There are no sufficient data regarding the NPP of moist tropical forests, particularly on the below-ground component. Many of the existing field studies have missed to estimate either one or more major components of the total NPP (Hertel *et al.*, 2009).

The present study tried to investigate most of the pool of NPP except for the coarse woody debris, root exudation, transfer to mycorrhizal hyphae and consumption by herbivores.

The mean NPP value presented in this study for both UF and DF stands of moist tropical forest of eastern Nepal is 20.74 Mg ha^{-1} yr^{-1} (equivalent to 9.57 Mg C ha^{-1} yr^{-1}). The total NPP of UF combining trees, shrubs and herbs (12.26 Mg C ha^{-1} yr^{-1}) is almost same with a mean NPP for tropical forests of central Africa (Bombelli *et al.*, 2009), and within the range of some Amazonian forests and old-growth tropical forests of the world; but lower than the values for eastern Amazonian forests of Peru and Brazil (Table 50).

Table 50. Net primary production (NPP) of different forests of the World.

Locality and forest types	NPP (Mg C ha^{-1} yr^{-1})			References
	Aboveground	Belowground	Total	
Amazon	5.1–11.4 (Average 64%)	3.0–8.1 (Avg. 36%)	9.3–17 (Avg. 12.8)	Aragão *et al.* (2009)
Amazonia	–	–	10–14.4	Malhi *et al.* (2009)
Peru (W. Amazonia)	–	–	14.2–15.1	Malhi *et al.* (2014)
Peru (Tropical, Montane)	–	–	7.05–8.04	Girardin *et al.* (2014)
Global mean (Tropical)	4.4*	–	–	Clark *et al.* (2001)
Global (Old tropical)	–	–	3.1–21.7	Clark *et al.* (2001)
Indonesia (Paleotropical)	86% of total	14% of total	6.7	Hertel *et al.* (2009)
N.E. Amazon	9.73 ± 0.56**	–	–	Banin *et al.* (2014)
Borneo	6.35 ± 0.34**	–	–	Banin *et al.* (2014)
Borneo	6.76	–	–	Katayama *et al.* (2013)
Central French Guiana (Lowland tropical rain)	8.81	–	–	Chave *et al.* (2008)
Africa (Tropical)	–	–	11.51	Bombelli *et al.* (2009)
Nepal (Moist tropical Sal)	14.89	7.21	22.1 ± 1.4	Mandal (1999)
Nepal (Tropical Sal)	–	–	5.0	Pandey *et al.* (2014)
Nepal (Tropical mixed)	–	–	5.8	Pandey *et al.* (2014)
Nepal (Moist tropical)	10.97–19.93	3.94–6.65	14.91–26.58	Present study

* Calculated from the global mean value of 8.8 Mg ha^{-1} yr^{-1} of Clark *et al.* (2001); **Wood only.

The total NPP of DF (6.88 Mg C ha^{-1} yr^{-1}) is comparable to the different tropical forests of world (Table 50), as well as with teak plantations in dry tropical forests of

India (Karmacharya & Singh, 1992a). Although in having higher biomass, the NPP of present forest is relatively low indicating its maturity. Generally, in old growth tropical forests the NPP remains either stationary or decreases with age. The higher NPP of some tropical forests may be linked to forest dynamics. The more dynamic forests with more gaps and light penetration favor faster growing trees and species with lower biomass and maintenance costs (Malhi *et al.*, 2009).

The higher biomass in moist tropical forests than drier forests could be associated with the higher productivity and lower mortality. Deciduous trees in wetter areas can hold onto their leaves longer (have a longer growing season) with the potential for higher productivity and are likely to have lower mortality. On the other hand, in drier forests water scarcity induces leaf abscission and dormancy in plants resulting in higher mortality while productivity, biomass accumulation, and maximum attainable biomass all decrease. Yavitt and Wright (2001) added that increasing water availability may or may not increase productivity but restricting water certainly decreases productivity.

Allocation to belowground net primary productivity (BNPP) is relatively low as compared to aboveground net primary productivity (ANPP) in both UF and DF of present forest (Table 35). In the present study the shoot root ratio, excluding herbaceous shoot NPP (as the belowground NPP of herbs was not estimated in this study), is nearly 3 indicating more carbon investment in the growth of above-ground organs than in roots. Doughty *et al.* (2013) also reported the shoot root ratio of 2.55 for Amazonian forest. Mature forests, having a high canopy, would allocate a smaller proportion of their carbon to below-ground structures (Sarmiento *et al.*, 2005). But Hertel *et al.* (2009) found a very high shoot root ratio of 17 for a paleotropical natural forest of Sulawesi, Indonesia.

Aboveground NPP of UF (8.54 Mg C ha^{-1} yr^{-1}, excluding herbs) is comparable with that of Amazonian forests, paleotropical forests of Indonesia, lowland tropical rain forest of Central French Guiana (Table 50), and tropical forest of Borneo, Indonesia (Paoli & Curran, 2007); while quite low than the eastern Amazonian forest (23.08 Mg C ha^{-1} yr^{-1}) (Doughty *et al.*, 2013). Moreover, ANPP of DF (4.54 Mg C ha^{-1} yr^{-1}, excluding herb) is near to paleotropical forests, and mean of the world tropical forests.

As far the BNPP is concerned (1.77–2.98 Mg C ha^{-1} yr^{-1}), it is comparable to the Amazonian tropical forest (Table 50).

Disturbance has direct effects on NPP either by increasing resource availability or indirect effects through changes in community functional properties. The disturbance results in canopy opening, which increases competition for light, favour new leaf production, and finally above-ground allocation increases (Aragao *et al.*, 2009). But in present study, percentage allocation to aboveground parts was almost same in both UF and DF. It may be the result of severe lopping activities in DF, which is also indicated by less percentage of NPP allocation to twig and leaf, and higher percentage allocation to bole and branch in DF. Relatively higher percentage of NPP in coarse root of DF indicated higher allocation in root to collect more water and nutrients in nutrient deficient soil.

In the present study, among different components of trees, leaf accounted highest percentage (43% in UF and 42% in DF) of tree NPP. It was almost similar to the finding of Hertel *et al.* (2009, 41.8%) for a paleotropical forest of Sulawesi, Indonesia and that of Doughty *et al.* (2013, 39%) for eastern Amazonian tropical forest. Malhi *et al.* (2011) studied a global dataset of NPP allocation between canopy, woody tissue and fine roots in tropical forests, and found an equal partitioning of resources between all three main components (34% canopy, 39% wood, and 27% fine roots). Present data of UF, excluding herb NPP, also showed almost same pattern of allocation (33% canopy, 46% woody tissue including coarse root, and 21% fine roots). Further, Malhi *et al.* (2014) reported the NPP allocation of 42 and 59% in canopy, 27 and 26% in wood, and 31 and 15% in fine roots in two forests plots of south-eastern Amazon. They concluded that more fertile plot allocated more NPP to canopy and low NPP to fine roots. It was in accordance to the resource allocation theory, with more investment in nutrient acquisition at the nutrient poor site.

Fine root, although sharing a very small percentage to total plant biomass, is one of the major belowground components of the NPP. In present study, fine root production was estimated as 2.9 Mg ha^{-1} yr^{-1} in DF to 5.2 Mg ha^{-1} yr^{-1} in UF (equivalent to 1.28–2.30 Mg C ha^{-1} yr^{-1}). This appears within the ranges of 1.1–6.2 Mg ha^{-1} yr^{-1} given by Vogt *et al.* (1986) for tropical forests globally.

Higher allocation of NPP in shrubs of DF as compared to that of UF may be due to open canopy created as a result of logging and lopping of trees. The shrubs produced more foliage in UF as compared to DF; it may be the mechanism to receive more sunlight under the almost closed canopy of trees. The higher NPP of herbs in UF might be associated with higher moisture and nutrients due to accumulation of more litter on the soil.

5.5.4 Carbon budget and flux in undisturbed and disturbed forest stands

Aboveground C storage in both stands was 82% of the total stored in vegetation and 64–69% of that stored in the stand (vegetation plus soil). These values compare with the aboveground storage of 83% vegetation C and 51% stand C in a dry tropical forest in India (Singh & Singh, 1991a). Relatively higher contribution of aboveground parts to the stand C in present forest as in other tropical forests may be due to the presence of large sized trees with wide canopies.

The contribution of aboveground (67–69%) and root (31–33%) parts to stand NPP in both forest stands is comparable to 72% NPP for aboveground parts as suggested by Singh and Singh (1991a). The higher contribution of wood parts to the total C input as compared to foliage in DF may be due to the lopping of branches and twigs. On the other hand, closed canopy of trees in UF accounted for higher input of C compared to wood.

The transfer of C from foliage compartment to the litter compartment involved 100% of herbaceous aboveground production plus 86% of foliage production while the remaining amount i.e., about 14% of foliage production did not find its way into leaf litterfall, and is presumed to be lost during senescence (Singh & Singh, 1991a).

Litterfall and fine root biomass are important vectors of nutrient recycling in forest ecosystems. Their turnover is usually determined by species, age groups, canopy cover, weather conditions and biotic factors. Total C input into soil through litter plus root turnover was 6.78 and 3.35 Mg ha^{-1} yr^{-1} in UF and DF, respectively; indicating substantial retention of C in the vegetation over the annual cycle (45% in UF and 51% in DF). This budget shows that the present forest is C- accumulating system, acting as a significant global C sink, as other wet tropical forests (Pan *et al.*, 2011). However, this may be an artifact since coarse wood litterfall and its turnover, and the turnover of coarse roots, was not measured in this study.

5.5.5 Fine root dynamics

5.5.5.1 Spatial variation in fine root biomass (FRB)

The annual mean FRB in the present study (6.6 Mg ha^{-1}) was comparable to that of boreal forest (5.28 Mg ha^{-1}) (Yuan & Chen, 2010), and dry forest in Sri Lanka (5.72 Mg ha^{-1}) (Kuruppuarachchi *et al.*, 2013).

So far the spatial variation, it showed distinct gradient in the content along the disturbance regime. Higher FRB is related with the higher leaf production in the UF. The lower FRB in DF could be the result of less canopy cover (Harteveld *et al.*, 2007) or a higher fine root turnover (FRT) rate and high bulk density of soil which prevents the penetration of fine root. Similar trend was also reported by Barbhuiya *et al.* (2012) and Leuschner *et al.* (2009). However, Ibrahima *et al.* (2010) found opposite trend where FRB was significantly higher in the disturbed tropical forests than undisturbed forests. It suggests that fine roots may respond quickly to land-use change, so causing higher FRB in DF.

Higher FRB on nutrient-poor stand and a lower FRB in fertile stand may be associated with the differences in soil nutrients, especially available P and soil N (Maycock & Congdon, 2000). The nutrient deficient soil of DF needs a high standing crop of FRB to fulfill the nutrient requirement of the plants. The cause for the higher FRB in UF of the present study may be due to the higher SOC, total N, total P, K and soil moisture at this site (Gautam & Mandal, 2013). The significant difference in FRB between UF and DF of the present forest reflects that the impact of disturbances on FRB was large, but recovery of fine roots was relatively slow.

5.5.5.2 Vertical distribution of FRB

Fine root biomass decreased significantly along the soil depth in the present study. Similar trend was reported by Richter *et al.* (2012). Sixty five to 69 % FRB in the upper soil depth in the present study was comparable to the findings of Ibrahima *et al.* (2010) who found 70–82% FRB in the 0-10 cm soil depth. Valverde-Barrantes *et al.* (2007) reported 60% of the fine root in the upper 15 cm soil of tropical forest while Noguchi *et al.* (2014) found 74% of the FRB within the upper 20 cm soil layers.

The amount of litter, nutrients and organic matter on the soil surface that finally affect the availability of water might be the cause for the accumulation of fine roots in the upper depth of the forests. It may be linked to the plant species and physical environment. The higher amount of FRB in upper soil depth of DF may be a nutrient conservation mechanism under low soil resource availability.

5.5.5.3 Fine root biomass and soil variables

In the UF, total FRB was negatively correlated with almost all soil variables suggesting that the soil fertility alone might not be more crucial for plant growth. Moreover, which soil factor/s is most accountable for the negative correlations between soil variables and FRB need further study. Powers and Peréz-Aviles (2013) observed negative correlations with silt, pH, calcium, magnesium, N, and P.

No correlation was found between soil chemical variables and FRB in European beech forest (Richter *et al.*, 2012). Similarly, no significant correlation was observed between available P and FRB whereas soil N showed negative correlation with FRB (≤ 2 mm) (Maycoc & Congdon, 2000). The addition of K, and both K and N together decreased FRB (Wright *et al.*, 2011). In the Boreal forest, FRB decreased significantly with N and P availability in soil (Yuan & Chen, 2010). In contrary, Graefe *et al.* (2010) found a positive response of N, P, and K fertilization on root growth. Soil nutrients may affect fine root mass either directly by affecting root production or indirectly by influencing the composition of species which differ in underground allocation.

In contrary to a weak positive correlation between FRB and soil moisture content in UF, McGroddy and Silver (2000) found a strong positive correlation between them in humid tropical forests. On the other hand, Lima *et al.* (2010) found an opposite relationship between fine root growth and soil water availability.

5.5.5.4 Seasonality in FRB

In the present study, distinct seasonality was observed in fine root biomass which was also reported in other studies (Mandal, 1999; Pei *et al.*, 2012). The maximum FRB of both root size classes during rainy season in both stands might be associated with the higher nutrient availability and soil moisture. The decrease in the amount of fine roots in winter (by 35–37%) and summer (by 52–55%) seasons indicates a rapid turnover of fine roots. Pei *et al.* (2012) reported significant increase in FRB from April, which peaked in August and then decreased. Green *et al.* (2005) also reported higher fine root growth during wet season in tropical forest.

5.5.5.5 Variation in fine root production (FRP)

Fine root production in UF in present study (5.2 Mg ha^{-1} yr^{-1}) was slightly lower than the global average for tropical forests (5.96 Mg ha^{-1} yr^{-1}), and higher than boreal (3.11 Mg ha^{-1} yr^{-1}) and temperate (4.28 Mg ha^{-1} yr^{-1}) forests (Finér *et al.*, 2011a). Moreover, it is also higher than the value of Hertel *et al.* (2009; 2.1 Mg ha^{-1} yr^{-1} equivalent to 0.9 Mg C ha^{-1} yr^{-1}) for paleotropical forest. Fine root production is almost half to the value of Malhi *et al.* (2014) for a lowland south-western Amazonian forest, Peru (2.11 and 4.54 Mg C ha^{-1} yr^{-1}) and that of Doughty *et al.* (2013) for eastern Amazonian forest, Brazil (3.68 and 6.41 Mg C ha^{-1} yr^{-1}).

In the present study, FRP decreased along the increasing soil depth and disturbance. Similar trend of FRP along the soil depth was also observed by Xiao *et al.* (2008)**,** and along the disturbance by Harteveld *et al.* (2007). The spatial pattern of FRP may be associated with the differences in soil N concentration (Uselman *et al.,* 2007), species composition and soil properties (Finer *et al.*, 2011a; Yuan & Chen, 2012b), or canopy cover and stand basal area (Harteveld *et al.*, 2007).

As in UF in present case, the positive correlation between FRP and soil N was also observed in earlier studies (Pei *et al.*, 2012; Yuan & Chen, 2012b). Some other studies showed negative (Maycock & Congdon, 2000), or uncertain (Nadelhoffer, 2000) relationship between FRP and soil N. Some previous studies observed positive (Yuan & Chen, 2012b) or even negative (Uselman *et al.*, 2007) correlation between FRP and soil P as in present UF and DF, respectively.

Jimenez *et al.* (2009) reported close relationships between FRP and edaphic factors in tropical forest. It suggests that FRP is mainly dependent on soil resources, especially nutrients and moisture. On the other hand, Richter *et al.* (2012) found no correlation between them.

5.5.5.6 Fine root turnover (FRT)

Fine root turnover in the present forest (0.78 in UF and 0.86 yr^{-1} in DF) was comparable to the value of Finér *et al.* (2011a) for Boreal forests (0.77 yr^{-1}), and less than temperate (1.21 yr^{-1}) and tropical (1.44 yr^{-1}) forests. Fine root turnover may be affected by the species composition and soil properties mainly nutrients, moisture, and temperature. The FRT increased with the fertilization of K, and both K and N together in the forest soil (Yavitt *et al.*, 2011), and also along the intensity of disturbance (Leuschner *et al.*, 2009). The higher FRT in DF of present forest may be due to the lower soil organic matter, total N, P, K, microbial biomass and moisture in the soil. Fine root turnover also depends upon the soil C pools (Matamala *et al.*, 2003).

5.5.5.7 Carbon stock in fine roots

The C stock of fine roots varies according to the species composition, type of forest, and diameter class. In the present study, a strong vertical decrease in C stock of fine root with increasing soil depth was observed in both stands. The upper soil layer had higher percentage allocation (67–69%) of C stock in the fine roots as compared to the lower depth. It might be due to the higher water holding capacity and availability of nutrients which enhance the accumulation of more fine roots in the topsoil. Other studies on tropical forests also reported 70–80% of C stocks in fine roots in the upper soil depth (Hertel *et al.*, 2009; Ibrahima *et al.*, 2010).

CHAPTER– 6

6. STORAGE AND FLUX OF NUTRIENTS

6.1 INTRODUCTION

Nutrient dynamics is an important phenomenon for the understanding of ecosystem functioning and ecological status. The nutrient cycling in forest ecosystem comprises of cyclic circulation of nutrients between forest soils and plants. Nutrient uptake, their retention and release are the three components of nutrient dynamics in forest ecosystem. More uptake of nutrients and less return to the soil leads to degradation of land and finally, lowering the productivity.

Litter and fine roots are regarded as the forest nutrient pool linking inputs, output and turnover of nutrients. Nutrients accumulated in non-photosynthetic parts (stem and roots) form the retention component while those accumulated in leaves return to the ecosystem through litter fall. Further, fine roots also play a vital role in nutrient return to the ecosystem. Studies have indicated that major portion of the nutrients absorbed by plant species is returned to the forest floor or translocated within the plant and relatively small portion is retained each year in an annual accretion of biomass (Pritchett & Fisher, 1987).

Tropical forests constitute about half of the world’s forest area, contain approximately 25% of the world’s terrestrial biomass and soil C (Jobbagy & Jackson, 2000), exchange more water and CO_2 with the atmosphere than any other biome (Foley *et al.*, 2005), and exhibit higher rates of primary production and the amounts of nutrients cycled than those in temperate forests (Vitousek & Sanford, 1986). The capacity of tropical forests to mitigate increasing atmospheric CO_2 concentrations through accelerated growth will depend in part upon their ability to meet increasing demand for growth-limiting mineral nutrients (Cernusak *et al.*, 2013). Wright *et al.* (2011) reported that nutrients like N, P, and K all limit forest plants growing on fertile soil in the lowland tropics. However, despite the importance of tropical forests, the cycling of nutrients in these ecosystems are poorly understood (Murphy & Lugo, 1986; Vitousek & Sanford, 1986), particularly in the context of forest disturbance.

Disturbances in forest ecosystem often cause the disruption of community structure, nutrient cycling and loss of nutrients from the ecosystem which is likely to have significant effects upon the subsequent type and intensity of soil processes, biogeochemistry and functioning of the ecosystem as a whole within a landscape (Walley *et al.*, 1996). Resource availability and disturbance are important factors that shape the composition, structure, and functioning of ecosystems (Gleason *et al.,* 2010).

Quantitative documentation of nutrient storage and flux with respect to forest disturbance are not available about tropical forest ecosystems in Nepal. Therefore, present study was carried out in undisturbed and disturbed stands of moist tropical forest ecosystem in the eastern Nepal with following objectives: 1) to estimate the magnitudes of the storage of N, P and K in the vegetation with respect to forest disturbance; 2) to qualify the rates of uptake and internal recycling of nutrients in undisturbed and disturbed forest; 3) to understand the contribution of litterfall to nutrients cycling in both forest stands; and 4) to assess the contributions of fine roots in uptake and transfer of nutrients during forest disturbance.

6.2 LITERATURE REVIEW

Foliar nutrient concentrations and resorption efficiency was studied in dune chronosequence in Australia (Hayes *et al.*, 2014) and found community-wide variation in leaf nutrient concentrations and resorption. Further, a strong effect of soil nutrient availability was observed on nutrient-use efficiency of plants.

Schreeg *et al.* (2014) carried out fertilizer addition experiments in a lowland tropical forest in Panama. Results indicated that the N:P ratios of stems, roots, and older leaves were more responsive indicators of soil nutrient availability than those of new leaves.

Liu *et al.* (2013) conducted experiments in the subtropical forests of China and observed that elevated CO_2 and N addition could facilitate tree species to mitigate P limitation by more strongly influencing P dynamics than N.

Wright *et al.* (2011) maintained N, P, and K addition experiment for 11 years in a humid lowland tropical forest in Panama and argued that N, P, and K all limit forest plants growing on a fertile soil.

Biological stoichiometry of plant production was studied by Elser *et al.* (2010). They concluded that N:P ratios in plants can provide insight into nutrient limitation, vegetation composition and functioning of ecosystems under future environmental change.

Gleason *et al.* (2010) investigated the effects of soil fertility and disturbance on plant–soil interactions and nutrient cycling in Australian tropical rainforests and concluded that resource availability and disturbance are important factors that shape the composition, structure, and functioning of ecosystems.

Pregitzer and Zak (2010) carried out N-fertilization experiments in sugar maple (*Acer saccharum*) dominated forest and found that leaves were a stronger sink for labeled N than fine roots with the residence time of 6.5 years in leaf litter and 3.1 years in fine roots.

A global dataset of N and P concentrations in leaf-litter of woody plants was compiled from the literature (Kang *et al.*, 2010). At a global scale, the mean leaf-litter N and P and N:P ratio were 10.9 mg g^{-1}, 0.85 mg g^{-1} and 18.3, respectively. Leaf-litter N and P were significantly correlated.

Nirmal Kumar *et al.* (2009) quantified the nutrient content of aboveground biomass of teak (*Tectona grandis* L.) plantation in a tropical dry deciduous forest of Udaipur, Rajasthan, India. The nutrient contents (kg ha^{-1}) in the total biomass were 165.5 N, 20.9 P, and 35.0 K. In total, 42.9% of the dry matter accounted for crown biomass (leaves, branches, twigs and reproductive parts) whereas 57.0% of the dry matter accounted for trunk biomass (bole bark and bole wood).

Patino *et al.* (2009) studied branch xylem density variations across the Amazon and found that tree species growing on nutrient poor soils are characterized by dense wood, while tree species growing on nutrient rich soils are characterized by lighter wood.

Fyllas *et al.* (2009) studied foliar properties of Amazonian forest and reported that tree species growing on nutrient poor soils are characterized by low foliar nutrient concentrations as in eastern and central Amazon, while tree species growing on nutrient rich soils of western Amazon are characterized by higher foliar nutrient concentrations.

Yuan and Chen (2009) analyzed global data to quantify the amount of N and P in senesced leaf and reported highest tree foliar N:P values in tropical forests as compared to higher latitude ecosystems.

Townsend *et al.* (2007) studied the factors affecting the foliar N and P concentrations in tropical forests in Costa Rica and Brazil and found no relationship between N:P ratios and either latitude or mean annual precipitation. They identified species variability as a main cause, and the season and soil P availability as secondary causes for the variation of N:P values in tropical forests. They also observed that N:P values are generally more in tropical forests as compared to higher latitude ecosystems.

McGroddy *et al.* (2004) used data from the literature to examine the stoichiometry of C, N, and P in forest foliage and litter. The C:N:P ratios of foliage (1212:28:1) and litter (3007:45:1) reflected the increased proportion of C as compared to nutrients. Carbon: nutrient ratios in litter were consistently higher than in foliage, suggesting that resorption of nutrients is a globally important mechanism, particularly for P.

Mandal (1999) studied the nutrient dynamics in the Sal forest ecosystem of Nepal Himalaya and found nutrient return via litterfall in the order of N > K > P. Further, the N:P ratio in herbs was lower than tree leaves.

Karmacharya and Singh (1992b) studied the nutrient dynamics in reproductive components of teak trees in the dry tropics of India. They reported that the percentage nutrient resorption in reproductive parts was in the order N > P > K.

Singh and Singh (1991b) studied storage and flux of nutrients in a dry tropical forest in India and found that nutrient concentrations in different growth forms were in the decreasing order of herb > shrub > tree.

Patterns of N, and P cycling through litterfall were evaluated using published information from 62 tropical forests (Vitousek, 1984). In general, tropical forests had more N and little P in litterfall than most temperate forests. Fine litterfall in tropical forests were positively correlated with P but not with N concentrations in litterfall.

6.3 MATERIALS AND METHODS

6.3.1 Plant and litter chemical analysis

Samples of different tree components were collected from each sampling plots from the representative individuals of all available girth classes. Samples of shrubs from different components and herbs (aboveground) were collected from each site. Composite samples of all components of trees, shrubs and herbs were oven dried at 80 ^{o}C to constant weight.

Litterfall samples (leaf litter and non-leaf litter) collected from the litter traps at monthly intervals were pooled together in proportion to their volume to represent annual samples for each site. The oven dried samples of each component of plant, leaf litter and wood litter ground separately and passed through 1 mm mesh screen. Three separate samples of various components were analyzed for each site. The fine roots of < 2 and 2–5 mm diameter of all sampling locations were mixed separately, oven dried at 80 ^{o}C to constant weight and ground for chemical analysis.

The total N concentration was determined by micro-Kjeldahl method (Peach & Tracey, 1956). Using the method outlined by Allen *et al*. (1974), a portion of the plant sample was digested in triacid mixture (1:5:1, perchloric : nitric : sulphuric acid) and P was determined colorimetrically, and K and calcium (Ca) by atomic absorption spectrophotometer. Calcium was determined only in fresh green leaf and leaf litter samples. Lanthanum chloride was added in the samples used for the determination of Ca.

6.3.2 Computation procedure

The stocks of nutrients in the vegetation components were computed by multiplying the dry weights of components and their mean nutrient concentrations. The stocks in different components were summed to obtain total nutrient storage in the vegetation. The gross uptake of nutrients was calculated by multiplying the values of net production of different components with their respective nutrient concentrations. The nutrient uptakes by trees, shrubs, herbs and fine roots were summed to estimate the gross uptake by the vegetation (Tripathi & Singh, 1994).

The turnover time, as an index of nutrient cycling rate for different nutrients was computed as the ratio of stock / annual gross uptake (Singh, 1989). The nutrient re-translocation in the leaves during senescence was estimated by using nutrient: Ca ratios, assuming that Ca is immobile (Vitousek & Sanford, 1986):

$$\% \text{ re-translocation} = \frac{X - Y}{X} \times 100$$

Where, X = (nutrient concentration in green leaf) / (Ca concentration in green leaf),

and Y = (nutrient concentration in leaf litter) / (Ca concentration in leaf litter)

The net uptake of nutrients by trees, shrubs and herbs was computed by subtracting the amount retranslocated from the gross uptake.

The amounts of nutrients transferred to the forest floor were computed by multiplying the annual litterfall weight and nutrient concentration data. The nutrient-use efficiency was calculated following Vitousek (1982):

$$\text{Nutrient use efficiency} = \frac{\text{Net primary production}}{\text{Net nutrient uptake}}$$

The turnover rate (k) for each element on the forest floor was calculated as $k=A/(A+F)$, (Jenny *et al*., 1949), where A is the amount of nutrient added to the forest floor annually by litterfall and F is the nutrient content of the lowest value of standing crop of litter in the annual cycle. Turnover time (t) is the reciprocal of the turnover rate (k) and is expressed as $t = 1 / k$.

6.4 RESULTS

6.4.1 Nutrient concentration

Nutrient concentrations in different components of trees, shrubs, herbs and fine roots are summarized in Table 51. The relative concentrations of different nutrients, in diminishing order were: N > K > P in herbs, shrubs and trees, indicating that the plants are richer in N than K. The nutrient concentrations varied widely amongst components. In trees concentrations of all nutrients were highest in leaves followed in decreasing order by fine roots (<5 mm) and twigs and then by branches, bole and coarse roots.

N:P ratio in tree and tree leaves were 9.3 and 8.7 respectively. N:P ratio in shrubs was maximum (13.1), while in herbs it was minimum (8.2). Fine roots, the active absorptive parts for nutrient uptake from the soil, had higher concentration of nutrients and N:P ratio than coarse roots. In fine roots, concentration of nutrients were in the order N > K > P. Nutrient concentration in fine roots decreased with increase in root diameter (Table 51). Fine roots of < 2 mm size ranked next to tree leaves with respect to the concentrations of N and K. It is evident that the short lived and rapidly cycling components of tree (leaf and fine root) accumulated high concentrations of nutrients than the relatively permanent parts (bole).

Table 51. Nutrient concentrations (%) (mean ± SE) in tree, shrub, herb and fine root of moist tropical forest in Sunsari district, eastern Nepal.

Components	N	P	K
Trees			
Bole	0.57 ± 0.04	0.05 ± 003	0.57 ± 0.03
Branch	0.62 ± 0.06	0.06 ± 0.007	0.58 ± 0.03
Twig	0.69 ± 0.06	0.08 ± 0.005	0.57 ± 0.04
Leaf	1.73 ± 0.18	0.2 ± 0.02	1.12 ± 0.11
Coarse root	0.49 ± .03	0.05 ± 0.002	0.32 ± 0.02
Shrubs			
Stem	0.78 ± 0.07	0.07 ± 0.004	1.21 ± 0.12
Leaf	2.49 ± 0.31	0.19 ± 0.001	1.56 ± 0.20
Coarse root	0.67 ± 0.04	0.04 ± 0.004	0.49 ± 0.03
Herbs aboveground	1.47 ± 0.11	0.18 ± 0.015	1.42± 0.17
Stand fine roots			
0-2 mm	0.9 ± 0.05	0.07 ± 0.003	0.71 ± 0.05
2–5 mm	0.63 ± 0.03	0.05 ± 0.002	0.69 ± 0.04

6.4.2 Nutrient stocks in vegetation

The nutrient stocks in different components of plants differed considerably in undisturbed and disturbed forests (Table 52). The differences in nutrient stocks were accounted by the variations in biomass and not due to concentration. Thus, in the DF which showed lower biomass, the quantities (kg ha^{-1}) of nutrients in total vegetation was 2704.4 N, 252.9 P and 2470.8 K; while in UF with higher biomass, the quantities (kg ha^{-1}) of nutrients were 5738.2 N, 537.7 P and 5232.1 K. It showed that the vegetation of UF contained more than double N, P and K stocks than DF.

Table 52. Nutrient stocks (kg ha^{-1}) in tree, shrub, herb and fine root in undisturbed and disturbed forest stands of moist tropical forest of Sunsari district, eastern Nepal (mean ± SE).

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Trees	5612.5±481	527.0±54	5118.7±49	2594.0±144	243.5±22	2366.6±251
Bole (%)	62	58	68	62	58	68
Branch (%)	13	13	13	14	14	14
Twig (%)	4	5	4	4	5	3
Leaf (%)	7	8	5	6	8	5
C. root (%)	14	16	10	14	16	10
Shrubs	49.9±2.7	3.9±0.3	46.7±0.7	64.7±4.3	5.0±0.3	63.5±4.7
Stem (%)	31	36	52	36	42	57
Leaf (%)	50	49	33	44	44	28
Root (%)	19	15	15	20	16	15
Herbs	20.6±1.2	2.5±0.2	19.9±1.0	17.6±1.0	2.2±0.1	17.0±1.1
Stand fine root	55.2±3.1	4.3±0.3	46.8±2.6	28.1±1.8	2.2±0.1	23.7±2.2
0-2 mm (%)	81	81	75	82	82	76
2-5 mm (%)	19	19	25	18	18	24
Total Vegetation	5738.2±497	537.7±41	5232.1±402	2704.4±156	252.9±16	2470.8±187

The contribution of different components to total nutrient stocks was in the order: tree > stand fine root > shrub > herb, in both stands. In shrubs, relative contribution of different components to total nutrient stocks was in the order: leaf > stem > coarse root; however in trees the trends were: bole > coarse root > branch > leaf > twig > fine roots for all estimated nutrients. In trees, boles and coarse roots had lower nutrient concentrations but greater nutrient stocks than other components. Therefore, the maximum loss of all nutrients occurs through stem harvest.

Aboveground nutrient stocks comprised 84–89% of the total vegetation stocks in both undisturbed and disturbed forests. Nutrient stocks in both aboveground and belowground parts (coarse root + fine root) decreased with the forest disturbance. Fine root of smaller size class (0–2 mm diameter) contained quite greater nutrient stocks than that of larger size class (2–5 mm diameter) (Table 52). Compared to total nutrient stocks in the vegetation, allocation of different nutrients to belowground parts ranged between 11 and 16% at both forests. The sequential arrangement of nutrient storage in vegetation was: N > K > P in both forest stands.

6.4.3 Nutrient uptake and re-translocation

The gross uptake of nutrients (total amount of nutrients associated with net production) in different components of vegetation in both forest stands is presented in Table 53. As expected, UF showed higher gross uptake as compared to DF. In UF the ranges of gross uptake of nutrients in vegetation (kg ha^{-1} yr^{-1}) were: 282.4 N, 30.1 P, and 217.7 K, whereas in DF they were 156.8 N, 16.5 P, and 124.2 K. The gross uptake of nutrients was in the order of tree > herb > shrub. In trees, leaves and fine roots had lower biomass but greater gross uptake of nutrients than other components.

Table 53. Gross uptake of nutrients (kg ha^{-1} y^{-1}) in tree, shrub, herb and fine root in undisturbed and disturbed forest stands of moist tropical forest of Sunsari district, eastern Nepal (mean ± SE).

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Trees	208.8±15	23.2±1.3	151.3±8.2	106.8±7.5	11.8±0.5	77.9±2.8
Bole (%)	13	10	18	16	13	22
Branch (%)	3	2	3	3	3	4
Twig (%)	13	14	15	9	10	11
Leaf (%)	68	71	61	68	71	60
Coarse root (%)	3	3	3	4	3	3
Shrubs	5.3±0.3	0.4±0.02	5.6±0.3	6.9±0.4	0.5±0.02	7.6±0.5
Stem (%)	44	50	64	46	60	67
Leaf (%)	33	25	20	29	40	16
Root (%)	23	25	16	25	20	16
Herbs	25.0±1.7	3.1±0.1	24.1±1.8	19.1±1.0	2.3±0.01	18.5±1.3
Stand fine root	43.3±2.6	3.4±0.1	36.7±1.8	24.0±1.2	1.9±0.01	20.2±0.8
0-2 mm (%)	81	79	75	83	79	78
2-5 mm (%)	19	21	25	17	21	22
Total vegetation	282.4±18	30.1±1.7	217.7±13.4	156.8±8.2	16.5±1.0	124.2±9.5

A marked re-translocation of N, P and K was recorded in senescing leaves in different growth forms (Table 54). Re-translocation of N and K was lesser in herbaceous species than shrub and tree species, whereas re-translocation of P was minimum in shrubs. Re-translocation behaviour in trees showed an order of P > N > K. The net uptake of nutrients (actual amount of nutrients transferred from soil to plant after correction for re-translocation) is given in Table 55. Distinctly higher net uptake of nutrients was recorded in UF than DF. The net uptake of nutrients (kg ha^{-1} yr^{-1}) in the vegetation were 207.7 N, 19.4 P and 164.2 K in UF and 116.8 N, 10.7 P and 100.5 K in DF.

Table 54. Percentage nutrient re-translocation during leaf senescence in moist tropical forest of Sunsari district, eastern Nepal.

Components	Nutrients		
	N	P	K
Herbs	36	53	35
Shrubs	49	44	52
Trees	48	59	41

Table 55. Net uptake of nutrients (kg ha^{-1} y^{-1}) after adjustment for re-translocation in tree, shrub, herb and fine root in undisturbed and disturbed forest stands of moist tropical forest of Sunsari district, eastern Nepal (mean ± SE).

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Trees	140.4±13.9	13.5±0.8	113.5±4.8	72.0±2.2	6.8±0.3	58.7±2.9
Shrubs	4.5±0.2	0.36±0.01	5.0±0.3	5.9±0.4	0.4±0.02	7.0±0.4
Herbs	19.5±1.3	2.1±0.1	19.0±1.3	14.9±0.9	1.6±0.1	14.6±1.0
Stand fine root	43.3±2.6	3.4±0.1	36.7±1.8	24.0±1.2	1.9±0.01	20.2±0.8
Total vegetation	207.7±17	19.4±1.2	164.2±9.4	116.8±6.2	10.7±0.7	100.5±6.8

Trees shared 68–70% of total net uptake of different nutrients in UF, whereas the range of total net uptake in DF was 58–64%. Moreover, the share of shrubs and herbs (aboveground parts) to total net uptake ranged between 2–7% in UF and 9–15% in DF. The share of trees in total net uptake decreased with forest disturbance, whereas that of shrubs and herbs was higher in DF as compared to UF. Fine roots accounted for substantial fractions of total net uptake for all nutrients (18–22%) which was similar in both stands. The sequential arrangement of net nutrient uptake was: N > K > P in both stands. The relative contributions of different tree components to total net nutrient uptake were in the order: Leaf > Fine root > Twig > Bole > Coarse root/Branch.

6.4.4 Nutrient return through litterfall

The concentrations of all nutrients in leaf litter were higher than in non-leaf litter in both stands (Table 56). The total input of nutrients (kg ha^{-1} yr^{-1}) to the soil through litterfall in UF was more than double (99.7 N, 8.3 P, and 64.4 K) as compared to DF (46.6 N, 3.9 P, and 31.3 K) (Table 57). The contribution of different nutrients in the input to the soil through litterfall was in the order: N > K > P in both forest stands. Of the total annual nutrient input through litterfall, leaf litter accounted for 78–87% in UF and 85–90% in DF.

Table 56. Concentration of nutrients (%) (mean ± SE) in litter of moist tropical forest in Sunsari district, eastern Nepal.

Components	N	P	K	Ca
Leaf litter				
Trees	0.85±0.05	0.08±0.003	0.62±0.04	1.13±0.08
Shrubs	1.1±0.09	0.09±0.007	0.65±0.05	1.03±0.06
Herbs	0.81±0.04	0.07±0.006	0.8±0.05	1.03±0.07
Mean	0.92±0.05	0.08±0.005	0.69±0.06	1.06±0.06
Non leaf litter				
Trees	0.66±0.05	0.05±0.003	0.22±0.01	
Shrubs	0.7±0.07	0.05±0.003	0.24±0.02	
Mean	0.68±0.05	0.05±0.004	0.23±0.01	

Table 57. Amount of nutrients (kg ha^{-1} yr^{-1}) in litterfall in undisturbed and disturbed forest stands of moist tropical forest of Sunsari district, eastern Nepal (mean ± SE).

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Leaf	74.5±6.5	6.5±0.4	55.9±5.6	37.7±2.8	3.3±0.1	28.3±2.4
Non leaf	25.2±1.6	1.9±0.1	8.5±0.7	8.8±0.5	0.7±0.05	3.0±0.02
Total	99.7±8.0	8.3±0.7	64.4±4.1	46.6±3.3	3.9±0.2	31.3±2.6

6.4.5 Nutrient-use efficiency

Generally, the nutrient-use efficiencies were greater in trees followed in decreasing order by shrubs and herbs (Table 58). Difference with respect to N, P, and K-use efficiencies were distinct amongst different growth forms. With respect to individual growth forms general trends of nutrient-use efficiency included: increase in nutrient-use efficiencies with disturbance in trees, almost same trend in nutrient-use efficiencies with disturbance in herbs, and increase in N and P-use efficiencies with disturbance in shrubs.

Table 58. Nutrient-use efficiency of different nutrients in different growth forms in undisturbed and disturbed stands of moist tropical forest in Sunsari district, eastern Nepal.

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Herbs	87	810	89	87	813	89
Shrubs	122	1527	110	127	1875	107
Trees	136	1417	169	138	1465	170

6.4.6 Turnover of nutrients in standing vegetation

Turnover time for nutrients in vegetation showed variations due to growth form as well as with the forest disturbance (Table 59). Trees showed greater turnover time followed in decreasing order by shrubs and herbs in both forest stands. For the stand vegetation as a whole, the turnover time in both forests was maximum for K (19.9–24.0 years) followed by N (17.2–20.3) and minimum for P (15.3–17.9).

Table 59. Turnover time (year) for different nutrients in standing vegetation of undisturbed and disturbed stands of moist tropical forest in Sunsari district, eastern Nepal.

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Herbs	0.8	0.8	0.8	0.9	1.0	1.2
Shrubs	9.4	9.3	8.3	9.4	9.2	8.4
Trees	26.9	22.7	33.8	24.3	20.7	30.4
Total vegetation	20.3	17.9	24.0	17.2	15.3	19.9

6.4.7 Nutrients in litter mass and turnover of nutrients on forest floor

Litter on the forest floor (litter mass) varies seasonally with litterfall. Standing state of nutrients in litter mass decreased with forest disturbance. The nutrient stocks in litter mass were in the order: N > K > P in both forest stands (Table 60). Leaf litter contributed 68–82% of total nutrients in UF and 72–85% in DF. Of the total nutrients in litter mass, 63–65% nutrients were present in fresh litter and rest in partly decayed litter.

Table 60. Standing state of nutrients (kg ha^{-1}) (mean ± SE) in litter layer in undisturbed and disturbed stands of moist tropical forest in Sunsari district, eastern Nepal.

Components	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Total littermass	55.4±4.3	4.6±0.3	34.3±2.8	29.9±1.5	2.5±0.1	18.9±1.1
Fresh leaf litter (%)	45	47	54	46	48	55
Partly decayed leaf litter (%)	23	24	28	26	27	30
Fresh non-leaf litter (%)	20	17	11	18	15	9
Partly decayed non-leaf litter (%)	12	11	7	11	9	6

The turnover rate and turnover time for different litter nutrients on the forest floor are given in Table 61. The turnover rate of nutrients ranged 0.67–0.69 for N, 0.66–0.68 for P and 0.64–0.66 for K. The turnover rates were slightly higher in the UF and lower in the DF. The turnover time of litter nutrients ranged 1.45–1.49 for N, 1.47–1.51 for P and 1.53–1.55 for K. Turnover time for all nutrients were relatively higher in DF which may be due to immobilization of these nutrients in litter mass by the microorganisms.

Table 61. Turnover rate (*k*) and turnover time (*t*) of litter nutrients on forest floor in undisturbed and disturbed stands of moist tropical forest in Sunsari district, eastern Nepal.

Turnover rate and time	Undisturbed forest			Disturbed forest		
	N	P	K	N	P	K
Rate (per yr)	0.69	0.68	0.66	0.67	0.66	0.64
Time (yr)	1.45	1.47	1.53	1.49	1.51	1.55

6.4.8 Nutrient budget and flux

Nutrient budget for different nutrients in vegetation are presented in Table 62. The nutrient stocks in vegetation decreased from undisturbed to disturbed forest. Substantial quantities of nutrients were retranslocated during leaf senescence in both forest stands; the ranges for different nutrients (kg ha^{-1} yr^{-1}) were: 40.0–74.7 N, 5.8 – 10.7 P, and 23.7–53.5 K. The retranslocated amount was almost double in UF as compared to DF. Re-translocation: gross uptake ratio for different nutrients was almost same in both forests.

Table 62. Nitrogen, Phosphorus and Potassium budget for vegetation in undisturbed forest stand (UF) and disturbed forest stand (DF) of moist tropical forest in Sunsari district, eastern Nepal.

Components	Nitrogen budget		Phosphorus budget		Potassium budget	
	UF	DF	UF	DF	UF	DF
Nutrient stocks[1]	5738.2	2704.4	537.7	252.9	5232.1	2470.8
Gross uptake[2]	282.4	156.8	30.1	16.5	217.7	124.2
Re-translocation[2]	74.7	40.0	10.7	5.8	53.5	23.7
Net uptake[2]	207.7	116.8	19.4	10.7	164.2	100.5
Return, litterfall[2]	99.7	46.6	8.3	3.9	64.4	31.3
Return, fine root[2]	43.3	24.0	3.4	1.9	36.7	20.2
Total return[2]	143.0	70.6	11.7	5.8	101.1	51.5
% total return of net uptake	69	60	60	54	62	51
Retention in vegetation[2]	64.7	46.2	7.7	4.9	63.1	49.0
% retention of net uptake	31	40	40	46	38	49
Re-translocation: Gross uptake ratio	0.26	0.26	0.36	0.35	0.25	0.19

1. Kg ha^{-1}; 2. Kg ha^{-1} yr^{-1}

Nutrient return to the soil through litterfall exceeded over the return through fine roots. Litterfall returned about 1.5 times greater the amount of N, P and K than fine roots in both stands. Further, total return of N, P and K through both litterfall and fine roots was more than double in UF as compared to DF. In the UF percentage of total return with respect to net uptake were 69% for N, 60% for P and 62% for K, while in the DF the percentage values of total return were relatively less i.e. 60% for N, 54% for P and 51% for K (Table 62).

Conversely, percentage retention of net uptake of N, P and K was less in UF in comparison to DF. The nutrient budget distinctly indicated that retention of nutrients as percentage of net uptake were relatively less in UF (i.e. 31% for N, 40% for P and 38% for K), while these percentage values were higher in DF (i.e. 40% for N, 48% for P and 49% for K) over the annual cycle. The higher percentage of nutrient retention in DF represents the nutrient aggregation while lower retention in UF indicates that most of the nutrients are recycled.

6.5 DISCUSSION

6.5.1 Nutrient concentrations, stocks and turnover

Nutrient concentrations in the plants varied in different growth forms and components. They are related to the production of above- and belowground biomass, stand density, and soil. The ranges of nutrient concentrations in different growth forms were in the order: herb > shrub > tree. The same order of concentrations in such growth forms was also reported by Singh and Singh (1991b) in dry tropical forest of India. Amongst components, the leaves contained maximum concentrations of nutrients in all growth forms in the present study.

The elevated nutrient concentration in the leaves makes this component an important reserve of nutrients, although it represents only a small percentage of the whole tree biomass. However, as the proportional contribution of leaf decreased from shrubs to trees, the nutrient concentrations also decreased in the same order as suggested by Golley *et al*. (1975). The concentration of K in the present study was relatively higher in herbs and shrubs as compared to trees. Fahey *et al*. (1991) also suggested that grasses and herbs are often high in K compared with woody species.

The foliar nutrients, especially N and P are used as an index of nutrient status in ecosystems (Vitousek, 2004). N:P ratios in plants can provide insight into nutrient limitation, vegetation composition and functioning in ecosystems under future environmental change (Elser *et al.*, 2010). Schreeg *et al.* (2014) found that N:P ratios of stems, older leaves, and roots of woody plants better reflect soil nutrient availability than does the N:P ratio of new foliage. Townsend *et al.* (2007) found correlations between foliar nutrient concentrations and soil nutrient availability and also argued that foliar N and P concentrations may explain the processes such as net primary productivity (NPP), decomposition, nutrient mineralization, emissions, and leaching.

Variation in the availability of one nutrient relative to the other can alter plant nutrient ratios, for example, the N:P ratio can increase as a consequence of either an increase in N availability or a decrease in P availability. It is supposed that the tropical forests are generally rich in N but poor in P. This belief is supported by the higher tree foliar N:P values in tropical forests (Yuan & Chen, 2009) as compared to higher latitude ecosystems. Foliar N:P ratio vary with soil P availability (Townsend *et al.,* 2007). In tropical forests, foliar and soil P (Cleveland *et al.*, 2011), or N or N:P ratio (Elser *et al.,* 2007) are the main determiners of aboveground NPP.

In the present study the foliar N:P ratio showed a decreasing order of shrubs > tree > herbs. Mandal (1999) also reported lower N:P ratio in herbs than tree leaves. The higher foliar N:P ratio in trees may be due to high potential growth and photosynthetic rates, which allow them to use the available phosphorus relatively in greater demand. Herbs were rich in nitrogen and plant with high nitrogen status causes upto a 10-fold increase in root absorption capacity for phosphate and *vice versa* (Chapin III, 1980). It could be the possible cause for the lower N:P ratio in herbs than trees and shrubs. N:P ratio for trees in the present study was lower than that for tropical rain forests of Costa Rica and Brazil (Townsend *et al.,* 2007).

The nutrient stocks of the present forest may be compared with nutrient stocks of other tropical forests (Table 63). More than double nutrient stocks in the UF than DF is mainly explained by the difference in biomass between the stands. The higher value of fine root N stock at UF indicated that soil nutrient absorption in this stand was enhanced by higher root metabolism, while the lower fine root N stock at DF was related with low fine root biomass. The higher N stock in the fine root of < 2 mm diameter class reported in this study was in agreement with the findings of Comas and Eissenstat (2009).

Table 63. Comparison of nutrient storage (kg ha^{-1}) in vegetation of some tropical forests of the world.

Forests	Nutrients			References
	N	P	K	
Moist tropical* (Venezuela)	1980	290	1820	Hase & Fölster (1982)
Sub-tropical dry (Puerto Rico)	916	30.7	315	Lugo & Murphy (1986)
Dry deciduous (India)	680	53	451	Singh (1989)
Humid Sal (India)				
Old growth**	4454	403	2510	Singh & Singh (1989)
Seedling-coppice**	2948	261	1654	Singh & Singh (1989)
Moist tropical Sal (Nepal)	4036	330	2239	Mandal (1999)
Moist tropical (Nepal)	5738	538	5232	Present study

* Nutrients in aboveground biomass; ** Nutrients reported for tree layer only

Knowledge of the turnover rates of nutrients is a prerequisite for understanding the availability and cycling of nutrients such as C, N and P. This understanding is essential in describing ecosystem dynamics and in calculating plant nutrient needs. Turnover time for nutrients in the vegetation reflects the rate of nutrient cycling. Turnover time for nutrients in herbs was almost same in both stands of present forest. Turnover time of nutrients in both shrubs and trees was lower for all nutrients in DF (8.4–30 year) than UF (8.3-34 year) indicating a faster nutrient cycling in early stages of succession as in DF, than the stable forest. Trend in nutrient exchange rate is expected to be rapid during the early stages of succession and slower at the mature stages (Odum, 1969). Tripathi and Singh (1994) reported a low turnover time for all nutrients in the harvested site than mature site in bamboo savannas in the dry tropics of India.

6.5.2 Nutrient re-translocation and nutrient-use efficiency

Conspicuous internal cycling of nutrients was manifested by strong re-translocation from senescing leaves as is evident from the higher re-translocation: gross uptake ratio in present forest (Table 62). The re-translocation of nutrients is considered to be an adaptation to minimize the nutrient loss, and presumably to meet the nutrient demand of new growth (Fife & Nambiar, 1982). Different nutrients had different recycling properties. Amongst the three nutrients studied, N was the most rapidly retranslocated nutrient in both stands of present forest. Further, retranslocated amount (kg ha^{-1} yr^{-1}) of N, P and K were almost double in UF in comparision to DF showing efficient nutrient conservation mechanism in UF. Karmacharya and Singh (1992b) also reported the rapid resorption of N among other nutrients in teak fruits. Mean annual re-translocation of N, P, and K in leaves combining all growth forms ranged from 43–52% (Table 54). It is comparable with the value of Mandal (1999) reported for mature Sal forest of Nepal and Karmacharya and Singh (1992b) for reproductive part of teak trees in dry tropics of India (29–48%). Vitousek and Sanford (1986) reported the re-translocation of N in the range of 6–58% and for P in the range of 23–69% for certain moist tropical forests.

Up to 90% of the maximum leaf N and P, 70% of the K, but none of the Ca may be translocated out of senescing leaves before abscission. Generally, plants of high nutrient status have a larger percentage N and P in soluble and inorganic form and retranslocate a larger proportions of their leaf N and P than plants with low nutrient status (Chapin III, 1980).

In the present study, high re-translocation was observed in the UF, having high soil nutrient status (Gautam & Mandal, 2014). An efficient re-translocation is a typical feature of climax forest tree species (Staaf, 1982). High re-translocation of N and P was also noted on fertile sites than on sites with poor nutrient status. However, clear evidence is still not available with regard to the relationship between soil fertility and nutrient re-translocation (Aerts, 1996). Re-translocation process varies from species to species and may be genetically determined (Ostman & Weaver, 1982). Re-translocation, a nutrient conserving mechanism may lead to a degree of independence from soil as nutrient source but it also means a reduced transfer of nutrients through litter, a factor which may favour an even nutrient availability and tight cycling of nutrients in the ecosystem (Tripathi & Singh, 1994).

A large amount of the organic matter produced per unit of nutrient uptake is considered to indicate efficient nutrient use. Such efficiency is characterized by high carbon: nutrient ratio (low nutrient concentration) in litterfall or more carbon fixed per unit of nutrient taken up (Vitousek, 1984). The re-translocation of larger fractions of nutrients before litterfall, increased the nutrient-use efficiency in the both stands of present forest. The N-use efficiency of trees (136–138), in the present study is high and close to the value 130 for N reported for efficient forests (Vitousek, 1984). The P-use efficiency of trees (1417–1465) in both stands was higher than the value (1059) reported for tropical dry deciduous forest in India (Singh, 1989). Vitousek (1984) considered the value 3000 for efficient tropical forest in P-use.

Litter fall is a major functional part of any ecosystem as it plays a vital role in regulating nutrient cycling and organic matter content. Nutrient return to the soil pool is mainly defined by litterfall (66–70% for N, 67–71% for P and 61–64% for K), and rest is contributed by fine roots (Table 62). Nutrient return via litterfall in the present study was in the range (64–162, 2.6–8.8, 21–41 kg ha^{-1} yr^{-1}, respectively for N, P and K) as reported by Vitousek and Sanford (1986) for several moist tropical forests, and by Mandal (1999) in the Sal forest ecosystem of Nepal Himalaya. Rapid turnover of litter in the UF may continually regenerate the available N, P and K to support a high net production of vegetation, as is evident from high nutrient uptake in UF (Table 63).

To synthesize the results of different chapters, nutrient budget and fluxes has been presented in flow chart in Chapter 7 to make a coherent story.

CHAPTER– 7

7. GENERAL DISCUSSION

The present study was undertaken to examine the effect of disturbance on the structure and functioning of moist tropical forest ecosystem of Sunsari district, eastern Nepal. This chapter provides a general synthesis of the information generated on various aspects of the structure and functioning of forest ecosystem in the context of disturbance as reported in the Chapters 3, 4, 5 and 6. The nutrient cycling in undisturbed and disturbed forest stands is described in the form of flow diagram (Figures 29 & 30) which illustrate the stocks and net fluxes of various nutrients. Comparative account of ecosystem properties is presented in Table 64.

7.1 Effect of disturbance on plant properties

Plant properties such as floristic composition, family diversity, species diversity, plant biomass and production, fine root biomass and production, organic matter input through litter and fine roots were significantly affected by disturbance. Regarding the species composition, both herb and shrub species increased on disturbed stand due to opening of the canopy cover. Their species richness, density and even species diversity increased on the DF. The DF showed 19-29% dissimilarity with the UF. Conversely, on the tree layer, species richness, density and species diversity were higher in the UF, which were reduced on the DF. Due to the effect of disturbance, there was 26% dissimilarity between two forest stands. As the disturbance has reduced the density of the trees, this was also reflected in basal area (BA). The BA is reduced by 53.1% in DF in comparison to UF. Distribution of species content, density and BA of trees in different girth classes clearly exhibited (Figure 14) effect of disturbance in moist tropical forest.

Disturbance also affects significantly the level of stand biomass and production, fine root biomass and production and litter production (Table 64). These dry matter properties of plants reduced at DF. Consequently the carbon (C) stocks and sequestration also decreased due to disturbance in forest. This reflects that there would high C emission from the disturbed forest stand.

Table 64. Comparative account of ecosystem properties in undisturbed forest stand (UF) and disturbed forest stand (DF) of moist tropical forest in Sunsari district, eastern Nepal.

Parameters	**Forest types**	
	UF	**DF**
Plant properties		
Biomass (Mg ha^{-1})	960.40	449.10
Herbs*	1.40	1.20
Shrubs	4.40	6.10
Trees	948.0	438.4
Stand fine root	6.60	3.40
Net production (Mg ha^{-1} yr^{-1})	26.58	14.91
Herbs*	1.70	1.30
Shrubs	0.55	0.75
Trees	19.13	9.96
Stand fine root	5.20	2.90
BAR**	36	30
Litterfall (Mg ha^{-1} yr^{-1})	11.80	5.40
Litter mass (Mg ha^{-1})	6.70	3.60
Turnover; fine root (0-30 cm depth)	0.75	0.82
Turnover; litter	0.83	0.79
Soil properties (0-15 cm depth)		
Organic C (%)	3.07	1.8
Soil organic matter (%)	5.3	3.1
Carbon stock (Mg C ha^{-1} soil)	58.9	36.2
Total N (%)	0.24	0.14
Total phosphorus (µg g^{-1})	626.6	618.3
Exchangeable potassium (µg g^{-1})	346.3	268.1
Microbial biomass C (µg g^{-1})	558.4	438.5
Microbial biomass N (µg g^{-1})	50.7	39.9
Microbial biomass P (µg g^{-1})	12.3	9.7

* Aboveground parts; ** BAR (Biomass Accumulation Ratio)

Net production in total vegetation at UF and DF were correlated with the value of annual litter fall and fine root biomass. Turnover of litter was higher in UF than DF, while turnover of fine root showed reverse trend, it was higher in DF than UF. Due to disturbance the surface area of soil become dry in DF which may retard the turnover rate of litter while the soil layer is moderately disturbed, so turnover of fine root is high. The net uptake of C by the vegetation is far greater than that returned to soil by the turnover of fine root and litter. Therefore both stands of present forest act as C accumulating systems. Greater production efficiency at the DF and low production efficiency at the UF was also evident from the biomass accumulation value.

7.2 Effect of disturbance on soil properties

Soil microbial biomass, an active fraction of soil organic matter decreased by 21% at DF (Table 64). Highly significant relationship ($P < 0.01$) between soil properties and microbial biomass in both stands indicate that microbial biomass is highly sensitive to soil organic C, total N and total P. The level of soil microbial biomass may provide information for monitoring initial disturbance in soil biological processes at the ecosystem level (Hart *et al.*, 1989). Soil variables including microbial biomass carbon and nitrogen show positive relationship with biomass of trees also.

The environmental variables were correlated with fine root biomass and production. In UF, fine root biomass showed significant negative correlations with soil organic carbon, total P, microbial biomass C and N, whereas fine root production showed significant positive correlations with tem except total P.

Amount of organic matter in the soil is regulated by the addition of plant residues in the form of litter and fine root (Batjes, 1996). Due to turnover of litter and fine root, organic matter is added into the soil. The high turnover rate of fine root at DF added more nutrients into disturbed soil, showing nutrient conservation mechanism at the nutrient deficient site. Another approach of nutrient conservation was seen in the form of nutrient use efficiency. Regarding the growth form, nutrient use efficiencies were greater in trees followed in decreasing order by shrubs and herbs (Table 58). However, nutrient use efficiencies of trees and shrubs were higher at DF showing nutrient conservation at nutrient deficient site. Thus, greater nutrient use efficiency, high turnover rate of fine root, higher uptake of nutrients than return and higher nutrient use efficiency at DF, all favor the site to supply and conserve the nutrients at high rate than UF to manage the nutrients demand.

7.3 Nutrient dynamics in the context of disturbance

Nutrient cycling is an integrating process that brings together most other functions of the ecosystems, and therefore among all functions that regulate the activity of forest ecosystem, nutrient cycling is of critical importance. Nutrient cycling in undisturbed and disturbed stands of the present forest has been modeled in Figures 29 to 30. Average stand stocks of nutrients are given in compartments and the net annual fluxes between compartments are represented as arrows. The amount of nutrients present in the soil to a depth of 30 cm is considered as source. In these flow diagrams, N and P are better accounted for, because their total contents in the soil are estimated. In soil, the content determined for a cation (K) comprises its exchangeable state only. The direction of nutrient flux from soil to foliage indicates a one-way movement, although it is understood that the nutrients utilized by the foliage in organic matter synthesis are redistributed among different components during the assimilate transfers.

Aboveground nutrient stocks comprised 84–89% of the total vegetation stocks in both stands. In UF, of the total nutrients stored in the ecosystem (plant + litter + soil to a depth of 30 cm), 17–44% of the total N and P were stored in the vegetation, 55–81% in soil and only a negligible fraction (0.2–0.4%) in litter mass; whereas in DF, the vegetation comprised 9–37%, soil accounted for 63–91% and litter mass accounted for 0.1–0.4% of nutrient storage.

The total quantity of nutrients stored in the vegetation decreased with the forest disturbance. As nutrient stock in the vegetation is explained mainly by the level of biomass, it decreased in disturbed forest stand having low biomass value due to cutting of trees and lopping of branches.

Much reduced amount of nutrients in litter mass resulted due to rapid turnover of litter nutrients (64–69%) on the forest floor in both forest stands. With the disturbance, the nutrient storage capacity of vegetation decreased while that of soil increased in considerable amount. With respect to cation (K) the share of vegetation was 69–80%, of litter 0.5% and of soil 20–30% in both forest stands. The wide range of cation responses was due to higher allocation (69–80%) of K in the vegetation.

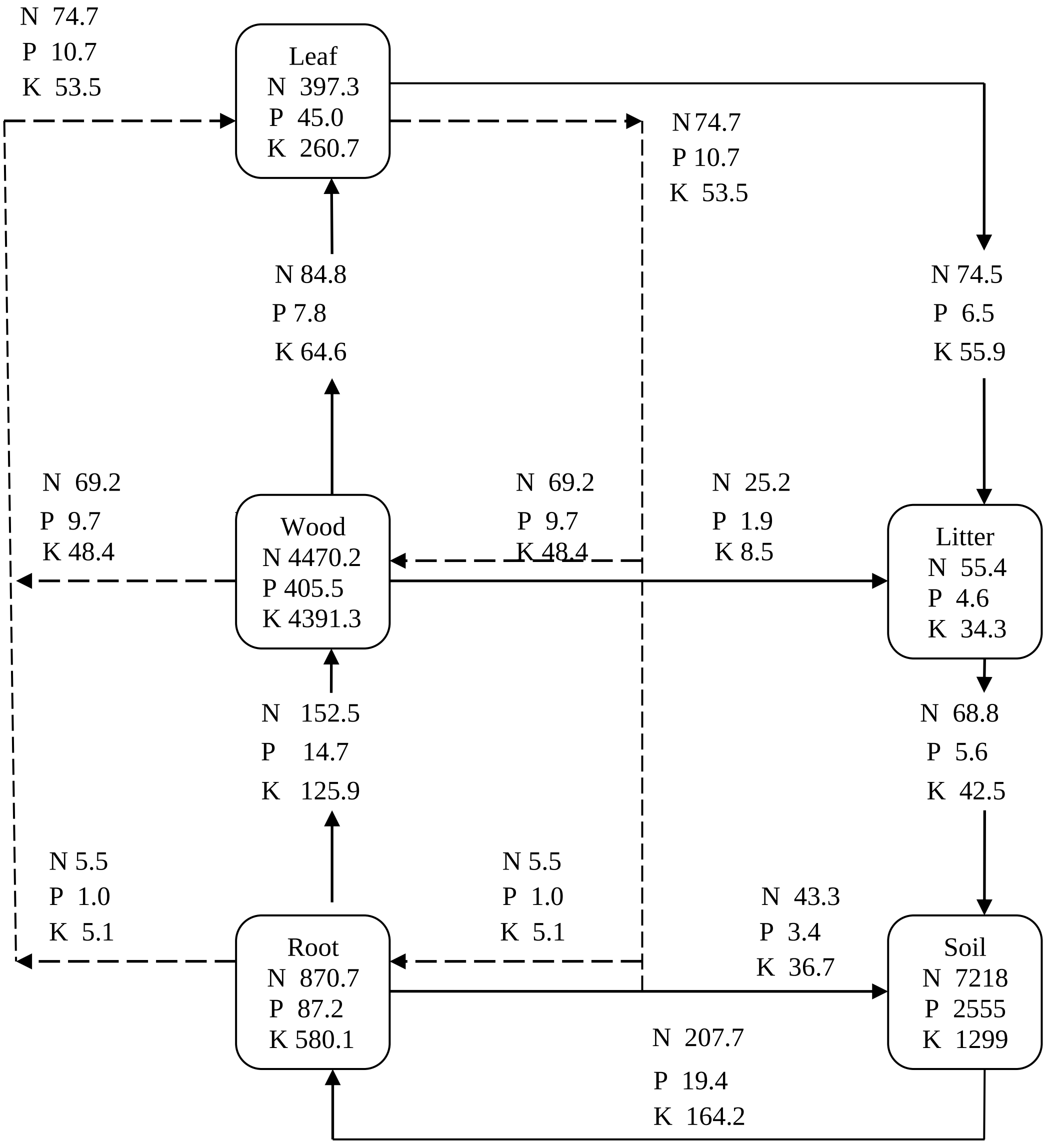

Figure 29. Model showing the distribution and cycling of nutrients, N, P and K in undisturbed forest stand of moist tropical forest of Sunsari district eastern Nepal. Values inside compartments represent nutrient stocks (kg ha^{-1}). Internal recycling is represented by the broken lines. Net annual fluxes between compartments are represented as arrows (kg ha^{-1} yr^{-1}). The root compartment includes coarse as well as fine roots. The wood compartment also includes aboveground non-leaf part of herbs (especially of the perennial forbs).

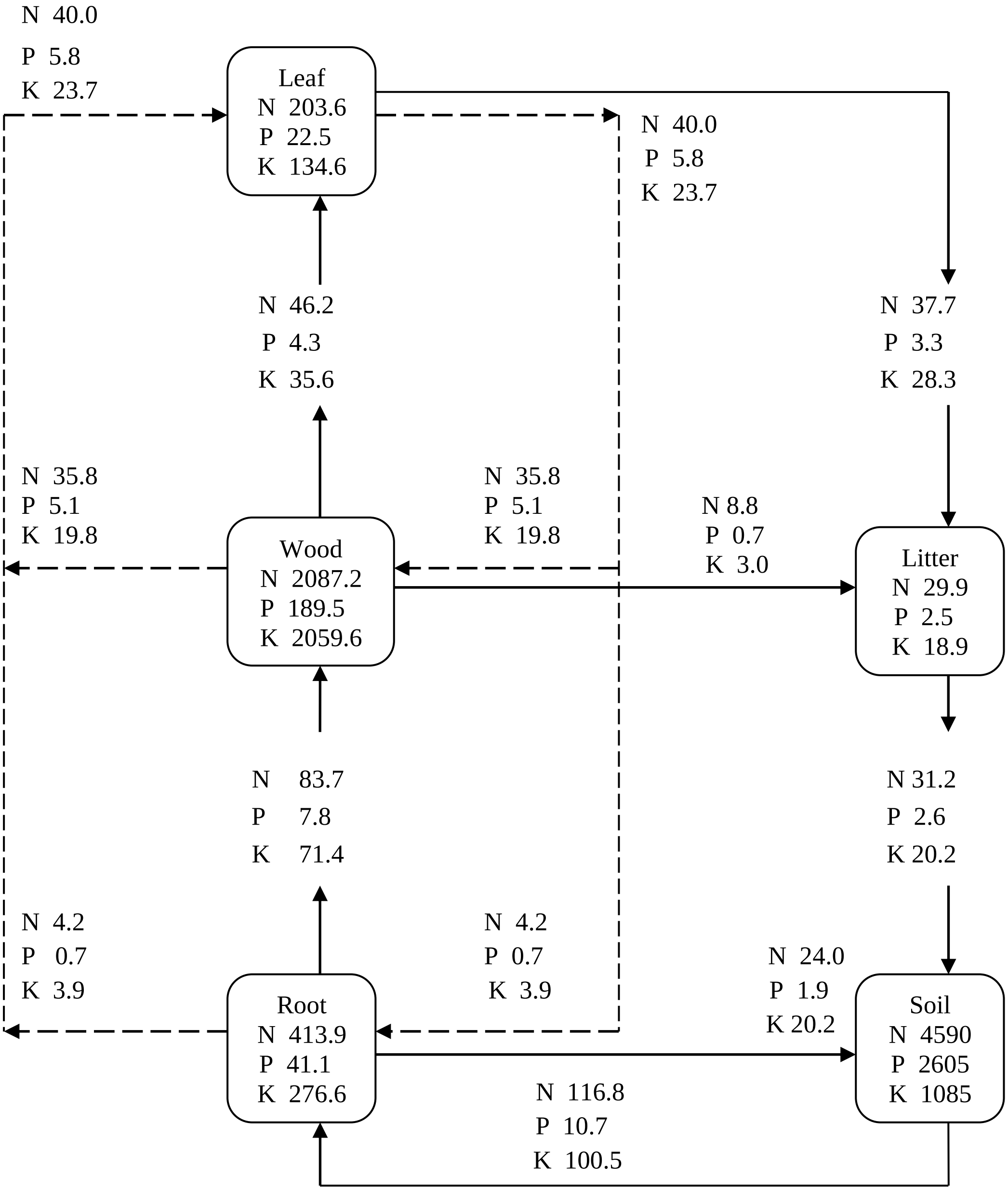

Figure 30. Model showing the distribution and cycling of nutrients, N, P and K in disturbed forest stand of moist tropical forest of Sunsari district eastern Nepal. Values inside compartments represent nutrient stocks (kg ha^{-1}). Internal recycling is represented by the broken lines. Net annual fluxes between compartments are represented as arrows (kg ha^{-1} yr^{-1}). The root compartment includes coarse as well as fine roots. The wood compartment also includes aboveground non-leaf part of herbs (especially of the perennial forbs).

With respect to the nutrient storage in the ecosystem, UF having higher proportion of nutrients in the vegetation (44% N, 17% P and 80% K) resembled tropical moist forests. Edwards and Grubb (1982) suggested higher nutrient capital in the plants (about 90% of the total available pool in the plants) as conventional idea of a tropical rain forest. In contrast, about 90% N, 98% P and 97% K was stored in soil in a Gaunica dry forest of Puerto Rico (Lugo & Murphy, 1986).

The nutrients re-translocated during leaf senescence in undisturbed forest were fairly higher than disturbed forest. Higher re-translocation in mature Sal dominated UF emphasizes the profound significance of internal cycling in the conservation of nutrients to support the production of new foliage in the succeeding growing season, and to diminish the demand from the soil. It is assumed that nutrients re-translocated from leaves in the woody species are stored in the wood, and of herbs in the belowground roots and rhizomes (Tripathi & Singh, 1994).

Of the total nutrient released to the soil, the contribution of fine roots was 30-34% N, 29-33% P, and 36-39% K. This emphasizes the importance of fine roots in nutrient cycling of moist tropical forest. The total nutrient return to the soil through the litterfall was 1.3 to 1.9 times more than that from the fine roots.

The net uptake of different nutrients decreased 1.6 to 1.8 times in disturbed forest as compared to undisturbed forest. Of the net uptake of different nutrients 60–69% in UF and 51–60% in DF, was returned to the soil through litter fall and fine root mortality. The nutrient budget indicated 31-49% of net uptake of different nutrients retained by vegetation over the annual cycle, retention being higher in DF than UF. Relatively higher percentage retention of nutrients in the vegetation of DF could be the nutrient conservation mechanism in nutrient poor soil of DF.

CHAPTER– 8

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

From the present study, which was carried out in undisturbed and disturbed forest stands of a moist tropical forest in Sunsari district of eastern Nepal, following conclusions have been drawn:

- Soil texture, pH and other edaphic factors may favor the regeneration and growth of high quality Sal (*Shorea robusta*) trees in the present forest.
- Disturbance in Sal dominated forest ecosystem cause the loss of nutrients (42% N, 2% P, 29% K) and vegetation mass and convert natural forest into a damaged and degraded systems.
- Disturbance alters the level of soil microbial biomass (about 22% each).
- Higher microbial biomass in UF as compared to DF may be due to the accumulation of higher organic matter in the soil (5.3% in UF and 3.1% in DF) as a result of higher inputs from aboveground litter and belowground fine roots.
- Forest disturbance and seasonality have distinct impacts on soil microbial biomass. Maximum value of microbial biomass in summer season (MB-C: 676.6 µg g^{-1} in UF and 533.3 in DF, MB-N: 59 µg g^{-1} in UF and 45.5 in DF, MB-P: 16.1 in UF and 11.6 µg g^{-1} in DF) may be due to their accumulation in soil when the plant nutrient demand are minimum, and minimum in rainy season (MB-C: 433 µg g^{-1} in UF and 362 in DF, MB-N: 43 µg g^{-1} in UF and 36 in DF, MB-P: 9.0 in UF and 8.0 µg g^{-1} in DF) may be due to high turnover of microbes when nutrient demand of plants are maximum for optimum growth.
- Forest disturbance has reduced the number of tree species by 33% (57 in UF and 38 in DF) and tree density by 50% (466 in UF and 234 individual ha^{-1} in DF).

- The higher basal area of trees in UF (116.6 m^2 ha^{-1}) is resulted by higher density of trees and their girth.
- The distribution of tree species is not uniform (but contagious or clumping pattern) in the forest. It is explained by species clustering patterns (significant cluster: 14 in UF and 13 in DF).
- Strong seasonality exists with respect to vegetative and reproductive phenology in dominant tree species.
- Forest disturbances decrease the stand biomass by 53% (960 Mg ha^{-1} in UF and 449 Mg ha^{-1} in DF) and NPP by 44% (26.6 in UF and 14.9 Mg ha^{-1} yr^{-1} in DF).
- Present forest acts as C-accumulating system (5.5 in UF and 2.5 Mg ha^{-1} yr^{-1} in DF) leading to an important global C sink (net uptake of C is far greater than the C returned to the soil through the turnover of root and litter).
- The most prominent C sink was found to be leaf with 42–43% of the total.
- Fine root dynamics vary with the disturbance of stand, seasons, soil depth and soil nutrients. In comparison to UF, the FRB and production was lower by 45-50% in DF (FRB: 6.6 Mg ha^{-1} in UF and 3.3 in DF; FRP: 5.2 Mg ha^{-1} yr^{-1} in UF and 2.9 in DF).
- The edaphic variables especially SOC, total N, and microbial biomass might have an influence on fine root turnover in moist tropical forests.
- Gross uptake and net uptake of nutrients decrease rapidly in the disturbed forest.
- The maximum loss of nutrients (N, P, K) occurs through stem harvest due to higher biomass.
- Present forest is efficient with respect to nutrient use efficiency. It is evident from higher re-translocation of nutrients (up to 70%) before litterfall.
- Higher re-translocation of nutrients from senescing leaves (up to 75 Kg ha^{-1} yr^{-1}), exhibit nutrient conservation mechanism and tight cycling of nutrients in UF.
- Relatively higher percentage retention of net uptake in the vegetation of DF (40% N, 48% P and 49% K) could be the nutrient conservation mechanism in nutrient poor soil of DF.

8.2 RECOMMENDATIONS

- The present undisturbed forest is rich in terms of biodiversity, biomass and production. Thus, Bhabar belt should be considered as best habitat for Sal production.
- As the disturbance causes the reduction in biodiversity and biomass production, tree cutting should be strictly prohibited as per the rule of Government.
- Present forest represents C accumulating system and therefore, should be managed properly to maintain the same species composition and structure of the forest.
- Present study may be helpful to understand the consequences of forest degradation leading to reduction in carbon sequestration capacity of the forest. It may be useful to set the mitigation measures of global warming as per the objective of $REDD^+$.

CHAPTER– 9

9. SUMMARY

Economically very important, Sal (*Shorea robusta* Gaertn.) dominated forests have been subjected to many disturbances in the eastern Nepal. Present study aimed to quantify the soil physicochemical properties and microbial biomass, species composition and forest structure, stand biomass and net production, and nutrient storage and flux within soil-plant system.

The present study was conducted in the Sal bearing moist tropical forest (locally called Charkoshe jungle), located in the Bhabar belt of Sunsari district eastern, Nepal (latitude 26°24'N to 26°52'N and longitude 86°53'E to 87°21'E), within the altitude range of 220 to 370 m, msl. The forest lies in the catchment area of Koshi River. The climate is tropical monsoon type. The mean monthly minimum temperature range from 10.9°C to 25.3°C and maximum temperature range from 22.6°C to 33.2°C. The average annual rainfall is 1998.6 mm. Relative humidity is higher from June to September with highest value in August (92%).

Soil texture in the study area was loamy type which has been considered suitable for good Sal regeneration and high quality trees. Soil moisture and water holding capacity decreased while bulk density and soil pH increased due to forest disturbance. The lower pH value in the soil of UF than that of DF may be due to the higher nitrification of NH_4^+ and subsequent production of H^+ ions. The soil organic carbon, total nitrogen, total phosphorus and potassium were higher in UF than DF, and their values decreased depth wise. The higher value of organic matter on the surface layer may be due to greater inputs of organic matter through the above ground litter decomposition. The carbon stock in soil was almost half in disturbed forest stand as compared to undisturbed one. It indicated that the forest area was severely affected by anthropogenic disturbances.

Annual mean levels of soil microbial biomass C, N and P decreased with forest disturbance. Several disturbance activities like logging, lopping, litter removal, forest fire, and grazing might have lowered the soil moisture leading to lower value of microbial biomass. Microbial biomass increased from rainy to summer season. The higher microbial biomass in summer may be due to its accumulation when the plant nutrient demands are minimum but the decomposition of belowground plant residues is continuously adding nutrients. Lower values in the rainy season may be due to the fast turnover of microbes and optimum utilization of nutrients by the plants when growth and development remains at the peak. ANOVA revealed that variations in microbial biomass were significant due to seasons ($p < 0.001$) in both stands.

Soil microbial biomass C and N as fractions of soil organic C and total N, respectively increased with forest disturbance and reached to 2.4 and 2.9. It indicates that the microorganisms accumulate and immobilize more soil nutrient like N under nutrient deficient soil. In the present study, the proportion of microbial P to total P was higher in UF. It implies that the microorganisms are more sensitive to C and N as compared to P along the disturbance regime. Both soil organic C and total N showed positively significant correlations ($P < 0.01$) with MB-C and MB-N in both forest stands, while total P exhibited significant positive relationships with MB-C ($P < 0.05$) and MB-P ($P < 0.01$) in UF.

Species content of herbs and shrubs increased while that of trees decreased with forest disturbance. High species number of herbs and shrubs in DF may be due to an open canopy favoring high rate of photosynthesis. Conversely, lower number of herb and shrub species in UF could be attributed to the dense canopy of trees which tend to suppress the undergrowth from obtaining sufficient sunlight required for germination, growth and development in light loving species. The higher tree species richness in UF may be due to higher soil moisture and nutrients. On the other hand, less number of tree species in DF is attributed to frequent and fluctuating disturbances and responses of species to such disturbances. Among total 47 species of herbs, 26 species were present in both undisturbed and disturbed forest stands, while 30 species were enumerated from UF and 43 species from DF. Among 16 shrub species, 12 and 15 species were recorded from UF and DF, respectively. Altogether, 981 individuals of trees were recorded which belonged to 60 species, 51 genera, and 32 families. Out of these, 57 species were present in UF while 38 species in DF. Most tree species showed contagious distribution in both forest stands whereas only 5 species in UF exhibited random distribution.

Shannon-Wiener index of species diversity and species richness of herbs and shrubs increased, while that of trees decreased from 3.08 to 2.80 and 9.11 to 6.78, respectively with disturbance. Equitability or evenness of herbs, shrubs and trees were higher in DF as compared to UF. Simpson's index (index of dominance) for herbs and shrubs decreased (from 0.08 to 0.05 and 0.18 to 0.13, respectively) while that for trees increased (from 0.08 to 0.11) with forest disturbance. Higher Simpson's index of trees in DF happens due to sharing of large portion of resources by few species only or related to the dominance of disturbance tolerance species like Sal in the forest.

Among 60 tree species (≥ 10 cm GBH), 11 were canopy trees (≥ 15 m height), 22 middle storey trees (8–15 m height) and the rest 27 understorey trees (< 8 m height). Most of the tree species showed the contagious (Clumping or aggregation) pattern of distribution in both forest stands. It is common in tropical forests due to low seed availability, restricted mode of seed dispersal or due to the large gap formation resulted by natural or anthropogenic disturbances. A strong seasonality was observed with respect to vegetative and reproductive phenology in dominant tree species of moist tropical forest in eastern Nepal.

Density of herbs and shrubs increased with disturbance. Stand density of trees (individual ha^{-1}) decreased from 466 in UF to 234 in DF. Reduced density in DF was largely attributed to a low proportion of young trees belonging to smaller girth classes due to selective cutting of straight boles of tree for use as poles by local peoples. The density of individual trees varied greatly in both forest stands ranging from 0.7–100 trees ha^{-1}. Basal area of trees (m^2 ha^{-1}) also decreased from 111.6 to 52.3 with forest disturbance. This reflects the removal of large and old trees from DF. The high basal area in UF resulted from very high stocking among the middle-size class (160–210 cm GBH) and also due to the availability of very larger size-classes (up to 610 cm GBH) older trees in fair number.

Based on species IVI, *Shorea robusta* occupied the top rank with 60.4 (20.1% of total IVI) in UF and 60.9 (20.3%) in DF. In terms of family importance value (FIV), Dipterocarpaceae occupied the top rank scoring 53.6 in UF and 53.9 in DF while based on number of species, the largest families were Euphorbiaceae (6 species) in UF and Euphorbiaceae and Mimosaceae (each with 4 species) in DF.

Stand biomass decreased due to forest disturbance. The higher biomass at UF may be related to the presence of more trees of larger girth classes. On the other hand, lower biomass in DF may be due to tree felling and removal for timber and poles. The total biomass estimated for the UF was 960.4 Mg ha^{-1} (equivalent to 452.06 Mg C ha^{-1}), while for DF it was 449.1 Mg ha^{-1} (equivalent to 211.33 Mg C ha^{-1}). Total biomass of the tree layer was 948.0 Mg ha^{-1} in UF, which decreased to 438.4 Mg ha^{-1} in DF, due to disturbance in the forest. The tree biomass in UF and DF was significantly different ($P < 0.001$). The biomass of shrubs increased from 4.4 Mg ha^{-1} at UF to 6.1 Mg ha^{-1} at DF. More shrub biomass in DF may be due to the open space and their efficient resource utilization ability. The higher biomass of herbs in UF as compared to DF may be due to the nutrient rich soil at this stand.

Annual mean FRB (< 5 mm in diameter) in 0–30 cm soil depth was almost double in UF (6.64 Mg ha^{-1}) than the DF (3.35 Mg ha^{-1}). The higher FRB in UF of the present study may be due to the higher soil moisture and resources. The lower FRB in DF could be the result of less canopy cover or a higher fine root turnover rate. In both stands, FRB of < 2 mm size class was almost three times greater than 2-5 mm size class. About 67–69% of annual mean FRB was present in upper soil depth in both forest stands. The amount of litter, nutrients and organic matter on the soil surface might be the cause for the accumulation of fine roots in the upper depth. FRB of both size classes were maximum in rainy season, followed by winter, and minimum in summer season in both forest stands. The maximum FRB during rainy season might be associated with the higher nutrient availability and soil moisture while lower fine roots in winter and summer seasons indicated a rapid turnover of fine roots. The variation in FRB due to stand, depth and season was significant in both forest stands ($P < 0.001$).

The total annual litterfall in UF was 11.8 Mg ha^{-1} yr^{-1} which decreased by 54.2% in DF. Leaves accounted for 69% (UF) to 76% (DF) of total litterfall. The proportion of litterfall was highest during April (27%). Litter production showed distinct seasonality peaking during dry summer season (more than 70% of total litterfall). It may be due to lower water content in soil and plant which triggers the synthesis of abscissic acid in leaf, which in turn stimulates senescence leading to leaf fall. Forest floor litter mass also decreased from 6.7 to 3.6 Mg ha^{-1} due to forest disturbance. The turnover rate of the litter mass in UF was slower while turnover time was faster as compared to DF. It may be associated with the higher microbial biomass and their activities in the soil of UF.

The total net primary production (NPP) of vegetation was 26.56 Mg ha^{-1} yr^{-1} (equivalent to an annual carbon sequestration of 12.26 Mg C ha^{-1} yr^{-1}) in UF and 14.91 Mg ha^{-1} yr^{-1} (i.e. 6.88 Mg C ha^{-1} yr^{-1}) in DF. Although in having higher biomass, the NPP of present forest is relatively low indicating its maturity. Total C input into soil through litter plus root turnover was 6.78 and 3.35 Mg ha^{-1} yr^{-1} in UF and DF, respectively; indicating substantial retention of C in the vegetation over the annual cycle (45% in UF and 51% in DF). This budget shows that the present forest is an accumulating system.

Among the different life forms in UF and DF tree, shrub, and herb comprised 72%, 2%, and 6% of NPP in UF and 67%, 5%, and 9% in DF, respectively; while rest NPP was contributed by stand fine root. The most prominent carbon sink was found to be leaf that accounted for 42–43% of the total NPP.

The allocation of NPP in shrub was higher in DF (0.75 Mg ha^{-1} yr^{-1}) than UF (0.55 Mg ha^{-1} yr^{-1}). The NPP of herbs (aboveground) ranged between 1.3 and 1.7 Mg ha^{-1} yr^{-1} in DF and UF, respectively. Total aboveground net primary production (Mg ha^{-1} yr^{-1}) combining tree, shrub and herb was 19.93 in UF and 10.97 in DF, whereas belowground NPP comprised up to 25–26% of total NPP, in both forest stands.

Allocation to belowground net primary productivity (BNPP) is relatively low as compared to aboveground (ANPP) in both UF and DF. In the studied forest the shoot root ratio is nearly 3 indicating more carbon investment in the growth of above-ground organs than in roots. Fine roots comprised 74–79% of BNPP in both stands. The biomass accumulation ratio and total leaf to fine root ratio decreased with forest disturbance. Net production of trees was significantly higher in UF than DF ($P < 0.001$). Positive correlations were found between stand density, basal area, biomass and NPP in both stands.

Fine root production (FRP) was higher in UF (5.2 Mg ha^{-1} yr^{-1}) than DF (2.9 Mg ha^{-1} yr^{-1}), which was statistically significant ($P < 0.001$). The spatial pattern of FRP may be associated with the differences in species composition and soil properties. Combining both size classes, FRP was higher by 71–73% in upper depth in both forest stands. It revealed that FRP has less production in the lower depth. Turnover rate of fine root was faster for < 2 mm size class in both forest stands. Moreover, the fine root of both size classes showed faster turnover rate in the upper soil depth as compared to lower depth in both forest stands. Carbon stock in the fine roots was almost double in UF than the DF. The upper soil layer had higher percentage allocation (67–69%) of C stock in the fine roots as compared to the lower depth. It might be due to the higher water holding capacity and availability of nutrients.

The ranges of nutrient concentrations in different growth forms were in the order: herb > shrub > tree. Amongst components, the leaves contained maximum concentrations of nutrients in all growth forms which makes this component an important reserve of nutrients, although it represents only a small percentage of the whole tree biomass. The relative concentrations of different nutrients in diminishing order were: N > K > P in herbs, shrubs and trees, indicating that the plants are richer in N than K. In trees concentrations of all nutrients were highest in leaves. The foliar nutrients, especially N and P are used as an index of nutrient status in ecosystems which can give an idea of nutrient limitation, vegetation composition and functioning in ecosystems under future environmental change. N:P ratio in tree and tree leaves were 9.3 and 8.7 respectively. N:P ratio in shrubs was maximum (13.1), while in herbs it was minimum (8.2). Fine roots had higher concentration of nutrients and N:P ratio than coarse roots. Nutrient concentration in fine roots decreased with increase in root diameter.

The sequential arrangement of nutrient stocks in vegetation was: N > K > P in both stands. The quantities (kg ha^{-1}) of nutrients in total vegetation in DF were 2704.4 N, 252.9 P and 2470.8 K; while in UF, the quantities (kg ha^{-1}) of nutrients were 5738.2 N, 537.7 P and 5232.1 K. More than double nutrient stocks in the vegetation of UF than DF are mainly explained by the difference in biomass between the stands. It indicates that the maximum loss of all nutrients occurs through stem harvest. The contribution of different components in all nutrient stocks was in the order: tree > stand fine root > shrub > herb, in both stands. Fine root of smaller size class (0–2 mm diameter) contained quite greater nutrient stocks than that of larger size class (2–5 mm diameter).

The gross uptake of nutrients was higher in UF as compared to DF. In UF the gross uptake of nutrients in vegetation (kg ha^{-1} yr^{-1}) was: 282.4 N, 30.1 P, and 217.7 K, whereas in DF they were 156.8 N, 16.5 P, and 124.2 K. The gross uptake of nutrients were in the order of tree > herb > shrub. In trees, leaves and fine roots had lower biomass but greater gross uptake of nutrients than other components reflecting their importance.

Re-translocation indicates an internal cycling or conservation of nutrients in vegetation. It minimizes the nutrient loss to meet the nutrient demand of new growth. Undisturbed stand having high soil nutrient status showed high re-translocation of nutrients. Re-translocation of N and K was lesser in herbaceous species than shrubs and trees. Re-translocation behaviour in trees occurred in order of P > N > K. Distinctly higher net uptake of nutrients was recorded in UF than DF. The net uptakes of nutrients (kg ha–1 yr–1) in the vegetation were 207.7 N, 19.4 P and 164.2 K in UF and 116.8 N, 10.7 P and 100.5 K in DF. In both forest stands, trees shared 58–70% of total net uptake of different nutrients, whereas share of shrubs and herbs (aboveground parts) ranged between 2–7% and 9–15%, respectively.

The total input of nutrients (kg ha^{-1} yr^{-1}) to the soil through litterfall in UF was more than double (99.7 N, 8.3 P, and 64.4 K) as compared to DF (46.6 N, 3.9 P, and 31.3 K). The contribution of different nutrients in the input to the soil through litterfall was in the order: N > K > P in both forest stands. The nutrient-use efficiencies were greater in trees followed in decreasing order by shrubs and herbs. Turnover time for nutrients in standing vegetation showed variations due to growth forms as well as with the forest disturbance. For the stand vegetation as a whole, the turnover time in both stands was maximum for K (19.9–24.0 years) followed by N (17.2–20.3) and minimum for P (15.3–17.9).

Standing state of nutrients in litter mass followed the order: N > K > P in both stands but it decreased with forest disturbance. Of the total nutrients in litter mass, 63–65% nutrients were present in fresh litter in both forest stands. The turnover time of litter nutrients ranged 1.45–1.49 for N, 1.47–1.51 for P and 1.53–1.55 for K. Turnover time for all nutrients were relatively higher in DF which may be due to immobilization of these nutrients in litter mass by the microorganisms.

Nutrient return to the soil through litterfall exceeded over the return through fine roots. Further, total return of N, P and K through both litterfall and fine roots was more than double in UF as compared to DF. The percentage of total return with respect to net uptake was higher in UF than DF. Conversely, N, P and K retention in vegetation was less in UF in comparison to DF. The higher percentage of nutrient retention in DF represents the nutrient accumulation while lower retention in UF indicates that most of the nutrients are recycled.

Immobilization of N, P and K in litter mass and higher re-translocation of nutrients from senescing leaves for efficient use of nutrients through internal cycling, exhibited nutrient conservation mechanisms and tight cycling of nutrients in the undisturbed stand.

In conclusion, various types of forest disturbances had adverse effect on the soil physicochemical properties, microbial biomass, forest composition and structure, biomass and production, and nutrient dynamics. Forest disturbances also lowered the carbon sequestration capacity of the forest. If a continuous biotic pressure persists for a longer time, it will certainly destroy all the remaining forest into a naked land. To preserve highly productive and economically important Sal dominated present forest for future generations, immediate management actions should be taken by concerned authorities and forest users.

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APPENDICES

Appendix 1. Name of the tree species with their abbreviations.

Abbreviations used	Full forms
Acacia.cat	*Acacia catechu*
Acacia.ferru	*Acacia ferruginea*
Acer	*Acer oblongum*
Adina	*Haldina cordifolia*
Aegle	*Aegle marmelos*
Alangium.sal	*Alangium salviifolium*
Alb.mol	*Albizia julibrissin*
Albi.leb	*Albizia lebbek*
Albi.pro	*Albizia procera*
Alstonia	*Alstonia scholaris*
Anogeis	*Anogeissus latifolius*
Anthocephalus	*Neolamarckia cadamba*
Bassia	*Diploknema butyracea*
Bauhi.mal	*Bauhinia malabarica*
Bombax	*Bombax ceiba*
Bridelia retusa	*Bridelia retusa*
Careya	*Careya arborea*
Cassia.fis	*Cassia fistula*
Cassia.sp.	*Cassia sp.*
Cleistocalyx	*Syzygium nervosum*
Cordia	*Cordia dichotoma*
Cornus	*Cornus oblonga*
Croton	*Baliospermum solanifolium*
Dalbergia.lati	*Dalbergia latifolia*
Desmod.ooj	*Desmodium oojeinensis*
Dillenia	*Dillenia pentagyna*
Diospyros	*Diospyros tomentosa*
Ehretia	*Ehretia laevis*
Elaeagnus	*Elaeagnus latifolia*
F. glo	*Ficus glomerata*
F.lac	*Ficus lacor*
F. rum	*Ficus rumphii*

F.semi	*Ficus semicordata*
Garuga	*Garuga pinnata*
Gmelina	*Gmelina arborea*
Grewia	*Grewia optiva*
Heynea	*Heynea trijuga*
Holorrh	*Holarrhena pubescens*
Holopt	*Holoptelia integrifolia*
Lagerstro	*Lagerstroemia parviflora*
Lannea	*Lannea coromandelica*
Mallotus	*Mallotus pallidus*
Oroxylem	*Oroxylum indicum*
Phyllanth	*Phyllanthus emblica*
Premna	*Premna latifolia*
Sapium	*Falconeria insignis*
Schleichera	*Schleichera oleosa*
Semecarpus	*Semecarpus anacardium*
Shorea	*Shorea robusta*
Spondias	*Spondias pinnata*
Sterculia	*Sterculia villosa*
Stereos	*Stereospermum tetragonum*
Syzyg	*Syzygium cuminii*
Tamarind	*Tamarindus indicus*
Term.ala	*Terminalia tomentosa*
Term.be	*Terminalia bellirica*
Terminalia.che	*Terminalia chebula*
Trema	*Trema orientalis*
Trewia	*Mallotus rependus*
Zizy	*Ziziphus mauritiana*

Appendix 2. List of Publications

I. Mandal, T.N., & **Gautam, T.P.** (2011). Soil microbial biomass: A source of plant nutrients. *Vishleshan*, 10, 235–240.

II. **Gautam, T.P.**, & Mandal, T.N. (2012). Effect of disturbance on fine root biomass in the Tropical moist forest of eastern Nepal. *Nepalese Journal of Biosciences*, 2, 10–16.

III. **Gautam, T.P.**, & Mandal, T.N. (2012). Fine root biomass in relation to soil microbial biomass in tropical moist forest of eastern Nepal. *The Journal of University Grants Commission*, 1(1), 40–49.

IV. **Gautam, T.P.**, & Mandal, T.N. (2013). Soil Characteristics in Moist Tropical Forest of Sunsari District, Nepal. *Nepal Journal of Science and Technology*, 14, 35–40.

V. **Gautam, T.P.**, & Mandal, T.N. (2014). Effect of disturbance and seasonality on soil microbial biomass in moist tropical forest of eastern Nepal. *GEOBIOS*, 41(4), 99–105.

VI. **Gautam T.P.** and Mandal, T.N. (2016). Effect of disturbance on biomass, production and carbon dynamics in moist tropical forest of eastern Nepal. *Forest Ecosystems*. **Springer open access Journal** (DOI 10.1186/s40663-016-0070-y), Vol. 3(11): 2-10.