

Horizontal and vertical variations in soil properties under different pruning regimes in Albizia procera and Hardwickia binata based agroforestry systems under semi-arid conditions

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Abstract

Trees' canopy pruning is one of the most important management practices in agroforestry that allows understory crops to receive adequate sunlight. The effect of pruning on the productivity of intercrops is well known; however, information on its effect on soil properties is scanty. Hence, studies were conducted to determine 1) whether canopy pruning has any effect on soil properties and 2) what level of pruning should be adopted in selected agroforestry systems. Two separate agroforestry models, based on *Albizia procera* (10-year-old) and *Hardwickia binata* (20-year-old), were selected for the study, which included three factors: pruning level (0, 50 and 75%), sampling location (under and outside canopy) and soil depth (0–15 and 16–30 cm), each of which was replicated three times in a completely randomized block design. Canopy pruning yielded varying effects on the studied soil parameters without any definite relationship with pruning levels. Sampling location and soil depth had a significant effect on the studied parameters. Their values were found to be higher and favorable in the upper soil and under the tree canopy. The findings revealed that unpruned trees of *A. procera* caused the maximum improvement in soil, followed by trees subjected to 50 and 75% crown pruning, while in the case of *H. binata*, improvement in soil health in 50% pruning over no pruning was noticeable, but similar improvement in 75% pruning over 50% was not so prominent, implying that heavy pruning (75%) should be avoided to keep evapotranspiration under control. Thus, the study concludes that a moderate level of pruning (50%) is desirable in *A. procera* and *H. binata* based agroforestry under semi-arid conditions for efficient use of above- and below-ground resources and improved soil health.

Introduction

Agroforestry, a landuse practice that combines trees and crops in the same unit of land, emphasizes beneficial ecological interactions among its components. In agroforestry, deeper roots of tree components act as a "safety net", capturing nutrients that leach below the rooting zone of crops and recycling them back into the system (Jose et al. 2004). An important aspect of the benefits provided by trees in agroforestry is the beneficial effect of tree components on soil properties (Adhikary et al. 2017; Hombegowda et al. 2020; Prasad et al. 2016a). The most visible effects of tree planting in agroforestry systems include reduction in soil erosion, primarily through surface litter cover and understory vegetation; accumulation of organic matter through continuous root degeneration and litter decomposition; nitrogen (N) fixation; and enhancement of physical properties such as soil structure, porosity and moisture retention due to extensive root systems and tree canopy cover (Hombegowda et al. 2016; Prasad et al. 2016b). Several researchers have reported improvements in soil health as a result of incorporating trees into croplands (Pinho et al. 2012; Dollinger and Jose 2018). Apart from the benefits associated with agroforestry, it also has some disadvantages. de Carvalho et al. (2010) suggested that agroforestry is not a conventional formula appropriate for indiscriminate uses. In agroforestry, trees and understory crops compete with each other for sunlight, nutrients, moisture and other available resources, which may have a serious impact on the yield of the understory crops (Shukla et al. 2012). Matta-Machado and Jordan (1995) reported a decline in yield and productivity of understory crops in agroforestry systems. The main

reasons assigned to this reduction are above-ground competition for sunlight and/or below-ground competition for nutrients and water (Heinemann et al. 1997).

Sunlight is one of the most important principal limiting factors for the growth of understory vegetation in any agroforestry system (Shukla et al. 2009, 2018). In such systems, the tree's canopy restricts the amount of light reaching the understory crops (Reynolds et al. 2007). To improve crop production and minimize above- as well as below-ground resource competitions between trees and understory crops, one of the most common management practices in agroforestry is the pruning of trees' canopy. The canopy pruning reduces the competition for sunlight occurring between trees and understory crops, influences the root system to grow deeper, acquiring resources that would not be accessible to the crop, and supplies green manure to agroforestry systems (Fownes and Anderson 1991; Cannel et al. 1996; Lehmann et al. 1998; Prasad et al. 2016a, 2019). The canopy pruning not only facilitates the light requirements of understory crops but also reduces the water and nutrient demands of tree components, thereby reducing below-ground competition (Dilla et al. 2020). However, studies conducted by Chen et al. (2016) suggested that pruning the canopy increases the evapo-transpiration rate.

In agroforestry systems, trees lower the soil surface temperature, wind speed, and evapotranspiration rate while also improving biological and ecological processes such as nutrient cycling and soil microbial activity (Snapp et al. 2018). Various multipurpose tree species may have variable effects on the physical, chemical and biological properties of the soil, which may directly be related to the differences in their genetic make-up. At the ICAR-Central Agroforestry Research Institute (CAFRI), Jhansi, Uttar Pradesh, India, the suitability of various multipurpose tree species, namely *Acacia nilotica* (L.) Willd. Ex Delile (Babool), *Acacia senegal* (L.) Willd. (Kumat), *Aegle marmelos* (L.) Correa (Bael), *Albizia procera* (Roxb.) Benth. (White Siris), *Anogeissus pendula* Edgew. (Kardhai), *Dalbergia sissoo* Roxb. (Shisham), *Hardwickia binata* Roxb. (Anjan), *Pongamia pinnata* (L.) Pierre (Karanj) and *Tectona grandis* L.f. (Teak) for planting in agroforestry models are being tested. *A. procera* and *H. binata* have shown good growth and are extensively being planted in different types of agroforestry systems (Roy 1994; Bisaria et al. 1999; Newaj et al. 2012). Both species thrive well in the harsh climatic conditions of the Bundelkhand region of central India (Kumar and Choubey 2008; Newaj et al. 2012; Kamini et al. 2020; Prasad et al. 2023).

A. procera is a fast-growing, semi-deciduous, N-fixing and soil-improving tree species that provides wood for a variety of purposes (timber and fuel) as well as protein-rich, nutritious fodder for animals (Newaj et al. 2012). It grows naturally in India and is highly adaptable to a variety of environmental and soil conditions. *H. binata* has been shown to improve landuse efficiency and meet multiple needs, including those for timber, fodder, and fuel (Shanker et al. 2005; Singh and Rathod 2007). It is an Indian tree that, in addition to tangible benefits, also provides non-tangible benefits such as preserving soil and moisture, restoring degraded lands and sequestering atmospheric carbon (Kamini et al. 2020). Based on their multifarious benefits, both species have been enlisted among the 20 important multipurpose tree species in the Agroforestry Policy 2014 document. Thus, looking for the advantages associated with *A. procera* and *H. binata*, two separate agroforestry models based on these species were established at the research farm of the ICAR-CAFRI, Jhansi, wherein their canopies were used to remove for better permeability of

sunlight, as canopy pruning alleviates shading of crops and provides an effective means of increased capture of light by understory crops. Although a substantial amount of literature has been published emphasizing the importance of canopy pruning on the production of understory crops (Bhargava 2003; Pinkard et al. 2004; Singh et al. 2017), there is little scientific information available on the influence of canopy pruning on soil nutrient dynamics in agroforestry systems. As a result, a study was carried out to determine 1) whether canopy pruning (0 i.e. unpruned, 50 and 75%) exhibits any effect on soil properties and 2) what level of pruning (0, 50 and 75%) should be adopted in selected agroforestry systems. We hypothesized that adding pruned material to the soil through canopy pruning would improve its physical, chemical and biological properties, with moderate levels being more beneficial. We also expected this effect to vary horizontally (under and outside the tree canopy) and vertically (across two soil depths, 0–15 and 15–30 cm).

Materials and methods

The present study, which is a part of an ICAR-sponsored in-house project “development of soil quality index for assessing soil health of different agroforestry systems”, was conducted at the experimental research farm of the ICAR-CAFRI, Jhansi (25° 27' N and 78° 35' E at 271 m above mean sea level), Uttar Pradesh, India. Jhansi is situated in a semi-arid tract of the central plateau of India. The soil at the research farm is intermixed black and red soil (order Alfisol). Annual rainfall in the region ranges from 700 to 1150 mm with a mean value of 958 mm, of which about 80% is received within 10 weeks between July and mid-September during the southwest monsoon. The potential evapotranspiration is quite high (range: 1400–1700 mm) with a moisture index value of -40 to -50. The pattern of the rainfall is highly erratic, and monsoon rain is often accompanied by long, intermittent dry spells. The entire rainfall is received in less than 50 rainy days. Winter showers are rare and uncertain. Due to below-normal monsoon rain, every 5th or 6th year, drought occurs in the entire region. The mean annual temperature of the Jhansi is generally high, with a high degree of variation between minimum (5.8°C in January) and maximum (39.8°C in June) temperatures. Sometimes, the maximum temperature in the summer months (May and June) touches 48°C, which is the peak of the summer season.

Planting pattern and pruning levels

The study consisted of two well-established agroforestry models, viz. *A. procera* and *H. binata* based agroforestry systems. At the time of sampling, the *A. procera* based system was 10-year-old (year of establishment: 2002), while the *H. binata* was 20-year-old (year of establishment: 1992), and they were planted in 8 m × 4 m and 10 m × 5 m spacing, respectively, in a completely randomized block design. In these systems, *Phaseolus mungo* Roxb. (blackgram; rainy season crop) – *Triticum aestivum* L. (wheat; winter season crop) cropping sequences were followed for intercrop cultivation, for which all standard packages of practices were followed. In *A. procera* based agroforestry, intercropping was done in both the summer and winter seasons. On the other hand, in *H. binata* based agroforestry, only the summer crop was used to grow, while during the winter, the field remained fallow. In both systems, three levels of pruning, i.e., 0 (no pruning or unpruned), 50 and 75% of the canopy, were applied. For this purpose,

branches consisting of twigs as well as leaves were removed. The level of shoot pruning was based on the percentage of the total height of the trees. In plot with a 50% pruning level, branches were pruned on 50% of the total bole height (i.e., trees remained with a 50% live crown ratio), and in plot with a 75% pruning level, tree branches were pruned on 75% of the total bole height (i.e., trees remained with a 25% live crown ratio). In a plot with a 0% pruning level (unpruned or control), only sanitation pruning was applied. Every year, pruning was done in the month of October (at least one month before the sowing of winter crops), and the pruned biomass (twigs, foliage etc.) incorporated into the soil as green manure. In the *A. procera* based agroforestry system, on an average, 1.99 and 2.27 t ha⁻¹ of pruned biomass were added in 50 and 75% of the pruning treatments, respectively. Similarly, in the *H. binata* based system, on an average, 1.73 to 2.36 t ha⁻¹ of pruned biomass were added in 50 and 75% of the pruning treatments, respectively. In both models, tillage and other inter-culture operations were performed with the use of a tractor. In these models, all the plots (pruned and unpruned) were given similar tillage operations; however, the pruned plots received vigorous mechanized tractor-driven ploughing as compared to tilling in the unpruned plot, as unpruned trees created some hindrance in the operations. The soils of the selected models were intermixed red and black (Model 1) and black (Model 2). The physico-chemical properties of selected agroforestry models were as follows: Model 1: alfisol (45.6% sand, 22.2% silt and 32.3% clay), pH- 6.99 (1:2.5 H₂O), electrical conductivity (EC)- 0.34 dS m⁻¹, organic carbon (C)- 0.52%, available N- 150.33 kg ha⁻¹, available phosphorus (P)- 11.32 kg ha⁻¹ and available potassium (K)- 113.17 kg ha⁻¹; and Model 2: vertisol (41.1% sand, 24.2% silt and 34.7% clay), pH- 7.00 (1:2.5 H₂O), EC- 0.50 dS m⁻¹, organic C- 0.40%, available N- 150.00 kg ha⁻¹, available P- 12.00 kg ha⁻¹ and available K- 180.00 kg ha⁻¹.

Soil sampling

In both models, three trees in each pruning treatment (0, 50 and 75%) were marked. Before collecting soil samples, plant cover was carefully removed from the soil surface. From the marked trees, the samples were drawn from two locations, under the tree canopy (within radii of 1 m from the tree trunk) and open spaces between the trees, i.e., outside the tree canopy (5-7m away from the tree trunk) using a soil auger, to study horizontal variation in soil properties. At both locations, the soil samples were taken from two soil layers, viz., 0–15 (surface soil) and 15–30 cm (sub-surface soil), to assess the vertical variation in soil properties. Thus, a total of 36 soil samples (3 pruning levels × 2 locations × 2 soil depths × 3 replications) from each model were taken. Such soil samples were collected from three sampling points around each marked tree, which were clubbed to get composite soil samples. All the collected samples were immediately stored in sealed plastic bags, labelled, brought to the laboratory, and stored in the refrigerator. Prior to using the soil for analysis, the samples were air dried and sieved through a 2 mm sieve, which removed fine roots and other plant debris from the soil samples.

Soil analysis

Soil bulk density (BD) was determined from the soil cores (Veihmeyer and Hendrickson 1948), and porosity (POR) was calculated from the BD using the formula: $POR = [1 - (BD/PD)] \times 100$, where PD is the particle density (Baruah and Barthakur 1999). Soil pH and EC were determined at a 1:2.5 soil–water ratio using a glass electrode and a conductivity bridge, respectively. Cation exchange capacity (CEC) was measured by the sodium saturation method (Jackson 1973). Soil organic carbon (SOC) was determined by the dichromate oxidation method of Walkley and Black (1934), available N by the alkaline potassium permanganate distillation method of Subbiah and Asija (1956); available P by extracting samples with 0.5 M NaHCO₃ and determining P colorimetrically using molybdate (Olsen et al. 1954); and available K using 1N NH₄OAc (pH 7) as an extractant (Jackson 1973). Microbial biomass carbon (MBC) was measured by the fumigation extraction method (Jenkinson and Ladd 1981). Soil dehydrogenase activity (DHA) was determined using the method of Klein et al. (1971). Potentially mineralizable nitrogen (PMN) was determined using the method of Chhonkar et al. (2007).

Statistical analysis

A three-way analysis of variance (ANOVA) was performed to test the effect of crown pruning, sampling location and soil depth individually and their interactions on various SOC parameters. The least significant difference ($p < 0.05$) values were used to compare the treatment differences. The means of different treatments were compared using Duncan's multiple range test (DMRT). The entire set of data was statistically analyzed using the Web Agri Stat Package developed by the ICAR Research Complex Goa, India.

Results

A. procera based agroforestry system

Results revealed that all individual factors had a significant effect on soil pH (Table 1). Its pooled means were higher at 50% pruning level (6.47), outside the canopy (6.42) and sub-surface soil (6.60). The combined effect of pruning level $\times$ location and location $\times$ soil depth was also found to be significant. Maximum pH was found outside the canopy of 50% pruned trees; and in sub-surface soil taken from outside the canopy (Table 2). A maximum pooled mean of EC was found in unpruned trees (0.152 dS m⁻¹). The combined effect of pruning level $\times$ soil depth on EC was found to be maximum in surface soil associated with unpruned trees (Table 2). Similarly, the highest pooled means of SOC were found in unpruned trees (0.67%), beneath the canopy (0.69%), and on the surface soil (0.67%), while CEC was highest at 75% pruning (13.95 Cmol kg⁻¹) (Table 2).

Pruning level, location and soil depth individually showed significant effects on N, P and K content (Table 1); their maximum values were recorded in unpruned trees (173.00 kg ha⁻¹ N, 18.87 kg ha⁻¹ P and 133.55 kg ha⁻¹ K), beneath the canopy (179.68 kg ha⁻¹ N, 19.64 kg ha⁻¹ P and 135.44 kg ha⁻¹ K) and surface soil (196.13 kg ha⁻¹ N, 19.15 kg ha⁻¹ P and 128.20 kg ha⁻¹ K). The combined effects of all two-way interactions on N and K contents were recorded at their maximum under the canopy of unpruned; surface

soil of 50% pruning level; and surface soil under the tree canopy. Interaction between pruning level $\times$ location $\times$ soil depth recorded maximum P content in the upper layer of the soil collected from beneath the canopy of unpruned trees (Table 3).

The plot with unpruned trees had the highest MBC (193.85 g g^{-1}), DHA ($44.93 \text{ g TPF g}^{-1} \text{ day}^{-1}$) and PMN ($29.36 \text{ kg ha}^{-1} \text{ week}^{-1}$) among the pruning treatments (Table 3). Their significantly higher values were observed in soil from under the canopy (MBC: $185.64 \text{ } \mu\text{g g}^{-1}$, DHA: $47.66 \text{ } \mu\text{g TPF g}^{-1} \text{ day}^{-1}$ and PMN: $28.21 \text{ kg ha}^{-1} \text{ week}^{-1}$) and in the upper soil layer (MBC: $187.51 \text{ } \mu\text{g g}^{-1}$, DHA: $70.65 \text{ } \mu\text{g TPF g}^{-1} \text{ day}^{-1}$ and PMN: $28.97 \text{ kg ha}^{-1} \text{ week}^{-1}$), respectively, than in outside canopy and sub-surface soil. The two-way interaction between pruning level and sampling location showed a significant ($p < 0.05$) effect on the MBC and DHA (Table 1). Soil MBC was higher in under the canopy soil collected from unpruned trees ($199.08 \text{ } \mu\text{g g}^{-1}$), and the DHA, in under the canopy soil collected from 50% pruned trees ($51.42 \text{ } \mu\text{g TPF g}^{-1} \text{ day}^{-1}$). Sampling location and soil depth significantly ($p < 0.05$) affected DHA and PMN. These were maximum in surface soil collected from the under the canopy (DHA: $77.52 \text{ } \mu\text{g TPF g}^{-1} \text{ day}^{-1}$ and PMN: $33.48 \text{ kg ha}^{-1} \text{ week}^{-1}$), and the minimum values were recorded in sub-surface soil taken from outside the tree canopy (Table 3). The three-way interaction between pruning level, sampling location and soil depth significantly ($p < 0.05$) affected MBC and DHA, while the other two parameters, i.e., SOC and PMN remained unaffected (Table 2). Maximum MBC was recorded in the upper soil layer collected from the under the canopy of unpruned trees ($201.33 \text{ } \mu\text{g g}^{-1}$), and DHA in the upper soil layer collected from under the canopy of 50% pruned trees ($84.24 \text{ } \mu\text{g TPF g}^{-1} \text{ day}^{-1}$) (Table 3).

H. binata based agroforestry system

The unpruned tree plot recorded significantly higher soil BD (1.57 g cm^{-3}) (Table 5). Significantly higher pooled means of soil pH were recorded at the 75% pruning level (7.26), outside the tree canopy (7.23) and sub-surface soil (7.23) (Table 5). The combined effects of pruning level $\times$ location, pruning level $\times$ soil depth, and location $\times$ soil depth were found to be maximum under the canopy of a 75% pruned tree; sub-surface soil collected from the 75% pruned tree; and sub-surface soil collected from outside the canopy. The interactive effect of all three factors was found to be maximum in the deeper layer of the soil taken from outside the canopy of trees pruned up to 50% bole height (Table 5). Similarly, maximum pooled means of EC were recorded in 75% pruned trees (0.124 dS m^{-1}), outside the canopy (0.102 dS m^{-1}) and sub-surface soil (0.102 dS m^{-1}). The combined effect of pruning level $\times$ sampling location on the EC was the maximum outside canopy of 75% pruned trees (Table 5). Significantly higher pooled means of SOC were found at the 75% pruning level (0.57%), under the canopy (0.55%) and on the surface soil (0.56%). The combined effect of pruning level $\times$ soil depth was maximum in surface soil associated with 75% pruned trees (Table 5). Soil CEC was significantly higher in 75% pruned trees ($14.55 \text{ Cmol kg}^{-1}$) and surface soil ($14.71 \text{ Cmol kg}^{-1}$) (Table 5).

The pruning level and soil depth individually showed significant effects on N and P contents (Table 4). Their maximum values were recorded at 75% pruning level ($271.97 \text{ kg ha}^{-1} \text{ N}$ and $14.96 \text{ kg ha}^{-1} \text{ P}$) and

surface soil ($263.27 \text{ kg ha}^{-1} \text{ N}$ and $15.04 \text{ kg ha}^{-1} \text{ P}$) (Table 6). The pooled means of K content were significantly higher at the 75% pruning level ($165.58 \text{ kg ha}^{-1}$), under the tree canopy ($159.80 \text{ kg ha}^{-1}$) and on the surface soil ($157.92 \text{ kg ha}^{-1}$). Two-way interactions also exhibited significant effects on the availability of K (Table 4). It was maximum beneath the canopy of 75% pruned trees; surface soil collected from 75% pruned trees; and surface soil collected from outside the tree canopy (Table 6). The interactive effect of all three factors was found to be maximum in surface soil taken from outside the canopy of trees pruned up to 75% of bole height (Table 6).

A significantly higher pooled mean of soil MBC was recorded at the 75% pruning level ($172.02 \mu\text{g g}^{-1}$). The combined effect of pruning level $\times$ soil depth was found to be maximum in surface soil collected from 75% pruned trees (Table 6). Significantly higher pooled means of DHA were recorded at 75% pruning level ($92.84 \mu\text{g TPF g}^{-1} \text{ day}^{-1}$), under the canopy ($81.36 \mu\text{g TPF g}^{-1} \text{ day}^{-1}$) and surface soil ($94.13 \mu\text{g TPF g}^{-1} \text{ day}^{-1}$). Interactive effects of pruning level $\times$ soil depth and location $\times$ soil depth recorded maximum DHA in surface soil collected from 75% pruning level; and surface soil under the canopy (Table 6). PMN was significantly affected by pruning level and location (Table 4), with higher pooled means recorded at 75% pruning level ($146.26 \text{ kg ha}^{-1} \text{ wk}^{-1}$) and under the canopy ($126.38 \text{ kg ha}^{-1} \text{ wk}^{-1}$), respectively. The combined effect of pruning level $\times$ location and location $\times$ soil depth recorded maximum PMN under the canopy of 75% pruned trees; and sub-surface soil under the tree canopy (Table 6).

Discussion

A close perusal of the data suggests that there is no relationship between various levels of canopy pruning and the studied soil parameters. The pruning reduced BD in *H. binata* based agroforestry, which could be due to the ploughing of the plot, having pruned trees via tractor-drawn disc ploughing that loosens the soil and ultimately reduces the soil BD. Higher soil BD associated with unpruned trees may be due to the hindrance provided by a larger canopy of unpruned trees, which restricts soil tillage, increasing compactness, and, thus, soil BD. Pruning variably affects soil pH, EC, SOC and CEC in both agroforestry models. It decreased EC and SOC in *A. procera*, and EC in *H. binata*; and increased pH and CEC in *A. procera*, and pH, SOC and CEC in *H. binata* based agroforestry systems. The values of soil pH at different pruning levels did not show any definite pattern. Dai et al. (1998) suggest that changes in soil pH depend on soil properties, vegetation cover, weather conditions, and the deposition of acidifying materials. It can be changed in either direction (increase or decrease), which depends upon the initial value of the soil pH (Hong et al. 2018). Further, results suggest that pruning (either 50 or 75%) increased soil pH in the present study, which could be due to the addition of pruned material in the soil (Toth et al. 2011). Soil EC decreased with the increase in pruning level in *A. procera*. However, in *H. binata*, it did not show any definite trend. Further, results showed an increase in CEC with the increase in pruning level, and this might be due to an increase in soil pH. The SOC in *H. binata* increased with the increase in pruning level, and in *A. procera*, it decreased. Higher SOC in pruned plots associated with *H. binata* is attributed to the addition of green biomass to the soil, which, on decomposition, builds up soil organic carbon (Yuan and Yue 2012). On the other hand, the opposite result obtained with *A. procera* could be explained on the basis of

the continuous dropping of leaves from unpruned trees and the decay of fine roots, which causes SOC accumulation (Prasad et al. 2005, 2023). Prasad et al. (2023) explained the cause of lower SOC in pruned plots. According to them, relatively more exposure of the soil in the pruned plots to sunlight increases the mineralization process and thus reduces SOC content. The CEC level increased with the increase in pruning level. These contrasting findings could be attributed to the overriding effects of the inherited characteristics of the experimental soil of the studied models, as well as the type of landuse that existed prior to the implementation of agroforestry practices. Landuse conversion from one system to another is critical for soil fertility accumulation and nutrient dynamics (De Stefano and Jacobson 2017).

Pruning of the tree canopy negatively affected the availability of major soil nutrients (N, P and K) in *A. procera* and positively in *H. binata*. This variability in the studied models can be explained on the basis of the variation in the genetic make-up of the studied plant species and the inherent soil characteristics (Ulery et al. 1995; Finzi et al. 1998; Prasad et al. 2023). The variation in availability of major soil nutrients in studied agroforestry models could also be due to variation in pruned tree litter and its decomposition pattern, as pruned material produced by different plant species might be mineralized differently (John et al. 2007). The nutrients taken up by the different understory crops (summer and winter crops in *A. procera*, and only the summer crop in *H. binata*) can also explain the variations in the availability of major soil nutrients in the studied agroforestry models.

Further, results showed enhanced biological properties (DHA, MBC and PMN) in the soil with the increase in pruning level in *H. binata* based agroforestry. This could be explained on the basis of the increase in the quantity of litter added to the soil with an increase in pruning levels. Various researchers have suggested that the quantity and quality of leaf litter are able to cause variations in soil MBC, DHA and PMN (Belsky et al. 1989; Arunachalam et al. 1996). Canopy pruning exerts its effect on the growth of the tree's root system, which grows deeper and affects the root system (Lehman et al. 1998), and the root system developed after canopy pruning may significantly affect the soil biological processes (Xu et al. 2013). However, in the case of the *A. procera* based agroforestry model, a reverse trend was found. MBC dropped from 1.2 to 14.2%, DHA from 5.0 to 5.7%, and PMN from 14.9 to 26.1% in crown-pruned plots. These reductions could be due to the relatively higher mineralization in pruned plots as compared to unpruned plot. According to Rasse et al. (2005), higher SOC content can explain higher MBC in the unpruned plot of *A. procera*. According to Berthrong et al. (2009), tree litter accumulated under a tree canopy preserves soil moisture and improves the microenvironmental conditions that support increased soil microbial activity. The decrease in soil DHA in pruned plots (50 and 75%), as reported in the present study, may be attributed to cultural operations (tillage and intercultural operations), as disturbance in the soil causes variation in microbial activities. Apparently, insufficient tillage in the control plot due to hindrances in mechanical operations might have overridden the effects of tree canopy pruning on soil DHA. Guicharnaud et al. (2010) reported a 13.6–22.7% reduction in soil DHA in tillage plots when compared with the soil DHA reported in no tillage plots. Low DHA in a pruned plot could also be due to low soil moisture content (Wiatrowska et al. 2021). On the other hand, higher soil DHA in the unpruned plot could also be due to higher SOC, as the latter has a positive correlation with the former (Brkljaca et al. 2019). The study also reported the maximum PMN in the unpruned plot. The PMN has a direct

relationship with SOC because covalent bonds between organic C and N inseparably link C and N mineralization (Ros et al. 2011). Poffenbarger et al. (2017) suggest that an increase in the amount of crop residue builds up SOC, thereby increasing PMN.

Further, the study reported higher SOC, N, P, K, MBC, DHA and PMN under the canopy of *A. procera*. Similarly, values of SOC, K, DHA and PMN were higher under the *H. binata* canopy. The higher SOC under the tree canopy, as reported in the present study, is attributed to the higher amount of tree litter (leaves, twigs etc.) and decayed roots beneath the canopy. The presence of soluble and insoluble forms of organic carbon, such as sugars, organic acids, mucilage, sloughed cell walls, and root hairs, is also responsible for an increase in SOC under the tree canopy (Hütsch et al. 2002). Our results, in terms of SOC, corroborate the findings of Gallardo (2003), who reported a 47.9% higher SOC under the canopy of *Quercus ilex* when compared with the SOC recorded beyond the canopy. Further, the study reported a 0 (*H. binata*) to 12% (*A. procera*) increase in N content; 5 (*H. binata*) to 20% (*A. procera*) in P content; and 15 (*H. binata*) to 21% (*A. procera*) in K content under the canopy over the values recorded from outside the canopy of respective tree species. Higher concentrations of N, P and K beneath the canopy in the studied models could be due to a greater level of mineralization and microbial activity under the canopy. Improvements in the micro-environment under the canopy might have yielded these resource islands (Belsky et al. 1989; Reich et al. 2005). The present study reported a 0.1 (*H. binata*) to 1.9% (*A. procera*) increase in MBC; 10.4 (*H. binata*) to 22.2% (*A. procera*) in DHA; and 25.5 (*A. procera*) to 29.8% (*H. binata*) in PMN under the canopy over the values recorded from outside the canopy of respective tree species. The relatively higher value of MBC under the tree canopy is directly linked with the higher value of SOC content under the canopy, as SOC acts as a substrate for microbes (Pausch and Kuzyakov 2018). Fang et al. (2016) suggested that consistent C inputs through litterfall, the production of fine roots and their exudations, and mycorrhizal associations are the main driving factors that affect microbial biomass in soils. Higher soil DHA levels under the canopy could be due to the relatively higher moisture content beneath the canopy. Our findings supported those of Prasad and Mertia (2005), who found higher DHA under the canopies of six common agroforestry tree species in the arid region of Rajasthan, India. Higher DHA levels under the tree canopy could also be due to the higher SOC content reported under the canopy in the present study. Our findings are consistent with those of Garcia-Orenes et al. (2010), who found that plots with higher SOC content had higher DHA. Accumulation of litter on the soil surface enhances soil microbial biomass as well as the activity of associated enzymes, which could explain the higher enzymatic activities in terms of DHA and PMN in the present study (Hu et al. 2006). Higher PMN concentrations under the canopy are attributable to high foliar N content and rapid N circulation through litterfall. The PMN originates mainly from microbial biomass and plant tissues, and these are the main sources of the organic N pool. The higher value of PMN under the tree canopy can also be explained on the basis of the higher microbial activity beneath the tree canopy. Microorganisms living near the tree base can get nutrients by producing extracellular enzymes as a result of SOM decomposition (Bowles et al. 2014).

Further, results showed that soil depth had a significant effect on the studied parameters. The values of almost all studied parameters were higher in the surface soil, except pH in *A. procera*, and pH and EC in *H.*

binata. The higher SOC in the upper soil could be due to a relatively better return of biomass for decomposition at the surface of the soil. As in the present study, pruned material from tree components was left in the field and allowed to decompose, which may have improved soil organic content. Comparatively higher SOC in the surface layer of the soil could also be due to more biological activity occurring in the top soil, which was found to decrease with increasing soil depth (Jobbagy and Jackson 2000). The study also reported higher CEC in the upper layer of the soil, which could be due to higher SOC in the top soil layer. McAlister et al. (1998) and Adugna and Abegaz (2015) reported more or less similar results. They found a strong association between SOC and CEC. Higher soil pH, as recorded in both studied agroforestry models, in the sub-surface layer could be due to an increase in basic cation along the soil depth, which increases soil pH from the top to the bottom of the soil profile (Fetene and Amara 2018). The higher EC value recorded from sub-surface soil is attributed to the leaching and soil erosion caused by continuous farming (Abate and Kibret 2016). The higher amounts of N and P in surface soil are attributed to the application of fertilizers to understory crops. As mentioned earlier, intercropping is being practiced in both agroforestry models, wherein inorganic fertilizers (di-ammonium phosphate and urea) are applied. This can explain the higher N and P in the top soil layer. Higher K content in surface soil is attributed to the liberation of K from the decomposition of litterfall as well as the solubilization of insoluble forms of K present in soil due to organic decomposition (Singh and Singh 2017). On the other hand, the low availability of N, P and K in sub-surface soil could be due to comparatively less organic content in the deeper soil layer. The availability of N, P and K across soil depths can also be explained by a phenomenon suggested by Jobbagy and Jackson (2001). According to them, the nutrient cycling mediated by plants exerts an influence on the vertical distribution of nutrients, especially in the case of more limited nutrients. The greater concentration of these nutrients in top soil is attributed to the fact that they are more important for plants; hence, they are subject to greater uptake and cycling, being absorbed from deeper layers and returned to the soil surface through litter fall. This process of uptake functions in opposition to leaching, which moves nutrients downward and acts more strongly on those nutrients that are in lower demand by plants. Results further reported that soil MBC, DHA and PMN were comparatively higher in the upper soil, which could be due to the accumulation of more SOC in the surface soil that acts as a substrate for microbes and provides conducive micro-environmental conditions. In a recent study, Liddle et al. (2020) highlighted that SOC promotes MBC through the release of water-soluble organic C and reported an increase in MBC from 700 to 2240 mg kg⁻¹ when SOC increased from 25 to 90 g kg⁻¹. Further, in the present study, soil DHA was found to be decreasing with the increase in soil depth. Our results corroborate the findings of Velmourougane et al. (2013), who reported a reduction in DHA with an increase in soil depth in different agro-ecological sub-regions of India. According to Zaman et al. (2002), the DHA in soil depends on the content of soluble organic C, and an increase in SOM in top soil is responsible for enhanced soil enzyme activities. Input through litterfall increases the overall soil oxidative activity because the organic molecules (small and simple) start leaching downward from the litter layer to the surface soil, providing a labile organic substrate for soil microbes and better enzyme activities (Velmourougane et al. 2013). The present study also reported variation in the vertical distribution of PMN; it was found to be higher in the surface soil layer (0–15 cm), which decreased with the increase in soil depth. This could also be explained on the basis of the higher SOC content in the surface soil layer. The

amount of SOC has a strong relationship with total soil N (Cheng et al. 2016). The highest fractions of SOC and total N present inside macroaggregates are the products of microbial activity that contribute to the binding of microaggregates into macroaggregates. Cheng et al. (2016) suggest that soil C decomposition potential and PMN have a strong relationship with the SOC and total N content.

Conclusion

In the present study, sampling location (under and outside the tree canopy) and soil depth (surface and sub-surface) had direct effects on the studied physical, chemical and biological properties of soils. Values recorded under the canopy and surface soil outweighed the values found outside the canopy and sub-surface soil, respectively. Pruning treatments (50 and 75%) employed in the study did not reveal any discernible trend in the studied parameters. In *A. procera* based agroforestry, improvement in soil health was recorded at its maximum in unpruned plots, followed by 50 and 75% pruned plots, while in *H. binata* based agroforestry, improvement in soil health in 50% pruning over no pruning was noticeable, but similar improvement in 75% pruning over 50% was not so prominent. This implies that a moderate level (50%) of canopy pruning is desirable under semi-arid climatic conditions, which not only improve soil health but also provide sufficient sunlight to the understory crops. The study also seems to suggest that heavy pruning (75%) of the trees should be avoided to minimize the evapotranspiration rate under semi-arid conditions.

Declarations

Authors' contribution

RP designed the experiment; VDT and NKS analyzed the soil samples; AG and AS analyzed the data; RP, AA, AS, RN and RS drafted the manuscript, and later it was revised by RP, AA, AS and SD. All the authors read the final draft and approved the manuscript.

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Tables

Tables 1 to 6 are available in the Supplementary Files section

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