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Macronutrient Status of Soils under Different Plantation Cycles of Poplar (*Populus deltoides* Bartr.) Based Agroforestry System in Punjab

Ravinder Kaur, Baljit Singh[1*] and Salwinder Singh Dhaliwal

Department of Soil Science, [1]Department of Forestry and Natural Resources
Punjab Agricultural University, Ludhiana-141 004, India
**E-mail: singh-baljit@pau.edu*

***Abstract*:** The study was conducted to determine depthwise (0-15, 15-30, 30-60 and 60-90 cm) available primary (N, P and K) and secondary (Ca, Mg and S) macronutrients in five land use systems viz., sites having continuous poplar (*Populus deltoides*)-based agroforestry system (AFS) for 10, 20 and 30 years (Y), fodder (pearlmillet/sorghum)-fodder (oats/berseem) rotation (F-F) and fallow land. Available N, P and K in different soil layers were generally lowest in fallow land (62.7, 16.78 and 120.5 kg/ha, respectively in surface depth) and increased significantly with adoption of AFS and were highest in 30 Y plantation site of AFS (183.1, 43.53 and 195.2 kg ha^{-1}, respectively in surface depth). These were highest in surface and declined with increase in depth. In 0-15 cm soil depth, an increase of 13, 84.3 and 29.6% in exchangeable Ca, exchangeable Mg and available sulphur was observed in mature (30 Y) plantation sites over young (10 Y) plantation sites of AFS. The macronutrient index value was low for N, medium to high for P and low to high for K in different treatments. Therefore, the long-term adoption of poplar based agroforestry helps in improving the soil health, productivity and sustainable agriculture.

***Keywords*:** Agroforestry system, Fodder-fodder rotation, Macronutrient index value, Primary macronutrients, Secondary macronutrients

Paddy-wheat rotation is the main cropping system in Punjab and other parts of north western India. The continuous paddy straw burning results in annual nutrient losses at an estimated amount of 3.85 million tons of organic carbon (OC), 59 thousand tons of nitrogen (N), 20 thousand tons of phosphorus (P) and 34 thousand tons of potassium (K) and it has a detrimental impact on nutrient budget of soil (Kumar et al 2015). When crop residue is burnt, the existing minerals present in the soil are ruined, which subsequently hamper the next crop's cultivation. Moreover, straw carbon, nitrogen and sulphur are fully burnt in the cycle of burning and ultimately lost in the environment. According to Singh et al (2008), around 17 million tons of paddy straw is produced every year in Punjab, of which 90% is burnt in open fields. A solution to address such nutrient declines is the adoption of agroforestry systems, because the trees have a profound impact on soil nutrient pools as deep and extensive tree root systems enable them to accumulate significant quantities of nutrients below the crop root zone and move them to the surface soil through litterfall and root turnover (Allen et al 2004, Singh et al 2016). However, the return of nutrients through litterfall differs widely depending on parameters such as tree species, spacing, age of plantation, intercrops and management strategies (Singh 2009, Sirohi and Bangarwa 2017, Kaur et al 2020).

Among numerous tree species, thinly crowned poplar (*Populus deltoides* Bartr.) has emerged as a prominent tree of short rotation for agroforestry in north-western India due to its economic viability and more sustainability. In addition, its rapid growth, pruning-tolerant nature, low level of competition with associated crops and generation of supplementary income from its wood has resulted into its considerable acceptance among farmers (Kumar et al 2019). Besides these, many studies have reported higher content of available and total nutrients in poplar based agroforestry systems in comparison to sole cereal crops rotation such as rice-wheat, maize-wheat, cotton-wheat and soyabean-wheat (Sharma et al 2015, Prakash et al 2018, Di bene et al 2011). Poplar plantation accretes approximately 20.1 Mg ha^{-1} litterfall over 6 year period which upon mineralization adds macronutrients such as N (176 kg ha^{-1}), P (21.7 kg ha^{-1}), K (133 kg ha^{-1}), Ca (368 kg ha^{-1}) and S (55.4 kg ha^{-1}), respectively which improves soil health (Singh 2009). This signifies that poplar incorporation in existing cereals rotation should be encouraged in order to maintain soil nutrient status for ecological sustainability and this will ultimately reduce the use of chemical fertilizers in agricultural systems. In many studies, positive impact of chronosequence of agroforestry systems on soil fertility has been reported; for instance by Nath et al (2015) in bamboo-based agroforestry systems and Sharma et al (2009) in alder-cardamom agroforestry system.

However, the studies on effect of different rotations or planting cycles of poplar based agroforestry on soil nutrient build up are lacking. Therefore, the present study was conducted in order to appraise the impact of different plantation cycles of poplar based agroforestry system (AFS) and other land uses (fodder-fodder rotation and fallow land) on content of major nutrients in the soil profile.

MATERIAL AND METHODS

Selection of study sites: Soil samples were taken from Khehra Bet and other surrounding villages in Ludhiana district (latitude 30°91'N and longitude 75°85'E) of Punjab, India. The area receives an annual rainfall of 700-800 mm per annum, more than 75 percent of which is recorded over the three monsoon months (July-September). Maximum and minimum mean monthly temperatures vary from 17.4°C (January) - 39°C (May) and 6.0°C (January) -26.8°C (July), respectively.

Sites were chosen where poplar-based agroforestry system (AFS) had been adopted for the past 10, 20 and 30 years in addition to fodder - fodder cropping system (pearlmillet/sorghum-oats/berseem) and control (no poplar/crop). Five replications of each system were selected. The selected sites were similar in soil texture of the surface layer (0-15 cm). First, 2nd and 3rd plantation cycles represented about 10, 20 and 30 years of continuous poplar stands, respectively. Along with these poplar plantations, five sites having fodder-fodder cropping system and five control sites (without crops or trees), were also selected for comparison of soil characteristics. Pearlmillet or sorghum in the *kharif* (summer) season was grown by farmers as intercrops in the inter-row area for the first 3 years of plantation age, while wheat in the *rabi* (winter) season was grown throughout poplar rotation due to deciduous nature of trees in winters. No crop was grown in *kharif* season after 3 years of tree age. The fertilizers were applied to the intercrops as per the recommended practices. For pearlmillet, sorghum and wheat; 100 and 60, 12.5 and 40, and 125 and 62.5 kg of N and P_2O_5 per hectare respectively, were applied.

Description of soil sampling: Five replications were chosen for each plantation cycle of poplar and other agro-ecosystems (treatments). Six spots from these chosen sites were randomly selected for soil sampling under each treatment. Soil samples were taken from each treatment and replication, using an auger from 0-15, 15-30, 30-60 and 60-90 cm soil depths. A composite soil sample was obtained by accurately mixing the soil from these six random spots. Soil samples were air dried, ground and passed through a 2 mm sieve to assess different soil characteristics. Acronyms for the treatments are: Sites having poplar plantation for 10 years (10 Y), 20 years (20 Y), 30 years (30 Y), fodder-fodder cropping system (F-F) and fallow (no poplar or crop) (FL).

Laboratory analysis: Particle size distribution (mechanical analysis) was assessed by using the International pipette method (Jackson 1973). Furthermore, by using obtained percentages of sand, silt and clay, the texture was determined using TAL 4.2 software programme (Table 1). Water holding capacity was examined by using the standard procedures (Jackson 1973).

Available Nitrogen (N) was assayed by the Alkaline-Permanganate method described by Subbiah and Asija (1956). Available phosphorus (P) was scrutinized calorimetrically in 0.5 M $NaHCO_3$ extract on Elico spectrophotometer as outlined by Olsen et al (1954) and available potassium (K) was determined by flame photometer after extraction with neutral normal ammonium acetate (1 M CH_3COONH_4)as described in Jackson (1973). Exchangeable calcium (Ca) and magnesium (Mg) in the soil were evaluated by versenate titration method as suggested by Cheng and Bray (1951). Available sulphur (S) was estimated colorimetrically by turbidimetric method with 0.15% calcium chloride ($CaCl_2.2H_2O$) extractant (Jackson 1973).

Macro-nutrients index value (MNIV) was calculated to compare the levels of soil fertility of one treatment with those of another by obtaining a single value for each macronutrient. Therefore, nutrients index values of primary macronutrients were calculated by using methodology of Parker et al (1957).

From the proportion of soils under low, medium and high available nutrient categories, MNIV is represented by the following expression:

$$\text{Macro-nutrient index value (MNIV)} = \frac{(NL*1) + (NM*2) + (NH*3)}{NT}$$

Table 1. Depth-wise proportion of primary particles (%) and soil texture in different land use systems

	Soil depths (cm)			
	0-15	15-30	30-60	60-90
Sand	68.09-78.77	66.57-77.37	68.03-83.83	66.90-79.27
Silt	8.47-13.31	12.07-15.87	6.73-18.50	7.50-17.51
Clay	12.07-18.6	9.73-21.37	9.43-14.43	9.43-15.60
Soil texture	Sandy loam	Loamy sand-Sandy clay loam	Loamy sand-Sandy loam	Loamy and-Sandy loam

Where, NT stands for total number of samples analyzed in a given area.

NL, NM and NH represent the proportion of total soil samples falling in the low, medium and high nutrient categories and are assigned weightage of 1, 2 and 3, respectively.

Correspondingly, areas with macro-nutrient index value below 1.5 could be considered low category, those with MNIV in between 1.5 to 2.5 could be considered medium category, and those with values above 2.5 could be grouped as high category in native supply of that nutrient.

Statistical analysis: The data thus obtained were contrasted for significance of the differences by Least Significant Difference (LSD) with Tukey's Honestly Significant Difference (HSD) post hoc test at 5 percent level of significance by Analysis of Variance (ANOVA) using completely randomized design in SAS software version 9.4.

RESULTS AND DISCUSSION

Physical properties: The soil texture in 0-15 cm soil layer was sandy loam in all land use systems, with sand ranging from 68.09-78.77%, silt from 8.47-13.31% and clay from 12.07-18.6% (Table 1). The lowest water holding capacity (WHC) in 0-15 cm soil depth was observed in fallow land (31.79%), which was significantly lesser than all the treatments (Fig. 1). Meanwhile, it increased considerably with increase in number of years under poplar from 39.7% in young plantation site (10 Y) to 44.2% in mature AFS (30 Y) in the surface soil layer. Similar trend was reported in subsurface layers where it increased from 10 year old to 30 year old AFS.

The higher WHC of AFS than F-F and FL may be attributed to addition of litter biomass and extensive root systems which might have altered the distribution of micro and macropores and thus helped the soil to retain more water (Ramya et al 2021). Ramesh et al (2008) stated that water retention capacity of soil was directly proportional to organic matter and clay content. Temporal positive effect can also be seen in AFS as WHC increased linearly in all depths in mature AFS (30Y) than young AFS (10 Y) and it can be ascribed to higher accumulation of organic matter through litter and root mass in older plantation cycles in contrast to younger AFS. It has been made clearer by the findings of Nath et al (2015) who reported a strong positive empirical relation (r^2 = 0.95) between WHC and age of bamboo based AFS plantation cycles.

Available primary macronutrients: The content of available N, P and K in all the treatments were found to be diminishing with the depth as the plough layer (0-15 cm) had higher content in comparison to subsurface layers (Table 2). The order of macronutrients in the soil profile (0-90 cm) of every treatment followed an order K>N>P and all were higher in the mature plantation cycles of agroforestry system in comparison to other land uses (Fig. 2). Box plot representation of available K (Fig. 3) signifies that adoption of vegetation on fallow land and chronosequence of AFS resulted in noticeable increase in the range as well as mean value. For instance, 75% of the soils under 10 Y agroforestry had available K ranging between 148 to 160 kg ha^{-1} as

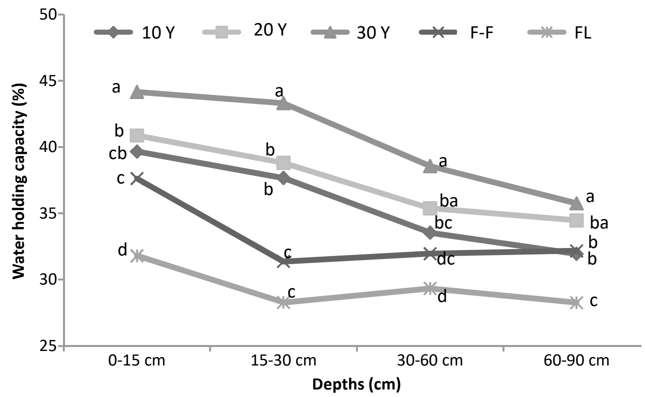

Fig. 1. Depthwise distribution of water holding capacity under different poplar plantation cycles and other land uses. Values in the same row within same soil layer followed by same small letters are not significantly different at P<0.05 [LSD: 3.12 (0-15 cm); 3.41 (15-30 cm); 3.30 (30-60 cm); 3.36 (60-90 cm)]

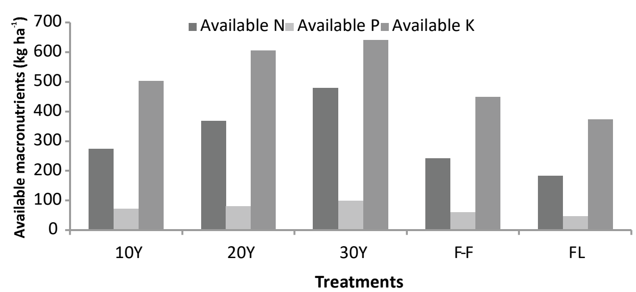

Fig. 2. Distribution of available nutrients in 0-60 cm soil profile under different poplar plantation cycles and other land uses

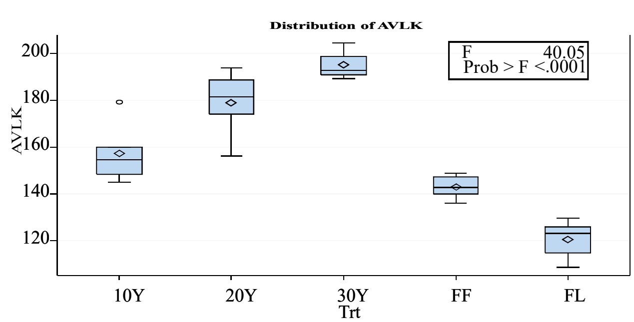

Fig. 3. Box plot representation of available K in surface soil with chronosequence of poplar based agroforestry system and other land use systems

opposed to 191 to 199 kg ha^{-1} under 30 Y in 0-15 cm depth of soil. Available K in the soil profile (0-90 cm) was highest in mature plantation cycles (641 and 605 kg ha^{-1}) in 30 and 20 year old agroforestry followed by younger plantation cycle (504 kg ha^{-1}) than F-F sequence (449 kg ha^{-1}) and least 372 kg ha^{-1} in fallow land (Fig. 2). In comparison to plough layer, the available K declined drastically in FL by 54.8% compared to 42.3% and 33.8% decline in F-F and mature plantation cycle of AFS (Table 2).

In comparison to FL, adoption of AFS or F-F led to significant increase in primary macronutrients (P and K) but significant increase in available N in surface soil layer was only reported under AFS. In plough layer (0-15 cm), both major primary macronutrients (available N and P) increased considerably with advancement of AFS i.e. up to 37.8% and 17%, respectively in 20 Y plantation cycle over 10 Y and further inclined to 43.2% and 33.9%, respectively in 30 Y plantation cycle. Available N, P and K contents were conspicuously higher in the upper layer (0-15 cm) in comparison to lower layers. However, sub-surface layers also followed the same order i.e. agroforestry > fodder-fodder > fallow land in all the depths. Higher content of nutrients in AFS and F-F system is due to the regular addition of organic matter through leaf litter and rhizodeposition in the agroforestry system and a finer but dense network of root mass of fodder crops that has remained in the soil year after year, both of which increase the overall turnout of N through biological processes (Konthoujam et al 2021). In addition, released organic decomposition products such as organic anions regulate the adsorption-desorption reactions of P and K by forming complexes or chelates with Fe, Al, Mg and Ca, which would otherwise restrict the availability of P and K. Singh (2009) reported that a total of 20.1 Mg ha^{-1} litterfall was added during 6 year rotation of poplar plantation which added approximately 176, 21.7 and 133 kg ha^{-1} of N, P and K, respectively through litterfall. Numerous studies assessed the variability of primary macronutrients under agroforestry following different agronomic management practices such as different tree species (Singh et al 2010), soil texture (Mao et al 2012), different tree spacing (Sirohi and Bangarwa 2017) and tree canopy positions (Pandey et al 2000). Apart from these, plantation cycles of agroforestry also had a considerable effect on nutrient pools throughout the soil profile as the present study recorded relatively 97.2% N, 56.7% P and 23.9% K higher in mature plantation cycle (30 year) over 10 year old agroforestry system in 0-15 cm soil depth. Lower available macronutrients in uncultivated soil are presumably attributed to lack of vegetative cover, more soil degradation and higher losses by leaching (Moges et al 2013).

Secondary macronutrients: The positive impact of the age continuum of poplar-based agroforestry can also be witnessed in case of secondary macronutrients (calcium, magnesium and sulphur), which increased dramatically from the early successional stage (10 Y) to the mid-successional stage (20 Y) and added substantial quantities of soil nutrients after 30 years of agroforestry establishment. In 0-15 and 15-30 cm soil depth, an increase of 13% and 6.79% exchangeable Ca (Exch-Ca), respectively and 84.3% and 61.3% exchangeable Mg (Exch-Mg), respectively was observed in mature (30 Y) plantation sites over young (10 Y) plantation sites of agroforestry system (Table 3). Among land uses, Exch-Ca and Exch-Mg followed the order: agroforestry system [8.08-9.13 Ca; 2.93-5.40 Mg cmol (+) kg^{-1}] followed by fodder-fodder [7.89 Ca; 2.60 Mg cmol (+) kg^{-1}] and fallow land [5.90 Ca; 1.76 Mg cmol (+) kg^{-1}] in surface soil (0-15 cm). Irrespective of land uses, decrease in exchangeable bases (Ca and Mg) was observed in all the treatments with increase in depth from 0-15 to 15-30, 30-60 and 60-90 cm (Table 3). However, the diminution of both Exch-Ca and Mg in case of land uses was highest in FL (51% Ca and 40% Mg) followed by F-F sequence (49% Ca and 27% Mg) and10Y AFS (40.8% Ca and 23% Mg). Available S in the soil profile (0-90 cm) was highest in mature plantation cycles (128.3 and 117 kg ha^{-1}) in 30 and 20 Y old agroforestry followed by younger plantation cycle (102 kg ha^{-1}) than F-F sequence (95 kg ha^{-1}) and least 80.9 kg ha^{-1} in fallow land (Table 3). Integration of trees and fodder crops in fallow land built considerable amount of available S in plough layer (0-15 cm) by 19.4% and 12.1% in 10 Y AFS and F-F. Subsequently, advancement of AFS further accrues available S by 40.2% and 54.7% after 20 and 30 Y of AFS establishment on fallow land.

Higher content of Exch-Ca and Mg under tree based systems may be ascribed by leaf litter composition of poplar as it exhibited higher level of Ca and Mg in the leaves as a constituent of cell wall. Singh (2009) reported that 368 kg ha^{-1} and 55.4 kg ha^{-1} of Ca and S were added to the soil through litterfall by 6 year old poplar plantation throughout its rotation age. Similarly, Singh et al (2018) also asserted that exchangeable bases were well maintained in agroforestry systems in comparison to agriculture land use as they reported higher concentration of Exch-Ca and Mg in all agroforestry systems. Higher level of available S under tree based system than F-F and FL can be owed to higher availability of organic matter with low C:S ratio, which upon mineralization enhances the availability of sulphate S in the soil (Wainwright et al 1986). In the effect of soil layer, secondary macronutrients were found to be higher in the top layer of all treatments, which was probably due to pumping of bases (Ca and Mg) and S element from the subsoil by the profuse root system of vegetation and returning them in to topsoil (Yimer et al 2008). In comparison to surface layer, the curtailment of secondary macronutrients in lowers layers was maximum in case of FL followed by F-F and poplar based AFS which may be ascribed to lack of vegetation in case of FL, shallow root system of F-F whose most of the roots are concentrated up to 30 cm layer and minimum in poplar as its roots can penetrate up to depth of 1 m.

Macro-nutrient index value (MNIV): The major macronutrients (N, P and K) were assigned macro-nutrient index values (Table 4) as a better way of nutrient management on sustainable basis. Nitrogen (N) had low critical value (1.0) in all the treatments. Phosphorus (P) was medium (1.6 and 2.4) in fallow and F-F sequence, whereas

Table 2. Effect of different plantation cycles of poplar based agroforestry in comparison to other land uses on depth-wise distribution of available primary macronutrients

Depths	Indicators (kg ha^{-1})	10 Y	20 Y	30 Y	F-F	FL	LSD (P=0.05)
0-15 cm	Available N	92.83^{c}	127.9^{b}	183.1^{a}	77.8^{dc}	62.7^{d}	18.87
	Available P	27.77^{c}	32.49^{b}	43.53^{a}	22.73^{d}	16.78^{e}	3.57
	Available K	157.5^{c}	178.9^{b}	195.2^{a}	143.0^{d}	120.5^{e}	13.68
15-30 cm	Available N	70.25^{c}	107.9^{b}	153.0^{a}	72.76^{c}	50.18^{d}	18.87
	Available P	17.95^{c}	20.31^{b}	25.20^{a}	14.80^{d}	12.74^{d}	2.13
	Available K	141.5^{b}	165.5^{a}	176.1^{a}	129.4^{b}	112.2^{c}	15.93
30-60 cm	Available N	67.74^{b}	85.30^{a}	90.32^{a}	50.18^{c}	42.65^{c}	13.85
	Available P	13.97^{b}	15.17^{b}	17.13^{a}	13.74^{b}	9.83^{c}	1.76
	Available K	132.3^{b}	156.9^{a}	140.5^{b}	93.97^{c}	85.12^{c}	13.77
60-90 cm	Available N	42.65^{a}	47.67^{a}	52.68^{a}	40.14^{a}	27.60^{a}	NS
	Available P	10.85^{b}	11.88^{b}	13.37^{a}	7.84^{c}	7.53^{c}	1.48
	Available K	72.35^{c}	103.9^{b}	129.3^{a}	82.54^{c}	54.43^{d}	14.36

Values in the same row within same soil layer and parameter followed by same small letters are not significantly different (P = 0.05) according to Tukey's honestly significant difference (HSD) post hoc test

Table 3. Effect of different plantation cycles of poplar based agroforestry in comparison to other land uses on depth-wise distribution of secondary macronutrients - exchangeable Ca [cmol (+) kg^{-1}], exchangeable Mg [cmol (+) kg^{-1}] and available sulphur (kg ha^{-1})

Secondary macronutrients	10 Y	20 Y	30 Y	F-F	FL	LSD (P=0.05)
0-15 cm						
Exch- Ca	8.08^{b}	8.96^{a}	9.13^{a}	7.89^{b}	5.90^{c}	0.63
Exch- Mg	2.93^{c}	3.64^{b}	5.40^{a}	2.60^{c}	1.76^{d}	0.54
Available S	27.70^{c}	32.53^{b}	35.90^{a}	26.01^{c}	23.20^{d}	2.75
15-30 cm						
Exch- Ca	7.95^{b}	8.05^{ba}	8.49^{a}	7.91^{b}	5.58^{c}	0.47
Exch- Mg	2.87^{cb}	3.36^{b}	4.63^{a}	2.74^{c}	1.22^{d}	0.50
Available S	27.52^{c}	31.04^{b}	34.83^{a}	26.18^{c}	22.38^{d}	2.23
30-60 cm						
Exch- Ca	6.55^{a}	6.74^{a}	6.91^{a}	5.75^{b}	4.19^{c}	0.36
Exch- Mg	2.36^{b}	2.85^{a}	2.92^{a}	2.11^{b}	0.93^{c}	0.38
Available S	25.41^{bc}	27.81^{ba}	30.32^{a}	22.47^{dc}	19.73^{d}	3.16
60-90 cm						
Exch- Ca	4.78^{b}	5.13^{b}	5.74^{a}	4.03^{c}	2.89^{d}	0.41
Exch- Mg	2.25^{b}	2.88^{a}	2.86^{a}	1.90^{c}	1.06^{d}	0.26
Available S	22.07^{b}	25.59^{a}	27.27^{a}	20.24^{b}	15.68^{c}	2.78

Values in the same row within same soil layer and parameter followed by same small letters are not significantly different (p = 0.05) according to Tukey honestly significant difference (HSD) post hoc test

Table 4. Macro-nutrients index value (MNIV) of different plantation cycles of poplar based agroforestry system and other land use soils

Chronosequence	Nutrients	Range (kg ha^{-1})	MNIV	Category
10 Y	N	87.8 - 100	1	Low
	P	21.8 - 33.9	2.8	High
	K	145 - 179	2	Medium
20 Y	N	100 - 150	1	Low
	P	29.0 - 36.1	3	High
	K	156 -193	2	Medium
30 Y	N	163 - 213	1	Low
	P	39.1 - 46.7	3	High
	K	189 - 204	2	Medium
F-F	N	62.7 - 87.8	1	Low
	P	19.8 - 25.4	2.4	Medium
	K	136 - 148	2	Medium
FL	N	50.1 - 75.2	1	Low
	P	11.7 - 18.5	1.8	Medium
	K	104 - 133	1.6	Low

* Macro-nutrients index categories are assigned on the basis of nutrient critical values: <1.50-low, 1.50-2.50-medium, >2.50-high

all plantation cycles of AFS were rated as high [2.8 (10 Y), 3 (20 Y) and 3 (30 Y)]. Potassium (K) was categorized low in no vegetation land use (FL) and highest (2.0) in F-F and all plantation cycles of AFS.

In order to compare the soil fertility levels of one region with those of another, it was obligatory to obtain a single value for each nutrient. Nutrient index (NI) value is a measure of nutrient supplying capacity of soil to plants. Higher P and K index value in mature plantation sites over rest can be attributed to higher addition of organic anions which increase their availability through solubilization or chelation mechanisms. Moreover, lesser consumption of available P and K by intercrops in comparison to available N could be the reason behind variability. Similarly, Nath et al (2015) also reported significant positive impact of chronosequence of bamboo based agroforestry system in improving soil fertility through profuse root system and on site nutrient conservation as they found positive correlation of increasing clump age with total N (R^2 = 0.95*), available P (R^2 = 0.94*) and exchangeable K (R^2 = 0.91*).

CONCLUSIONS

The introduction of poplar-based agroforestry system leads to a considerable accumulation of primary as well as secondary macronutrients in the soil and this content increased tremendously with advancement of AFS from young plantation cycle (10 Y) to mature sites (30 Y). This change is not restricted to plough layer but increment occur throughout the soil profile (0-90 cm). The order of macronutrients in the soil profile (0-90 cm) in poplar tree based system followed an order K>N>S>P. Apart from these, physical property such as water retention capacity also improved significantly with establishment of AFS on fallow land. Overall, buildup of macronutrients in mature sites over young sites suggests that a long-term adoption of agroforestry may help in mitigating the ill effects of continuous paddy straw burning and also a better alternate to improve soil health and productivity.

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