SOIL PROPERTIES OF SHOLA FORESTS INVADED BY BLACK WATTLE (*ACACIA MEARNSII*) IN THE WESTERN GHATS OF TAMIL NADU, INDIA

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Abstract. The Australian Black Wattle (*A. mearnsii)* threatens native habitats by outcompeting indigenous vegetation for water, soil nutrients and organic matter. The present investigation was conducted to study the soil properties of shola forests invaded by *A. mearnsii* plantations in the Kodaikanal Forest Division of the Western Ghats of Tamil Nadu, India. Soil samples were collected from *A. mearnsii* invaded shola forests of Poombarai forest range in the Kodaikanal Forest Division. For comparison purposes, soil samples were collected from shola forests, *A. mearnsii* plantation, grass land and pine plantations. Soil pH (5.02), organic carbon (5.82%), available nitrogen (201.6 kg ha^{-1}) and available potassium (334.5 kg ha^{-1}), exchangeable calcium (3.79 meq/100 g) and exchangeable magnesium (5.18 meq/100 g) were highest under *A. mearnsii* invaded shola forest at 0-30 cm depth. Available P was highest under *A. mearnsii* plantation (21.5 kg ha^{-1}). The control plot (shola forest), registered a pH of 3.94, organic carbon (5.80%), available nitrogen (180.4 kg ha^{-1}), available phosphorus (21.0 kg ha^{-1}), available potassium (318.3 kg ha^{-1}), exchangeable calcium (3.59 meq/100 g) and exchangeable magnesium (5.08 meq/100 g). The baseline data generated from the study can be utilized for undertaking appropriate decision making in the management of forests to control the invasion menace of *A. mearnsii* thereby improving the soil quality.
Keywords: *invasion ecology, habitat modification, invasive species, soil characteristics*

Introduction

A collective of Tropical Montane, evergreen forests locally known as sholas is situated in the higher mountain tracts of the Western Ghats, at an altitude above 1500 m interspersed with rolling grasslands. Shola forests have high ecological significance in protecting the headwaters of rivers by holding back water received by precipitation like a sponge, thus preventing rapid run-off. These diverse forests and grasslands were converted into commercially valuable plantations to meet the fuel wood requirement of tea industry during British period. Some of the introduced species like *A. mearnsii* have become invasive alien species in this ecosystem and became a serious threat to this high-altitude ecosystem (Myers et al., 2000).

The Australian Black Wattle (*A. mearnsii)* was introduced during the 1960s in State Forest lands located in the upper altitudes of the Palani hills- an eastern offshoot of the Western Ghats, a mountain range that runs parallel to the southwest coast of Peninsular India near the hill station of Kodaikanal (Mitchell, 1972; Mathew et al., 1975). *A. mearnsii,* a small to large, evergreen, single stemmed or multi branched tree threatens native habitats by outcompeting indigenous vegetation for water, soil nutrients and organic matter (Moyo and Fatunbi, 2010). Invasive alien plants alter the invaded

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community by shifting native biodiversity through a reduction in light penetration, changes in soil nutrients and hydrology and then modifying ecosystem functionality (Vardien et al., 2012). There are various mechanisms whereby invasive alien plants can alter soil ecosystems (Tererai et al., 2015). Studies have reported the mass of the leaf litter in areas invaded by *A. mearnsii* to be greater than that of un-invaded areas, thereby the dense layer inhibits the establishment of native seedlings (Pandey et al., 2014). Between 1849 and 1992, in the Nilgiris Biosphere Reserve, the sholas decreased from 8600 ha to 4225 ha and grasslands from 29875 ha to 4700 ha (Kumar, 1993).

Soil is the major source of nutrients for the growth of plants and determining the degree of soil physico-chemical characteristics are very necessary to evaluate the soil fertility. The nutrient transformation and its availability in soils depend on pH, clay minerals, cation and anion exchange capacity (Reddy and Reddy, 2010). Soils exhibit difference in properties in relation to the vegetation changes and vary spatially primarily in response to rooting and litter fall characteristics of the perennial vegetation on more or less the same soil material (Balagopalan et al., 1993). Invasive plant species can modify physical or chemical attributes of soil, including inputs and cycling of nitrogen and other elements (Ehrenfeld, 2003; Haubensaket al., 2004 and Hawkes et al., 2005; Tererai et al., 2015). The amount of soil nutrients especially soil nitrogen, phosphorus and carbon, soil pH, microbial N and P, decomposition rates and soil water repellents can be increased due to invasive alien plants compared to the natural site (Fan et al., 2010; Ruwanza et al., 2013; Ruwanza and Shackleton, 2016). However, in some studies, they may show the reverse trends (Ehrenfeld, 2003; Tererai et al., 2015). Nutrient dynamics may also become altered as a result of changes in the physical properties of the soil caused by the introduction of new species.

Studies on the properties of soil in invaded shola forests are required for proper management of the forests and utilization of resources. Studies on the assessment of soil properties under shola forests invaded by *A. mearnsii* in the Western Ghats of Kodaikanal are scanty. Therefore, the present study was proposed with an aim to study the soil properties of shola forests invaded by *A. mearnsii* plantations in the Western Ghats of Kodaikanal, Tamil Nadu, India.

Materials and methods

Location and site description

The present study was carried out in the Western Ghats of Tamil Nadu covering the Poombarai Range of the Kodaikanal Forest Division, Tamil Nadu, India (*Fig. 1*). Kodaikanal Forest Division lies within 10°6’ and 10°21’ North latitudes and 77°16’ and 77°42’ East longitudes and is surrounded by Kerala state in West, Indira Gandhi Wild life sanctuary, Pollachi in North-west, Dindigul forest division on the North-east and Theni revenue district in South. The altitude varies from 300 to 2654 m and this area experiences an average yearly rainfall of 165 cm. The average annual temperature in Kodaikanal 20.8 °C.

Soil sampling and analysis

Soil samples were collected from the different study plots *viz*, shola forests invaded by *A. mearnsii*, shola forests, *A. mearnsii* plantation, grass land and pine plantations during 2016-2018 (*Fig. 2*). At each of the study plot, soil samples were collected from three sites and at four depths *viz.*, 0-30, 30-50, 50-80 and 80-100 cm. Sites within each

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invasion treatment were approximately 200 m apart to provide a measure of independence (Galatowitsch and Richardson, 2005).

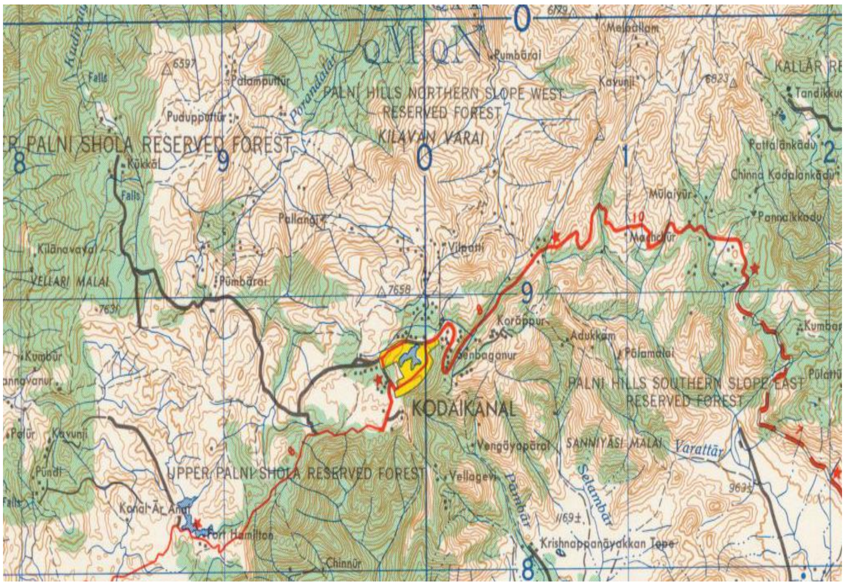

Figure 1. *Map showing the study area*

(a)

(b)

(c)

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(d)

Figure 2. *(a) Acacia mearnsii invaded shola forests. (b) Acacia mearnsii plantation. (c) A. mearnsii invaded grassland; Evergreen shola forest (d) Soil sampling in Acacia mearnsii invaded sites*

At each sampling point, an area of 0.5 m × 0.5 m was removed and a pit of 50 cm wide, 50 cm in length and 100 cm deep was dug. The soil was scrapped from three sides of the pit with the help of a kurpee at each depth. The soil was mixed thoroughly and transferred to a polythene bag with proper labeling. The samples were air-dried and sieved to pass through 2 mm mesh sieve for physico-chemical analysis. The pH of soil was determined using an aqueous suspension of soil (soil and water in 1:2.5 ratio) using a digital micro controller based pH meter with electrode, Make: Systronics (Jackson, 1973). Soil organic carbon was estimated by standard Chromic acid wet oxidation method (Walkley and Black, 1934). The available nitrogen in the soil was estimated by the alkaline permanganate method using Automatic Nitrogen Analyzer, Make: Pelican (Subbiah and Asija, 1956).

The concentration of available phosphorus was determined by Olsen, Bray 1 and Kurtz extraction methods using UV-Vis Spectrophotometer, Make: Shimadzu (Olsen et al., 1954; Bray and Kurtz, 1945). Available potassium was estimated by neutral normal ammonium acetate extraction using Flame Photometer, Make: Systronics (Stanford and English, 1949). The contents of exchangeable bases (Ca and Mg,) were determined by Versenate titration after extraction using 1 N ammonium acetate adjusted to pH 7.0 (Cheng and Bray, 1951). Available micronutrients *viz*, Fe, Mn, Zn and Cu were extracted using Diethylene Triamine Penta Acetic acid reagent and the micronutrients content were estimated using Atomic Absorption Spectrophotometer, Make: Shimadzu (Lindsay and Norvell, 1978).

Statistical analysis

The data obtained were subjected to statistical analysis in SPSS ® 19.0 version statistical software. One-way ANOVA was also applied to analyse and to compare the mean significant difference between each parameter under different sites. During the ANOVA test the soil properties were the dependent variables while sampling sites were the independent variables.

Results

Acacia mearnsii invasion on soil properties

Analysis of variance (ANOVA) testing the effects of *A. mearnsii* on soil properties among the study plots of Poombarai forest range at 0 to 30 cm depth is given in *Table 1*. The soils in all the sites were acidic in general and soil pH was highest under *A.*

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mearnsii invaded shola forest ($p < 0.001$)) at 0-30 cm depth and was followed by grassland. Shola forest registered the lowest pH (3.94) at 0-30 cm depth. At 30-50 cm, 50-80 cm and 80-100 cm, soil pH was highest under *A. mearnsii* invaded shola forest at (*Tables 2, 3* and *4*).

Table 1. *Analysis of variance (ANOVA) testing the effects of Acacia mearnsii on soil properties among the study plots of Poombarai forest range at 0 to 30 cm depth*

Soil properties	Study plots					F-value	p-value
	***A. mearnsii* invaded shola**	***A. mearnsii* plantation**	**Grassland**	**Pine forest**	**Shola forest**		
Soil pH	5.02 ± 0.03	4.13 ± 0.02	4.39 ± 0.02	4.15 ± 0.02	3.94 ± 0.02	296.68	< 0.001
Electrical conductivity (dS m^{-1})	0.42 ± 0.03	0.62 ± 0.06	0.41 ± 0.03	0.30 ± 0.03	0.36 ± 0.03	954.78	< 0.001
Organic carbon (%)	5.82 ± 0.03	3.97 ± 0.02	4.3 ± 0.02	5.54 ± 0.03	5.8 ± 0.03	835.15	< 0.001
Available nitrogen (kg ha^{-1})	201.6 ± 1.16	168.6 ± 0.97	164 ± 0.95	145.6 ± 0.84	180.4 ± 1.04	429.87	< 0.001
Available phosphorus (kg ha^{-1})	19.9 ± 0.11	21.5 ± 0.12	20.6 ± 0.12	20.1 ± 0.11	21.0 ± 0.12	29.97	< 0.001
Available potassium (kg ha^{-1})	334.5 ± 1.93	183.6 ± 1.06	164.8 ± 0.95	139.2 ± 0.80	318.3 ± 1.84	4262.04	< 0.001
Exchangeable calcium (meq/100 g)	3.79 ± 0.04	1.99 ± 0.02	3.59 ± 0.03	3.39 ± 0.02	3.59 ± 0.03	587.56	< 0.001
Exchangeable magnesium (meq/100 g)	5.18 ± 0.04	4.78 ± 0.04	4.09 ± 0.03	4.68 ± 0.04	5.08 ± 0.04	106.06	< 0.001
DTPA-Cu (ppm)	2.99 ± 0.03	1.2 ± 0.01	2.79 ± 0.03	0.6 ± 0.01	5.58 ± 0.05	4717.02	< 0.001
DTPA-Zn (ppm)	1.00 ± 0.01	0.5 ± 0.01	0.8 ± 0.01	0.3 ± 0.0	1.2 ± 0.01	2386.24	< 0.001
DTPA-Mn (ppm)	2.4 ± 0.01	0.6 ± 0.01	0.4 ± 0.0	0.2 ± 0.0	2.6 ± 0.02	14442.85	< 0.001
DTPA-Fe (ppm)	10.4 ± 0.06	7.6 ± 0.05	6.4 ± 0.03	5.9 ± 0.03	20.1 ± 0.11	8117.2	< 0.001

Table 2. *Analysis of variance (ANOVA) testing the effects of Acacia mearnsii on soil properties among the study plots of Poombarai forest range at 30 to 50 cm depth*

Soil properties	Study plots					F-value	p-value
	***A. mearnsii* invaded shola**	***A. mearnsii* plantation**	**Grassland**	**Pine forest**	**Shola forest**		
Soil pH	5.04 ± 0.03	4.23 ± 0.02	4.56 ± 0.02	4.23 ± 0.02	3.95 ± 0.02	266.12	< 0.001
Electrical conductivity (dS m^{-1})	0.4 ± 0.00	0.54 ± 0.06	0.38 ± 0.00	0.28 ± 0.00	0.38 ± 0.00	1302.0	< 0.001
Organic carbon (%)	5.11 ± 0.03	3.89 ± 0.02	4.25 ± 0.02	4.87 ± 0.03	5.6 ± 0.03	589.80	< 0.001
Available nitrogen (kg ha^{-1})	168 ± 0.97	154.2 ± 0.88	150.2 ± 0.87	124.2 ± 0.72	164.8 ± 0.95	384.59	< 0.001
Available phosphorus (kg ha^{-1})	19.7 ± 0.11	20.8 ± 0.12	20.4 ± 0.11	20.3 ± 0.11	20.6 ± 0.12	12.46	< 0.001
Available potassium (kg ha^{-1})	326.3 ± 1.88	152.8 ± 0.88	152.8 ± 0.88	130.2 ± 0.75	302.6 ± 1.75	5008.86	< 0.001
Exchangeable calcium (meq/100 g)	3.2 ± 0.02	2.0 ± 0.01	3.2 ± 0.02	2.8 ± 0.02	3.4 ± 0.02	1170.0	< 0.001
Exchangeable magnesium (meq/100 g)	4.8 ± 0.03	4.5 ± 0.02	3.6 ± 0.02	4.6 ± 0.03	4.7 ± 0.03	314.06	< 0.001
DTPA-Cu (ppm)	2.6 ± 0.02	1.0 ± 0.01	2.6 ± 0.02	0.4 ± 0.0	4.5 ± 0.03	9822.97	< 0.001
DTPA-Zn (ppm)	0.6 ± 0.01	0.3 ± 0.0	0.6 ± 0.01	0.2 ± 0.0	1.0 ± 0.01	4900.00	< 0.001
DTPA-Mn (ppm)	2.0 ± 0.01	0.4 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	2.0 ± 0.01	17775.00	< 0.001
DTPA-Fe (ppm)	8.2 ± 0.05	6.7 ± 0.04	6.2 ± 0.03	4.6 ± 0.03	14.6 ± 0.09	5645.86	< 0.001

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Table 3. *Analysis of variance (ANOVA) testing the effects of Acacia mearnsii on soil properties among the study plots of Poombarai forest range at 50 to 80 cm depth*

Soil properties	Study plots					F-value	p-value
	***A. mearnsii* invaded shola**	***A. mearnsii* plantation**	**Grassland**	**Pine forest**	**Shola forest**		
Soil pH	5.32 ± 0.03	4.35 ± 0.02	4.78 ± 0.03	4.85 ± 0.03	3.88 ± 0.02	416.25	< 0.001
Electrical conductivity (dS m^{-1})	0.34 ± 0.00	0.58 ± 0.01	0.49 ± 0.00	0.20 ± 0.00	0.21 ± 0.00	4264.5	< 0.001
Organic carbon (%)	4.25 ± 0.02	3.42 ± 0.01	4.02 ± 0.02	4.56 ± 0.03	5.23 ± 0.03	736.69	< 0.001
Available nitrogen (kg ha^{-1})	156.8 ± 0.90	150.6 ± 0.87	126.4 ± 0.73	118.6 ± 0.68	152.4 ± 0.88	442.38	< 0.001
Available phosphorus (kg ha^{-1})	18.2 ± 0.10	20.4 ± 0.11	18.2 ± 0.10	19.3 ± 0.11	19.4 ± 0.11	72.88	< 0.001
Available potassium (kg ha^{-1})	276.5 ± 1.59	145.2 ± 0.84	146.7 ± 0.85	126.4 ± 0.72	286.4 ± 1.65	4239.96	< 0.001
Exchangeable calcium (meq/100 g)	2.8 ± 0.02	1.2 ± 0.01	2.4 ± 0.01	2.6 ± 0.02	2.7 ± 0.02	2006.2	< 0.001
Exchangeable magnesium (meq/100 g)	4.6 ± 0.03	3.8 ± 0.02	3.2 ± 0.01	4.1 ± 0.02	4.5 ± 0.03	562.53	< 0.001
DTPA-Cu (ppm)	2.2 ± 0.01	0.6 ± 0.01	1.9 ± 0.01	0.2 ± 0.0	3.4 ± 0.02	13816.6	< 0.001
DTPA-Zn (ppm)	0.57 ± 0.01	0.2 ± 0.0	0.3 ± 0.0	0.1 ± 0.0	0.84 ± 0.01	6796.5	< 0.001
DTPA-Mn (ppm)	1.4 ± 0.01	0.4 ± 0.0	0.3 ± 0.0	0.1 ± 0.0	1.8 ± 0.01	16950.00	< 0.001
DTPA-Fe (ppm)	6.8 ± 0.04	4.3 ± 0.02	5.8 ± 0.03	4.2 ± 0.02	10.2 ± 0.06	4116.82	< 0.001

Table 4. *Analysis of variance (ANOVA) testing the effects of Acacia mearnsii on soil properties among the study plots of Poombarai forest range at 80 to 100 cm depth*

Soil properties	Study plots					F-value	p-value
	***A. mearnsii* invaded shola**	***A. mearnsii* plantation**	**Grassland**	**Pine forest**	**Shola forest**		
Soil pH	5.28 ± 0.03	4.38 ± 0.02	4.69 ± 0.03	4.73 ± 0.03	3.86 ± 0.02	379.44	< 0.001
Electrical conductivity (dS m^{-1})	0.36 ± 0.00	0.41 ± 0.00	0.32 ± 0.00	0.24 ± 0.00	0.14 ± 0.00	-	-
Organic carbon (%)	3.41 ± 0.02	2.84 ± 0.02	3.64 ± 0.02	3.92 ± 0.02	4.86 ± 0.03	1107.7	< 0.001
Available nitrogen (kg ha^{-1})	134.4 ± 0.77	140.7 ± 0.81	116.4 ± 0.67	104.8 ± 0.61	130.6 ± 0.76	399.86	< 0.001
Available phosphorus (kg ha^{-1})	19.0 ± 0.11	18.6 ± 0.10	18.0 ± 0.10	19.4 ± 0.11	18.8 ± 0.11	22.74	< 0.001
Available potassium (kg ha^{-1})	240.8 ± 1.39	133.4 ± 0.77	130.2 ± 0.75	118.6 ± 0.68	274.6 ± 1.59	4329.71	< 0.001
Exchangeable calcium (meq/100 g)	2.0 ± 0.01	1.0 ± 0.01	1.9 ± 0.01	2.2 ± 0.01	2.3 ± 0.01	2355.88	< 0.001
Exchangeable magnesium (meq/100 g)	3.7 ± 0.02	3.4 ± 0.01	2.9 ± 0.01	3.8 ± 0.02	4.0 ± 0.02	415.90	< 0.001
DTPA-Cu (ppm)	1.6 ± 0.01	0.4 ± 0.0	2.0 ± 0.01	0.1 ± 0.0	4.0 ± 0.02	15012.5	< 0.001
DTPA-Zn (ppm)	0.4 ± 0.01	0.2 ± 0.0	0.1 ± 0.0	0.1 ± 0.01	0.62 ± 0.01	7542.0	< 0.001
DTPA-Mn (ppm)	1.8 ± 0.01	0.2 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	1.2 ± 0.01	17400.00	< 0.001
DTPA-Fe (ppm)	5.7 ± 0.03	2.9 ± 0.02	5.0 ± 0.03	3.1 ± 0.02	8.4 ± 0.05	5262.58	< 0.001

Soil organic carbon (SOC) content in the Poombarai range was significantly influenced by *A. mearnsii* invasion (*Fig. 3*). SOC content in the study plots varied significantly ($p < 0.001$% by ANOVA) at different soil depths. Soil organic carbon was highest under *A. mearnsii* invaded shola forest (5.82%) and was on par with shola forest

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(5.80%) at 0-30 cm depth. This was followed by pine forest (5.54%), and grassland (4.30%). The lowest SOC was recorded in *A. mearnsii* plantation (3.97%).

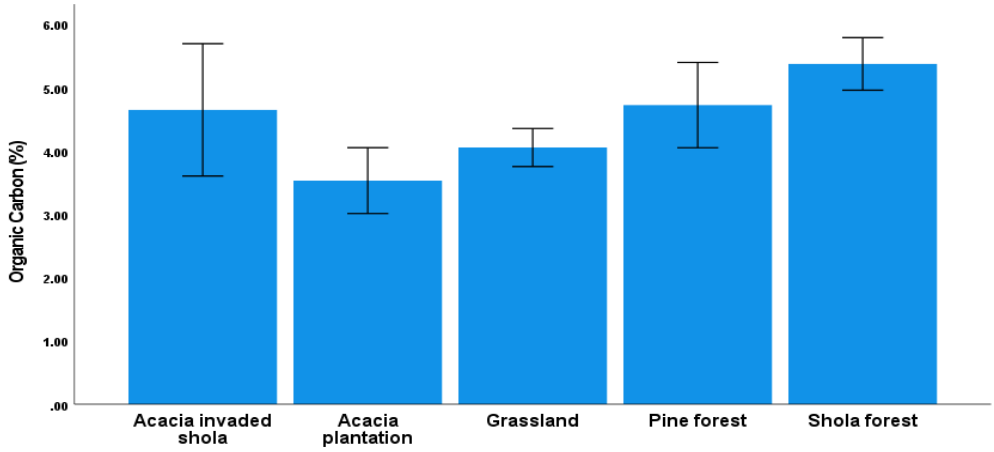

Figure 3. *A. mearnsii invasion on soil organic carbon (%) in Poombarai range*

The available nitrogen (kg ha^{-1}) in the different study plots of Poombarai range is presented in *Figure 4*. At different soil depths, the available nitrogen varied significantly ($p < 0.001\%$ by ANOVA) among the study plots. *A. mearnsii* invaded shola forest recorded the highest available nitrogen ($p < 0.001\%$) at 0-30 cm depth (201.6 kg ha^{-1}) and was followed by shola forest (180.4 kg ha^{-1}), and *A. mearnsii* plantation (168.6 kg ha^{-1}). The lowest available nitrogen was recorded in pine forest (145.6 kg ha^{-1}) at 0-30 cm depth (*Table 1*). With respect to soil depth, maximum available nitrogen was registered at 0-30 cm depth. The available nitrogen showed a decreasing trend with soil depth in all the study plots of Poombarai range. At 30-50 cm, 50-80 cm and 80-100 cm nitrogen availability was highest under *A. mearnsii* invaded shola forest ($p < 0.001\%$).

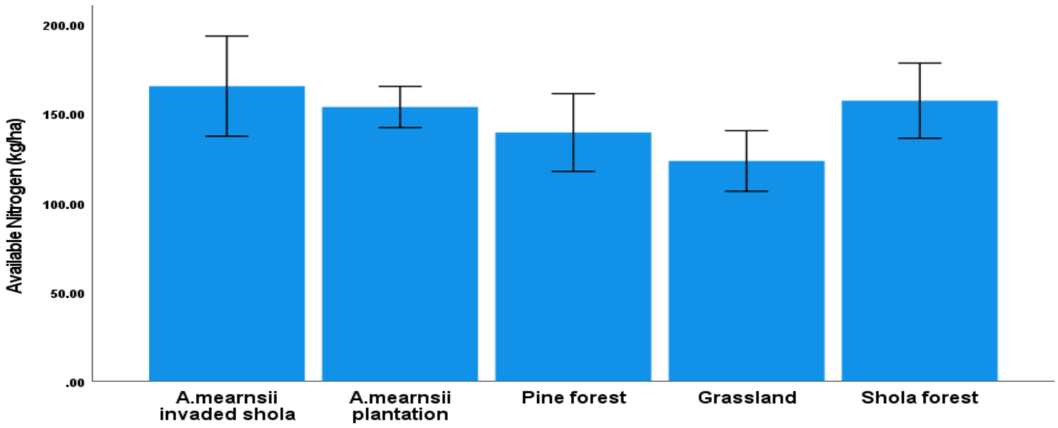

Figure 4. *A. Mearnsii invasion on available nitrogen (kg ha^{-1}) in Poombarai range*

Available phosphorus was highest under *A. mearnsii* plantation (21.5 kg ha^{-1}) at 0-30 cm depth. This was on par with shola forest (21.0 kg ha^{-1}) and was followed by pine

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forest, and grassland (*Table 1*). Available phosphorus was lowest in *A. mearnsii* invaded shola forest (19.9 kg ha^{-1}). At 30-50 cm and 50-80 cm, *A. mearnsii* plantation recorded the highest Available Phosphorus ($p < 0.001$) and was on par with shola forest (*Table 2* and 3). Pine forest registered greater available P (<0.001) at 80-100 cm (*Table 4*). The available potassium (kg ha^{-1}) in the different study plots of Poombarai range is presented in (*Fig. 5*). Available potassium varied significantly ($p < 0.001$%) among the study plots. *A. mearnsii* invaded shola forest recorded the highest available potassium (334.5 kg ha^{-1}) at 0-30 cm depth and was followed by shola forest (318.3 kg ha^{-1}). The lowest available potassium was recorded in pine forest (139.2 kg ha^{-1}) at 0-30 cm depth. With respect to soil depth, maximum available potassium was registered at 0-30 cm depth. The available potassium showed a decreasing trend with soil depth in all the study plots (*Table 1*).

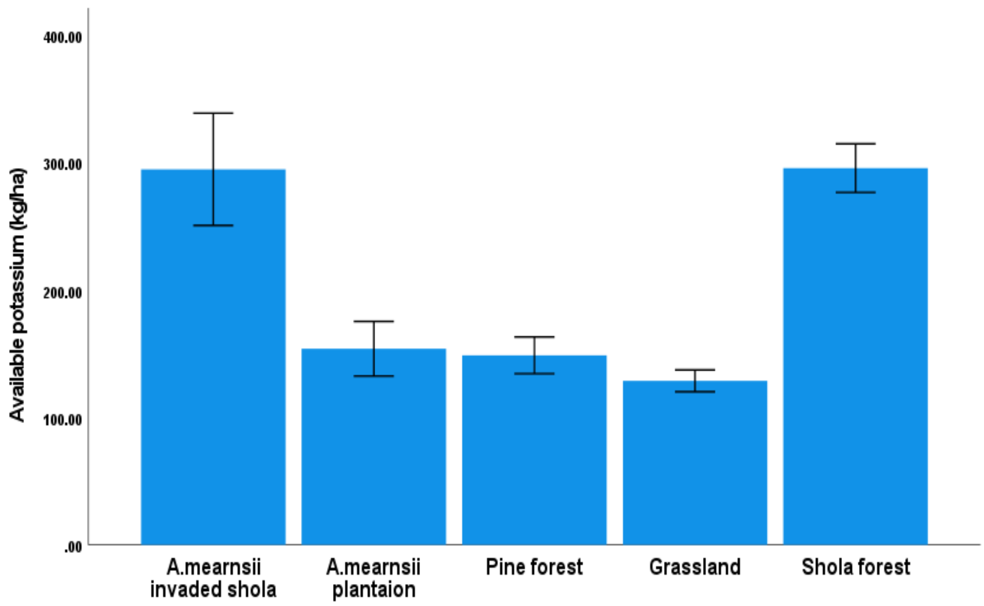

Figure 5. *A. Mearnsii invasion on available potassium (kg ha^{-1}) in Poombarai range*

The effects of *A. mearnsii* invasion on soil exchangeable calcium in the Poombarai range at 0 -30 cm is presented in (*Table 1*). The exchangeable calcium varied from 0.3 to 0.62 meq/100 g. The exchangeable calcium was highest under *A. mearnsii* invaded shola forest (3.8 meq/100 g) at 0-30 cm depth. This was followed by shola forest (3.6 meq/100 g) and grassland (3.6 meq/100 g). *A. mearnsii* plantation registered the lowest exchangeable calcium (2.0 meq/100 g) at 0-30 cm depth. Exchangeable calcium availability was highest ($p < 0.001$%) under shola forest and was on par with *A. mearnsii* invaded shola forest at 30-50 cm (*Table 2*).

The perusal of data on exchangeable magnesium in the different study plots revealed that, at 0-30 cm depth, *A. mearnsii* invaded shola forest recorded the highest exchangeable magnesium (5.2 meq/100 g). This was found to be on par with the shola forest (5.2 meq/100 g). The exchangeable magnesium showed a decreasing trend with soil depth in all the study plots (*Table 1*). At 30-50 cm and 50-80 cm, *A. mearnsii* invaded shola forest registered higher exchangeable magnesium ($p < 0.001$) and was on par with shola forest (*Tables 2* and *3*).

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Micronutrients availability

Among the different study plots, shola forests recorded the highest DTPA-Cu (5.6 ppm), DTPA-Zn (1.2 ppm), DTPA-Mn (2.6 ppm), DTPA-Fe (20.1 ppm) at 0-30 cm depth (*Table 1*; *Fig. 6*) and was followed by *A. mearnsii* invaded shola forest (3.0, 1.0, 2.4 and 10.4 ppm), and grassland (2.8, 0.8, 0.4 and 6.4 ppm). The lowest DTPA-Cu (0.6 ppm), DTPA-Fe (5.9 ppm), DTPA-Mn (0.2 ppm) and DTPA-Zn (0.3 ppm) was recorded in pine forest at 0 to 30 cm depth. At 30-50 and 50-80 cm, shola forest registered the highest DTPA-Cu, DTPA-Mn and DTPA-Fe ($p < 0.001$). Pine forest recorded the lowest availability of micronutrients with respect to copper, iron manganese and zinc (*Tables 2* and *3*). DTPA-Cu, DTPA-Zn and DTPA-Fe availability was highest ($p < 0.001$) under shola forest at 80-100 cm (*Table 4*).

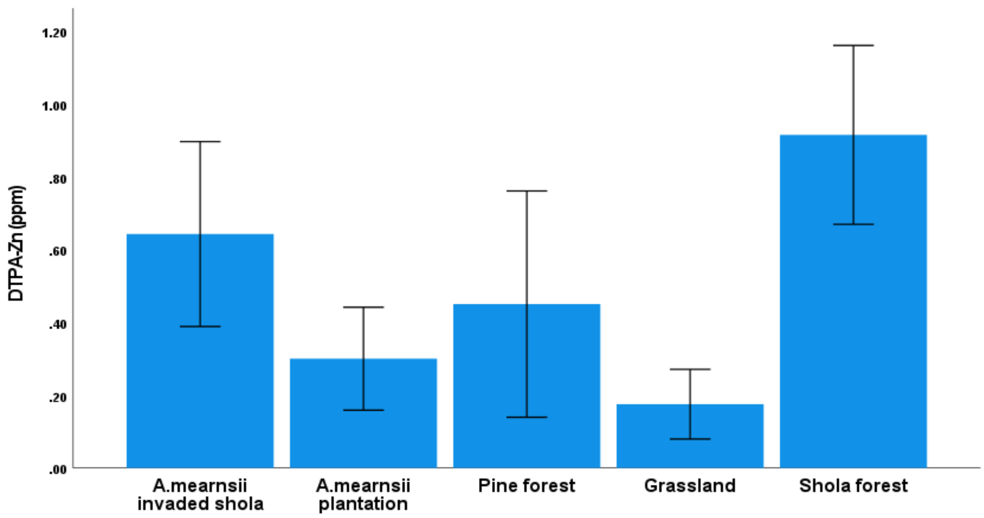

Figure 6. *A. mearnsii invasion on DTPA-Zn (ppm) in Poombarai range*

Discussion

Introduced plants affect soil nutrient dynamics by differing from native species in tissue chemistry, plant morphology and phenology (Ehrenfeld, 2003). Soil properties such as pH and the amount of base cations available in the soil differ greatly under trees of different species and when invading trees are compared with native vegetation (Dijkstra et al., 2001). The present study revealed higher pH under *A. mearnsii* invaded shola forest. Similar results were reported for *L. camara* infested soils by Fan et al. (2010) and Olusegun and Perrett (2011). High soil pH accelerated litter decomposition and thus plays a crucial role in regulating nutrient availability. Due to the high soil cation exchange process, soil cations are available in the root rhizosphere of the invasive species compared to native species resulting in high soil pH in the invaded sites. (Simba et al., 2013; Debnath et al., 2018). However, both increases and decreases in pH following plant invasion have been equally reported in the literature (Ehrenfeld, 2003).

Soil organic carbon was highest under *A. mearnsii* invaded shola forest. The results are concurrent with many other studies (Picone et al., 2003; Cheng et al., 2013). The combined effect of low temperature and high rainfall in shola forests restricts biochemical decomposition of organic residues in these soils and thus help maintain

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high organic carbon percentage, which in turn becomes responsible for the high cation exchange capacity and base saturation of these soils (Balagopalan, 1993). However, Debnath et al. (2018) reported equal amount of soil organic carbon in both invaded and natural sites. Available nitrogen, exchangeable calcium and magnesium were highest under *A. mearnsii* invaded shola forest. The increase in available nitrogen and exchangeable calcium and magnesium in *A. mearnsii* invaded sites could be due to decrease in nutrient sequestration following native shola species displacement. *A. mearnsii* drops a lot of litter beneath it and this probably account for the elevated nitrogen levels when the litter decays. These findings are consistent with the findings by Ehrenfeld (2003), who reported an increase in soil nitrate following *Lantana camara* invasion. Jovanovic et al. (2009) also reported an increase in nitrogen where *A. saligna* invaded Sand Plain Fynbos. Dusanka et al. (2021) also reported that soil in mixed plots (those populated with *Amorpha fruticosa*, *Fraxinus pennsylvanica* and *Acer negundo*) contained much higher levels of nitrifying bacteria (NB), organic matter (Om), nitrogen (N), and carbon (C) as well as lower carbon to nitrogen ratio (C:N) levels, compared to single species invaded plots and control plots.

In our study, *A. mearnsii* plantation recorded the highest available phosphorus and was on par with shola forest. Musil and Midgley (1990) found similar results on Sand Plain Fynbos. *Acacia saligna* infestation doubled the average concentration of calcium, magnesium, potassium, total nitrogen, manganese, boron and zinc. Burnt plots showed a significant increase for soil pH, calcium, manganese and available phosphorus.

Our findings revealed that, available potassium was highest under *A. mearnsii* invaded shola forest. The high soil cation exchange process might have resulted in increased soil cations availability in the root rhizosphere of the invasive species compared to native species and our results was supported by earlier findings of Simba et al. (2013), Ruwanza and Shackleton (2016) and Debnath et al. (2018). Similarly, a study on long-term invasive occupation by *Acacia longifolia* significantly altered soil properties, with increased levels of organic C, total N, and exchangeable cations (Ehrenfeld, 2003 and Fan et al. 2010). In the present study, the availability of micronutrients *viz*, DTPA-Cu, Zn Mn and Fe were higher under shola forest compared to other study plots.

Conclusion

For proper management of the environment and utilization of resources, studies on the properties of soil in invaded forest ecosystems are important. Without adequate knowledge of the dynamic interaction between soil, climate and forest management we cannot develop a proper soil management system. Soil properties such as pH, available nitrogen, available phosphorus, available potassium, exchangeable calcium and magnesium in the soil varied significantly under *A. mearnsii* invaded shola forests compared with native vegetation. Baseline data generated in the present study can be utilized by the State Forest Department for undertaking appropriate decision making in the eco-restoration of areas invaded by *A. mearnsii*. From a management point of view removal of *A. mearnsii* for restoration purposes, could reduce the effect of the invasive species on the soil properties. Therefore, appropriate methods for the management of *A. mearnsii* are necessary to circumvent potential threats to native biodiversity.

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APPENDIX

***Appendix 1.** Details of soil sample collection in Kodaikanal (Poombarai Range)*

S. No.	Soil depth	Location	GPS	Forest type
1	0-30 cm	Near Kundar Falls (**Kodaikanal)**	N 10° 12’ 54.3” E 077° 26’ 08.3” 2171 m	Pine forest plantation
2	30-50 cm			
3	50-80 cm			

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4	80-100 cm			
5	0-30 cm	Near Kundar Falls (**Kodaikanal)**	N 10° 21’ 58.2” E 077° 43’ 62.7” 2171 m	Pine forest plantation
6	30-50 cm			
7	50-80 cm			
8	80-100 cm			
9	0-30 cm	Kundar Falls (**Kodaikanal)**	N 10° 13’ 02.7 “ E 077° 25’ 33.3” 2185 m	Grass land
10	30-50 cm			
11	50-80 cm			
12	80-100 cm			
13	0-30 cm	Kundar Falls (**Kodaikanal)**	N 10° 21’ 72.0” E 077° 42’ 67.1” 2131 m	Grass land
14	30-50 cm			
15	50-80 cm			
16	80-100			
17	0-30 cm	Krishnan Kovil (**Kodaikanal)**	N 10° 13’ 40.6” E077° 25’ 23.9” 2236 m	*Acacia mearnsii* plantation
18	30-50 cm			
19	50-80 cm			
20	80-100 cm			
21	0-30 cm	Krishnan Kovil (**Kodaikanal)**	N 10° 22’ 82.4” E077° 42’ 32.3” 2224 m	*Acacia mearnsii* plantation
22	30-50 cm			
23	50-80 cm			
24	80-100 cm			
25	0-30 cm	FDA thottam (TNFD) inside the Krishnan kovil (**Kodaikanal)**	N 10° 14’ 08.9” E077° 25’ 39.8” 2222 m	*Acacia mearnsii* invaded grass land
26	30-50 cm			
27	50-80 cm			
28	80-100 cm			
29	0-30 cm	FDA thottam (TNFD) inside the Krishnan kovil (**Kodaikanal)**	N 10° 23’ 53.7” E077° 42’ 78.0” 2213 m	*Acacia mearnsii* invaded grass land
30	30-50 cm			
31	50-80 cm			
32	80-100 cm			
33	0-30 cm	Near Water flow after Krishnan temple (**Kodaikanal)**	N 10° 14’ 23.3” E077° 25’ 20.1” 2193 m	Shola forest
34	30-50 cm			
35	50-80 cm			
36	80-100 cm			
37	0-30 cm	Near Water flow after Krishnan temple (**Kodaikanal)**	N 10° 24’ 02.4” E077° 42’ 22.9” 2201 m	Shola forest
38	30-50 cm			
39	50-80 cm			
40	80-100 cm			
41	0-30 cm	Near Mahalakshmi kovil (**Kodaikanal)**	N 10° 14’ 56.5” E077° 24’ 53.5” 2194 m	*Acacia mearnsii* invaded shola forest
42	30-50 cm			
43	50-80 cm			
44	80-100 cm			
45	0-30 cm	Near Mahalakshmi kovil (**Kodaikanal)**	N 10° 24’ 86.8” E077° 41’ 46.0” 2103 m	*Acacia mearnsii* invaded shola forest
46	30-50 cm			
47	50-80 cm			
48	80-100 cm			

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