Research paper

Soil Nutrient Status and Its Impact on the Growth of Three *Rhododendron* Species in a Temperate Forest of the Eastern Himalayas, India

Sanjeeb Bharali,[1,4] Ashish Paul,[2] Mohamed Latif Khan[3]

【Summary】

Soils within forests not static but rather are dynamic in space and time, and they play key roles in plant growth and species' distributions within the forest. The present study examined variations in soil physicochemical properties in space and time and their impacts on the growth of 3 *Rhododendron* species in a temperate forest of the eastern Himalayas. Soil samples collected from different soil depths were analyzed on a seasonal basis for 2 consecutive years from 3 different study sites along an elevational gradient. To study the impacts of soil properties on growth, 3 *Rhododendron* species were selected: *R. kendrickii*, *R. grande*, and *R. mechukae.* The growth of these 3 species was studied through random tagging at each study site. Seasonal growth in height and collar diameter was recorded at 4-mo intervals for a period of 2 yr. Correlation analyses were conducted to understand the impacts of soil parameters on rhododendron growth. Soil physicochemical properties showed significant variations with depth, season, and elevation. The growth in height of *R. kendrickii* and *R. grande* showed positive correlations with pH, while that of *R. mechukae* exhibited a negative correlation. On the other hand, pH exhibited positive correlations with growth in collar diameter for all selected rhododendrons. Moreover, growth in height and collar diameter of all selected rhododendrons showed negative correlations with the soil moisture content, organic carbon, and total nitrogen. Available phosphorus and exchangeable potassium exhibited positive correlations with growth of both height and collar diameter of all selected *Rhododendron* species. There was seasonal variability in nutrient availability at different elevations. The soil was more acidic at higher elevations, and organic matter accumulation affected the availability of various nutrients required by the plants. Further, the growth of the selected *Rhododendron* species was affected by the nutrient availability at different study sites.

Key words: season, depth, elevation, growth, variation.

Bharali S, Paul A, Khan ML. 2014. Soil nutrient status and its impact on the growth of three *Rhododendron* species in a temperate forest of the eastern Himalayas, India. Taiwan J For Sci 29(1):33-51.

---

[1] Department of Environmental Studies, North Eastern Hill Univ., Shillong 793 022, Meghalaya, India.

[2] Department of Botany, Rajiv Gandhi Univ., Doimukh 791 112, Arunachal Pradesh, India.

[3] Department of Botany, Dr. Hari Singh Gour Central Univ., Sagar 470 003, Madhya Pradesh, India.

[4] Corresponding author, e-mail:sanjeebbharali@yahoo.co.in 通訊作者。

Received July 2013, Accepted December 2013. 2013年7月送審 2013年12月通過。

研究報告

印度東喜馬拉雅山溫帶森林土壤養分狀態和對三種杜鵑生長之影響

Sanjeeb Bharali,[1,4) Ashish Paul,[2) Mohamed Latif Khan[3)

摘 要

森林土壤在時間和空間尺度上並非呈靜止狀態。森林土壤對森林內植物生長和樹種分佈有決定性之影響。本研究探討東喜馬拉雅山溫帶森林土壤物理和化學性質在空間和時間上之變異和對杜鵑生長之影響。依海拔高選擇三處不同土壤深度之試驗地，進行兩年期土壤季節性變化之分析和對三種杜鵑(*Rhododendron kendrickii*、*Rhododendron grande*和*Rhododendron mechukae*)生長之影響。兩年內每4個月進行樹高和胸高直徑之量測。相關分析顯示土壤物理和化學性質和土壤深度與海拔高均呈高度相關。*Rhododendron kendrickii*和*Rhododendron grande*高生長和土壤pH呈正相關而*Rhododendron mechukae*高生長與土壤pH呈負相關。另一方面，3種杜鵑之直徑生長均顯示與土壤pH呈正相關。此外，3種杜鵑之高生長和直徑生長，均顯示與土壤濕度、土壤有機碳和總氮量呈負相關，但均顯示與磷和交換性鉀呈正相關。土壤養分季節性之變異在不同海拔處有不同之變化。海拔較高之處土壤較酸，累積之有機物質會影響植物生長所需之各種養分，所選之3種杜鵑生長均受到不同地區所含土壤養分之影響。

關鍵詞：季節、深度、海拔、生長、變異。

Bharali S、**Paul A**、**Khan ML**。2014。印度東喜馬拉雅山溫帶森林土壤養分狀態和對三種杜鵑生長之影響。台灣林業科學29(1):33-51。

INTRODUCTION

Changes in vegetation and climate are fundamental characteristics of mountain ecosystems, and result in variations in microclimates. Differences in the insolation period occur depending on the site aspect, thereby forming a range of microclimates in multifaceted landscapes. The microclimate is linked to soil moisture and the distribution of particular plant communities (Holland and Steyn 1975). Elevational gradients create various climates, and along with resultant soil differentiation, promote the diversification of plant species (Brown 2001, Lomolino 2001). There are spatial and temporal variations in physicochemical characteristics of forest soils due to variations in topography, climate, physical weathering processes, vegetative cover, microbial activities, and several other biotic and abiotic variables (Paudel and Sah 2003). According to Whittaker (1975) elevationally defined climatic and soil factors are considered to be primary determinants of changes in species composition and community structure in montane areas. Elevation itself represents a complex combination of related climatic variables closely correlated with numerous other environmental properties like soil texture, nutrients, substrate stability, etc. (Ramsay and Oxley 1997). At 1 elevation, cofactors like topography, aspect, inclination of the slope, and soil type further affect the forest composition (Holland and Steyn 1975). The vegetation of an area in turn plays an important role in the process of soil formation (Chapman and Reiss 1992).

Among various microenvironmental factors, soil nutrients are key factors affecting plant growth and species' distributions within a forest (Brunner et al. 1999, Molles 2002). Soils within forests are not static but instead are dynamic in space and time. Plant tissues of both the aboveground litter and belowground root detritus are the main sources of soil organic matter (SOM), which influences physicochemical characteristics of soils such as the pH, water-holding capacity (WHC), texture, and nutrient availability (Johnston 1986). The large increase in organic matter from woody debris results in "fertilization" of the forest floor, which adds to the elemental pools available for release by decomposers (Likens et al. 1978). Moreover, other processes such as evapotranspiration, decomposition, and nitrogen transformation also change (Witkamp 1971, Likens et al. 1978) along elevational gradients. The importance of nutrient factors in a community or region depends on their amounts and distributions (Saarsalmi et al. 2001). Nutrient supplies vary widely among ecosystems (Binkly and Vitousek 1989), resulting in differences in plant community structure and production (Ruess and Innis 1977). Many workers concluded that forest soils influence the composition of forest stands and ground cover, the rate of growth, and the vigor of natural reproduction (Bhatnagar 1965, Paudel and Sah 2003).

Rhododendron species act as keystone species in high-elevation regions of the eastern Himalayas and thus maintain biological communities in this fragile region. They form a wide variety of forests in temperate, sub-alpine, and alpine regions that support a large range of biodiversity, which provides food and shelter to wildlife, and also stabilize montane soil profiles and prevent soil erosion. Apart from these beneficial services, rhododendrons also have good horticultural value. Therefore, it is of utmost importance to assess the growth behaviors of rhododendrons with respect to elevation and soil parameters. Although many studies have been carried out in Arunachal Himalaya (Behera et al. 2002, Paul 2008), no study has been conducted to understand variations in soil parameters and their impacts on rhododendron growth along an elevational gradient. In light of this, in the present study, we examined (i) variations in soil physicochemical properties in space and time and (ii) their impacts on the growth of 3 *Rhododendron* species.

MATERIALS AND METHODS

Study site

The study was carried out in a temperate rhododendron forest in West Siang District of Arunachal Pradesh, India. Three sampling sites were selected along an elevational gradient at Shegong (1900~2100 m), Hanuman Camp (2100~2300 m), and Yarlung (> 2300 m). The study sites are within the Himalayan range and are characterized by rough topography with mountains, deeply incised valleys, escarpments, and plateaus. Broadly, the rock types of the study sites can be categorized into 2 distinct groups of (i) metasedimentaries and (ii) gneisses. According to climatic conditions, 4 distinct seasons can be characterized at the study sites. In December to February, representing winter, maximum snowfall takes place and temperatures drop below freezing. March to May represents spring with little rain, whereas June to September with the maximum total annual rainfall represents the rainy season (monsoon), and October to November represents autumn (post-monsoon) with few showers. Forests have sparse canopies, and the floor is covered with spongy humic layers. The dominant tree species of the study sites are *R. grande*, *R. kendrickii*, *Taxus wallichiana*, *Abies* spp., *Illicium griffithii*, and *Pinus wallichiana*.

Soil sampling and processing

Soil samples were collected in winter, summer, and the rainy seasons for 2 consecutive years. Triplicate samples were collected from 3 different depths (0~10, 10~20, and 20~30 cm) with a soil corer (5.5 cm in diameter) at each study site. Replicate samples at a given depth at each study site were thoroughly mixed to obtain a composite sample. Samples for bulk density were collected at each depth from respective study sites. Samples were collected in air-tight polythene bags and taken to the laboratory. In the laboratory after determining the moisture content, the soil samples were air-dried, crushed, and sieved through a 2-mm mesh sieve to remove stone particles and gravel and then passed through a 0.5-mm mesh screen for analyzing various physical and chemical properties. The soil texture, bulk density, soil porosity, and water-holding capacity (WHC) were analyzed once, whereas soil moisture, pH, organic carbon (SOC), total nitrogen, available phosphorus, and exchangeable potassium were analyzed on a seasonal basis.

Physical properties

The soil texture was determined by the hydrometer method described by Bouyoucos (1962). The soil bulk density and porosity were determined by following the methodology of Allen et al. (1974). The WHC was determined by Keen's box method (Piper 1942). The soil moisture content was determined gravimetrically, while the pH was determined electrometrically with a digital pH meter (Systronics-335, Ahmedabad, India) in a 1: 2.5 suspension of soil in deionized water (Anderson and Ingram 1993).

Chemical properties

SOC was determined according to Walkley and Black's (1934) rapid titration method. Total Kjeldahl nitrogen (TKN) was determined in a Kjeldahl nitrogen analyzer (Kjeldahl apparatus consisting of a KELPLUS KES 12L digestion block, KELPLUS KEL VAC suction unit, and KELPLUS DISTYL-EM distillation unit; Pelican, Chennai, India) following Allen et al. (1974). Available phosphorus was extracted from the soil using the Bray and Kurtz no. 1 procedure (Bray and Kurtz 1945) and estimated in a spectrophotometer (Systronics UV Visible Spectrophotometer 117, Ahmedabad, India). Exchangeable soil potassium was determined by extracting soils using 1 M ammonium acetate solution buffered to pH 7.0, followed by measuring the potash (Allen et al. 1974) in the extracts on a flame photometer (Systronics Flame Photometer 130, Ahmedabad, India). Each analysis was performed in triplicate, and the results are expressed in percentage.

All data were statistically analyzed using STATISTICA 6 (StatSoft, Inc. 2001) and interpreted accordingly.

Impacts of soil properties on rhododendron growth

To study the impacts of soil properties on growth, 3 *Rhododendron* species were selected: *R. kendrickii* Nutt., *R. grande* Wight, and *R. mechukae* Mao & Paul. Of these 3 species, *R. kendrickii* is the dominant species at Shegong, whereas *R. grande* dominates the Hanuman Camp site, and *R. mechukae* dominates at Yarlung. However, *R. mechukae* does not occur at Shegong. The growth of rhododendrons was studied through random tagging of 30 healthy, uniform individuals (of 1.5~2 m in height and 15~20 mm in collar diameter) of each species at all study sites. The seasonal growth in terms of height and collar diameter was recorded at 4-mo interval for a period of 2 yr (November 2008 to November 2010). The impact of soil parameters on the growth of these rhododendrons was studied using correlation analyses.

RESULTS

Bulk density and porosity

Soil bulk density at different depths and at the 3 study sites significantly varied (F = 928.85 and 70.13, respectively, $p < 0.001$). Bulk density increased with depth and elevation. On the other hand, porosity decreased with depth and elevation (Table 2).

WHC

The WHC of the soils did not show significant variations among sites. However, it significantly declined ($F = 74.0$, $p < 0.001$) with depth (Table 2).

Soil texture

Soil particle sizes showed a sandy-clay loam texture at respective depths and all study sites (Table 2).

Moisture content

The soil moisture content significantly differed (F = 118.4, 46.9, and 727.7, respectively, $p < 0.001$) at various soil depths, study sites, and sampling periods. It was significantly high in the upper soil layer and at higher elevations. Moreover, the highest soil moisture content was recorded during the rainy season (Fig. 1).

pH

Soils at all study sites were acidic in nature, ranging 3.83~4.98. The soil pH at different depths, study sites and sampling season significantly differed (F = 140.9, 373.4, and 133.4, respectively, $p < 0.001$). The soil pH gradually increased with depth, while it decreased with elevation (Fig. 2). The maximum soil pH was recorded in winter, and the minimum in the rainy season at all study sites.

SOC

SOC was found to be significantly higher ($F = 103.9$, $p < 0.001$) during the rainy season at all study sites (Fig. 3). It significantly increased with elevation and decreased with

Table 2. Physical properties of soils at the 3 study sites

Study site	Depth (cm)	Bulk density (g cm^{-3})	Porosity (%)	WHC (%)	Percentage of soil particles			Textural class
					Sand	Silt	Clay	
Shegong	0~10	0.65±0.00	75.60±0.13	73.47±2.66	79.79±0.01	0.20±0.00	20.01±0.01	Sandy clay loam
	10~20	0.89±0.04	66.54±1.33	66.27±1.04	79.77±0.01	0.20±0.00	20.03±0.01	Sandy clay loam
	20~30	0.96±0.03	63.65±0.98	51.86±2.16	79.77±0.01	0.20±0.01	20.03±0.01	Sandy clay loam
Hanuman Camp	0~10	0.68±0.01	74.47±0.55	75.86±2.07	79.77±0.01	0.20±0.01	20.03±0.01	Sandy clay loam
	10~20	1.04±0.04	60.63±1.33	61.69±2.12	79.77±0.01	0.21±0.01	20.03±0.01	Sandy clay loam
	20~30	1.25±0.04	52.70±1.48	56.50±2.48	79.83±0.01	0.14±0.01	20.03±0.01	Sandy clay loam
Yarlung	0~10	0.58±0.05	78.24±1.76	78.33±1.84	77.78±0.01	2.21±0.01	20.01±0.01	Sandy clay loam
	10~20	1.18±0.07	55.60±2.60	62.45±2.44	77.79±0.01	2.21±0.01	20.01±0.01	Sandy clay loam
	20~30	1.26±0.04	52.33±1.65	54.38±2.44	77.79±0.01	2.18±0.00	20.03±0.01	Sandy clay loam

Data are presented as the mean±standard error ($n = 3$).

WHC, water-holding capacity.

soil depth ($F = 196.48$ and 215.85, respectively, $p < 0.001$).

TKN

Soil total nitrogen contents (Fig. 4) at different depths, study sites, and sampling season significantly varied ($F = 235.79$, 70.44, and 41.84, respectively, $p < 0.001$). It decreased with soil depth and reached a maximum in the rainy season and a minimum in winter. Moreover, the total nitrogen content increased with elevation.

Available phosphorus

The soil available phosphorus exhibited a significant difference among sampling sea-

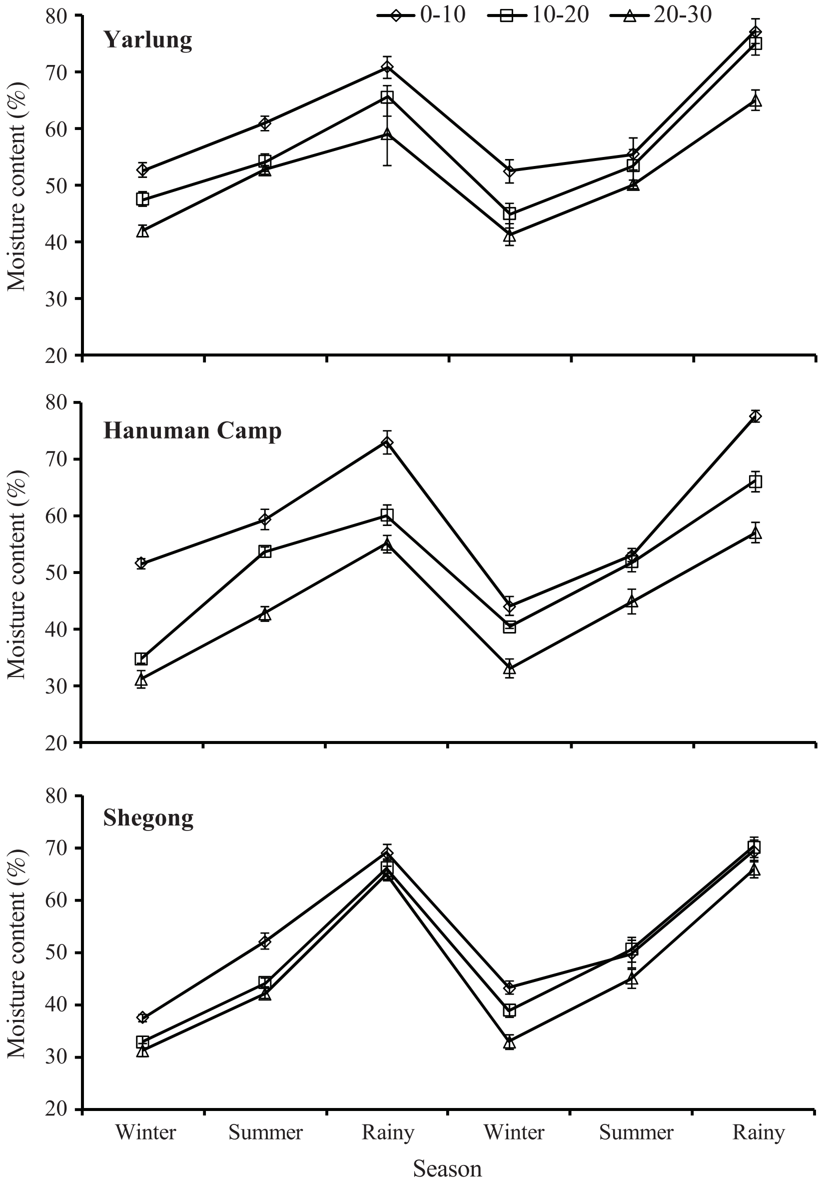

Fig. 1. Temporal variations in the soil moisture content (%) at the 3 study sites.

sons ($F = 67.8$, $p < 0.001$) and was the highest in summer (Fig. 5). Although it significantly declined ($F = 68.6$, $p < 0.001$) with depth, the difference between the top (0~10 cm) and bottom layers (20~30 cm) was clearer at Hanuman Camp. The soil available phosphorus significantly differed ($F = 35.8$, $p < 0.001$) among study sites. The maximum soil available phosphorus was recorded at Hanuman Camp, and the minimum at Yarlung.

Exchangeable potassium

Exchangeable potassium significantly differed ($F = 882.9$, 57.3, and 676.5, respectively, $p < 0.001$) with depth, site, and season (Fig. 6). The soil exchangeable potassium

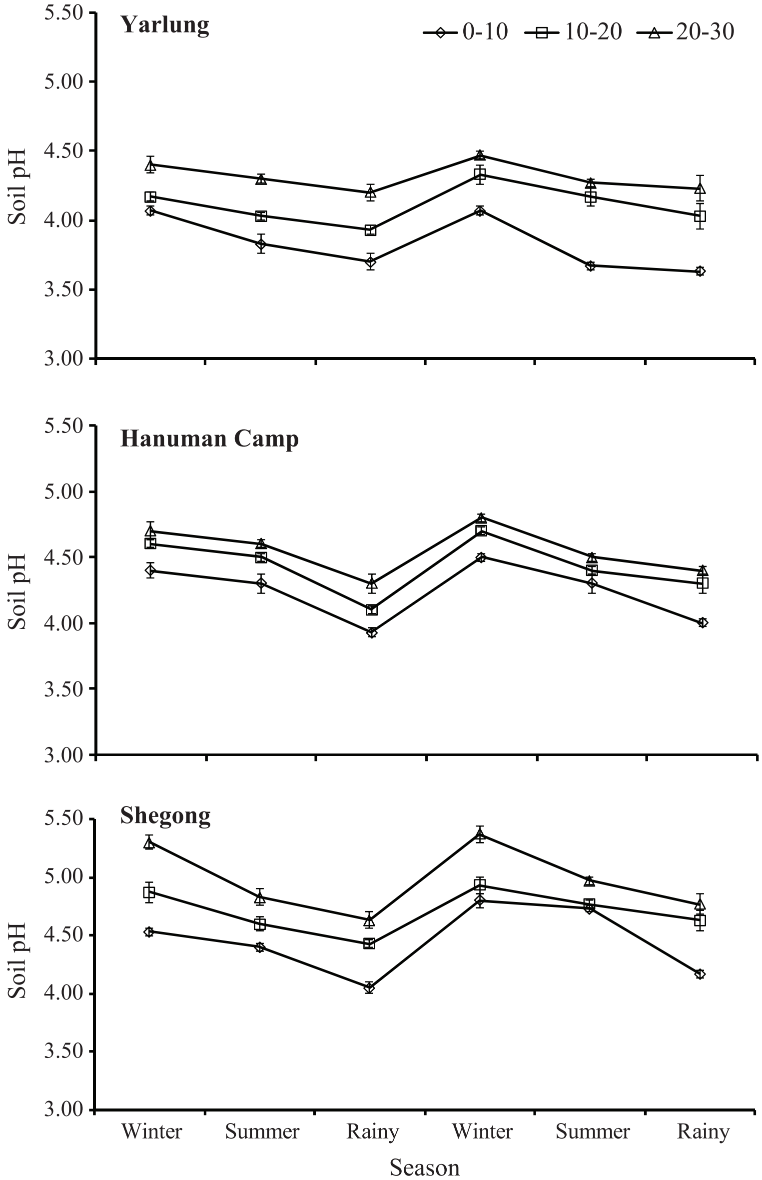

Fig. 2. Temporal variations in the soil pH at the 3 study sites.

was highest in the rainy season and lowest in winter, and decreased with depth at all study sites.

Impacts of soil parameters on growth

Total growth in height and collar diameter of the 3 selected *Rhododendron* species is presented in Table 3. The growth in height of *R. kendrickii* and *R. grande* was positively correlated with pH, while *R. mechukae* exhibited a negative correlation. On the other hand, pH was positively correlated with growth in collar diameter of all selected rhododendrons. Moreover, growth in height and collar diameter of all selected rhododendrons was negatively correlated with the soil moisture

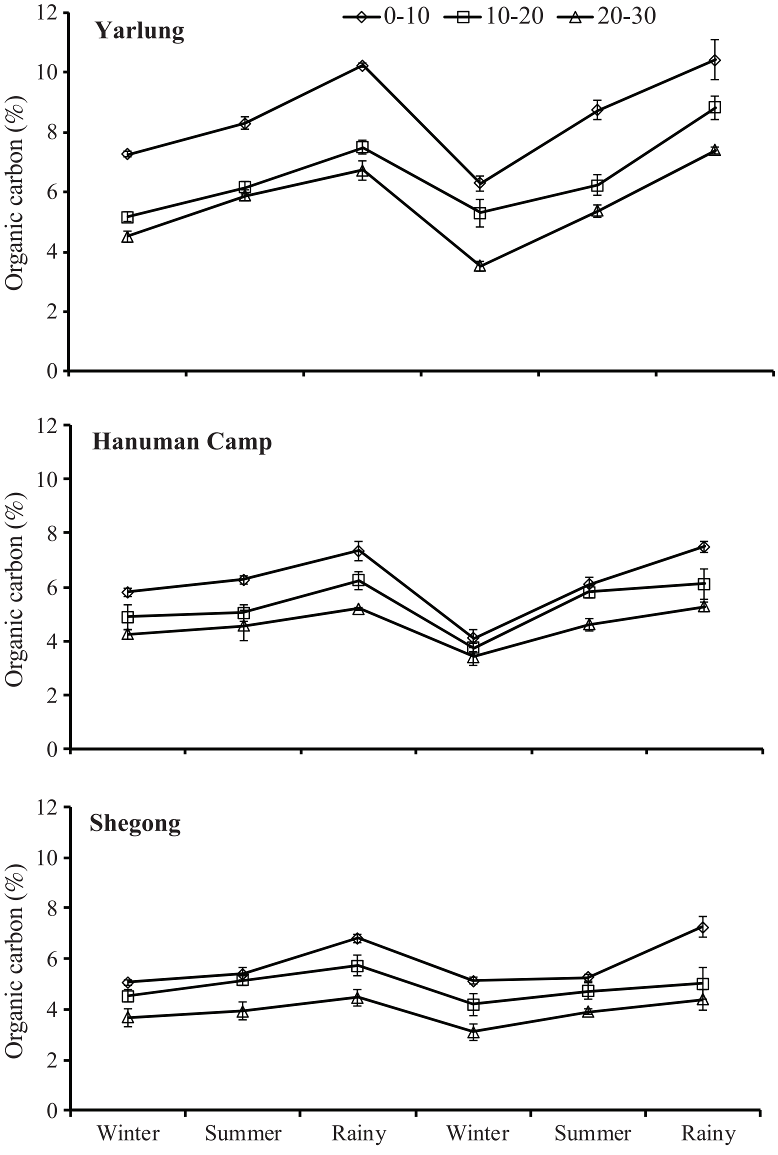

Fig. 3. Temporal variations in soil organic carbon (%) at the 3 study sites.

content, SOC, and total nitrogen. Available phosphorus and exchangeable potassium were positively correlated with growth in both height and collar diameter of all selected *Rhododendron* species. Figures 7 and 8 show scatterplots of correlations between growth in height and collar diameter, respectively, with soil physicochemical parameters.

DISCUSSION

A gradual increase in bulk density with soil depth was due to compaction of soils in the study area. A low bulk density in the surface layer may be due to a high concentration of roots, which loosen the soil (Aweto 1981). The soil porosity decreased with depth. This

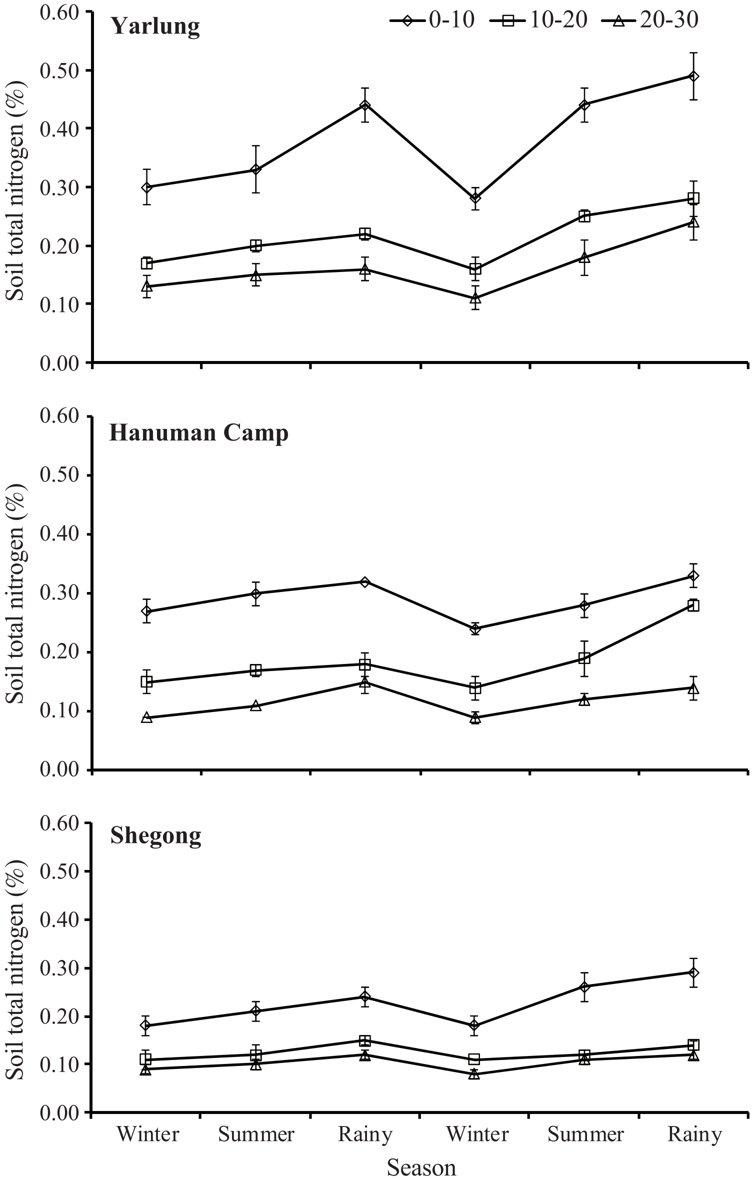

Fig. 4. Temporal variations in soil total nitrogen (%) at the 3 study sites.

shows that as the soil compactness increased, porosity decreased. Soil organic matter was reported to improve the availability of water and minimize the compactness of soils (Sands 1983, Squire 1983). The WHC decreased with depth, which could have been due to the occurrence of a high amount of organic matter on the surface soil layer that helps to retain water. Moreover, the WHC depends on the soil texture. The soil texture affects plant growth by affecting soil water and the soluble nutrient supply. Water infiltration is more rapid in very coarse-textured soils, and plants suffer due to a lack of an appropriate WHC in such soils (Gupta et al. 2010). In the present study, the soil texture was found to be

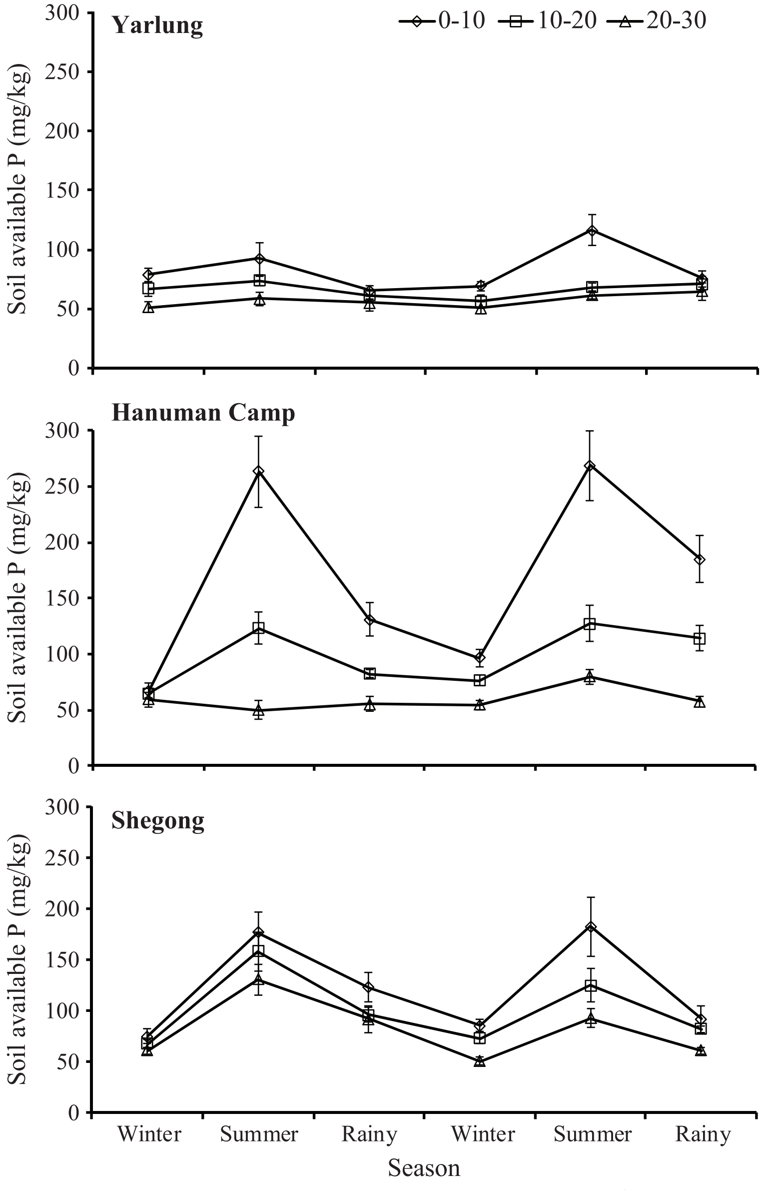

Fig. 5. Temporal variations in soil available phosphorus (P; mg kg^{-1}) at the 3 study sites.

sandy clay loam at all depths and study sites. In general, the study area was rocky in nature, and this may have been due to the fact that the soils had a higher percentage of sand. Soil texture, especially with a higher sand content, is important for a better WHC (Walter 1985), because of its buffering effect on evaporation, as water is able to infiltrate to sub-soil layers.

The soil moisture content is very dependent on the organic matter content of the soil. It was found that with increasing depth, the soil moisture content decreased. Further, it was found that the soil moisture content increased with increasing elevation. There was also a seasonal variation in the moisture content. This was due to variations in rainfall and

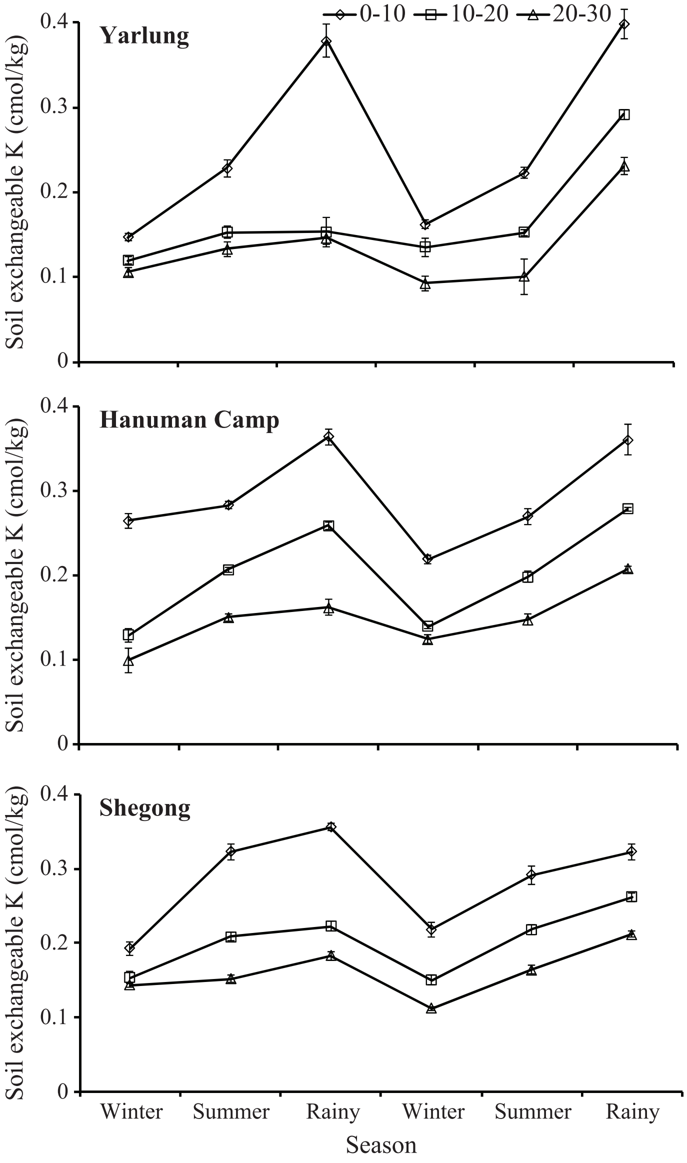

Fig. 6. Temporal variations in soil exchangeable potassium (K; cmol kg^{-1}) at the 3 study sites.

Table 3. Average annual growth of 3 *Rhododendron* species at the 3 study sites

Study site	*R. kendrickii*		*R. grande*		*R. mechukae*	
	Ht (cm)	CD (mm)	Ht (cm)	CD (mm)	Ht (cm)	CD (mm)
Shegong	5.75±0.30	5.03±0.15	4.71±0.16	4.60±0.14	–	–
Hanuman Camp	4.53±0.21	4.73±0.13	5.30±0.14	4.77±0.18	3.85±0.16	4.29±0.16
Yarlung	3.96±0.16	4.43±0.17	4.02±0.14	3.58±0.15	4.96±0.22	3.46±0.16

Data are presented as the mean±standard error ($n = 30$).
Ht, height; CD, collar diameter.

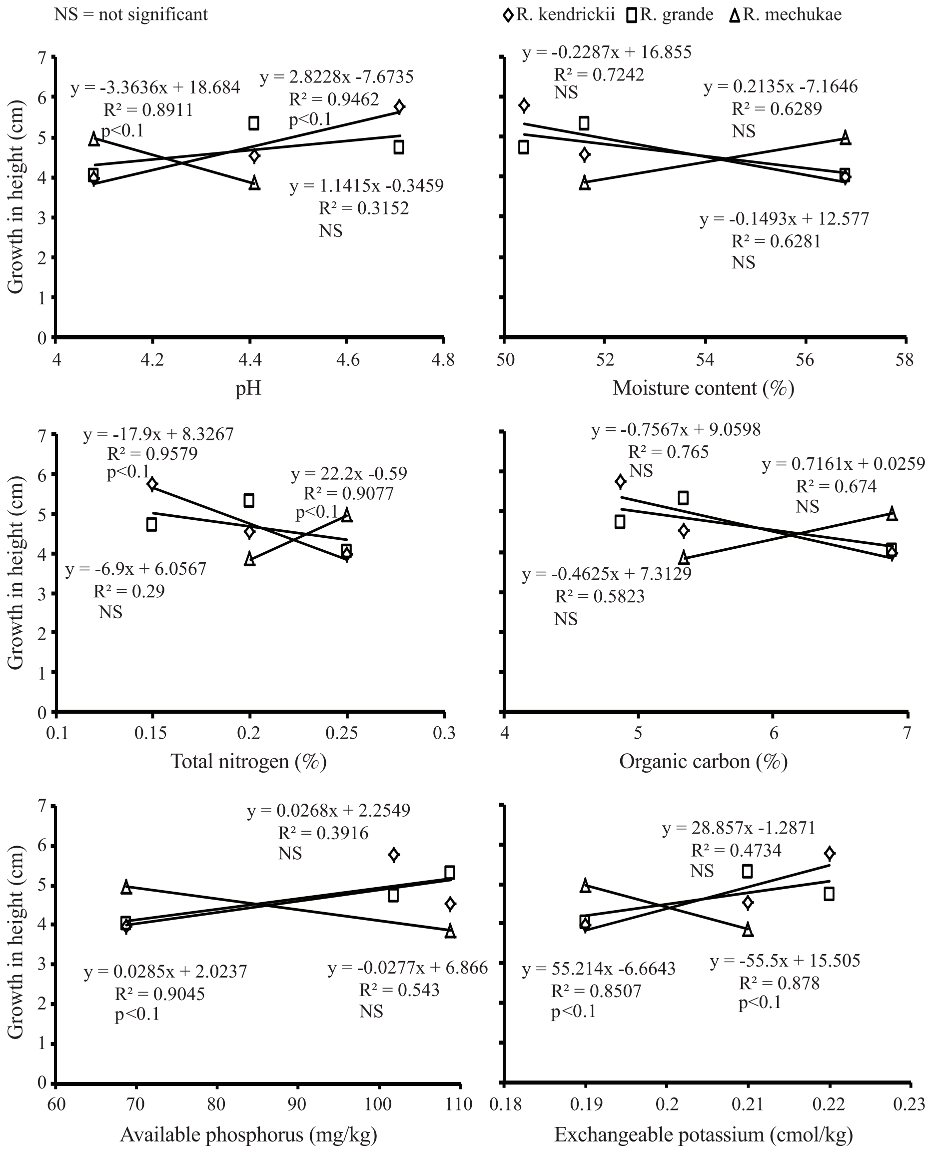

Fig. 7. Scatterplots showing relationships between soil physicochemical properties and growth in height of the 3 *Rhododendron* species.

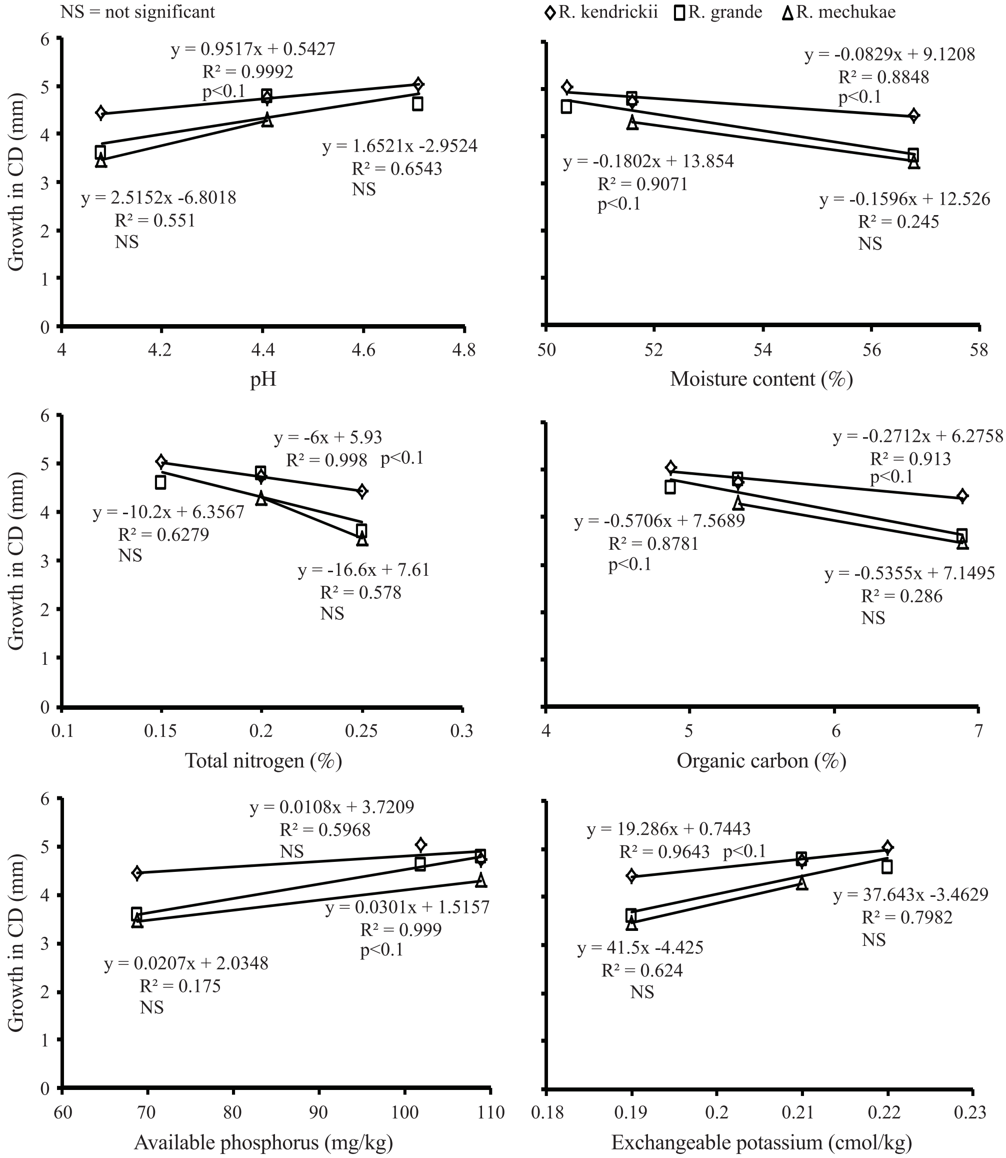

Fig. 8. Scatterplots showing relationships between soil physicochemical properties with growth of the collar diameter of the 3 *Rhododendron* species.

temperature. The highest soil moisture content was recorded in the rainy season, while it was lowest in the dry season. Singha (2005) also reported similar results of variations in moisture content with depth and season from temperate and sub-alpine bamboo forests of Western Arunachal Pradesh, India. Sharma et al. (2009) reported a rise in soil moisture content with increasing elevation and a gradual reduction in moisture with depth in a temperate broadleaf forest of Garhwal Himalaya. Similarly, Shrestha et al. (2007) also reported increasing soil moisture with elevation. Majila and Kala (2010) also emphasized the importance of air temperature and soil moisture content for forest tree distribution and structural changes of the forest along an elevational gradient on dry valley slopes of the Himalayas. Esen (2000) concluded from his study on the ecology of *R. ponticum* that soil moisture was the most important environmental factor shaping rhododendron abundance and growth in a Turkish eastern beech forest.

The pH of the soil at the study sites was acidic in nature. The low soil pH and acidic soils are typical conditions in places where ericaceous plants are dominant (Kaisheva 2006). There was an increase in the pH with depth, while the pH decreased with increasing elevation. Shrestha et al. (2007) also reported decreasing pH with increasing elevation in a birch (*Betula utilis* D. Don) forest in a trans-Himalayan dry valley in central Nepal. Generally, evergreen shrubs that grow in cold, mesic climates, including rhododendron, typically contain high concentrations of organic acids in their leaves and wood (Read 1984, Latham et al. 1996). The addition of exudates of these organic acids to the soil and the cold, mesic character of the weather decrease the rate of decomposition in the soil, resulting in debris accumulation on the forest floor over time (Pritchett and Fisher 1987, Biswas and Mukherjee 1994), which ultimately reduces the pH of the soil. Moreover, the pH considerably decreased during the late summer and rainy season, which may have been caused by the loss through leaching of basic cations due to the heavy rainfall in this period.

SOC at all study sites in the present study varied with space and time. The SOC content increased with elevation, while it decreased with soil depth at all study sites. On the contrary, Sheikh and Kumar (2010) reported a decrease in SOC with elevation in an oak and pine forest of Garhwal Himalaya. However, Du et al. (2011) reported a significant increase in SOC with elevation, while there was a gradual reduction in SOC with depth in the Lushan Mountains, China. Zhang et al. (2009) also reported similar results from the Qilian Mountains, China. The decrease in SOC with soil depth can be attributed to greater compactness, and reduced aeration and moisture content with depth, which eventually retard decomposition processes by soil microbes. Many other authors reported reduced SOC with depth from different temperate forests (Sundriyal and Sharma 1996, Sharma et al. 2009, Sheikh et al. 2009, Singh et al. 2011). Moreover, the SOC content was highest during the rainy season, while it was lowest in winter. This may have been due to favorable moisture and temperature conditions for microbial activity which increased the rate of decomposition in the rainy season (Wang et al. 2000). SOM also has multiple effects on soils, such as the soil's physical structure, the storage of nutrients, aeration, and stimulation of microbial activities (Tate 1987) and may affect 2 important factors of nutrients and soil moisture, which are important aspects affecting patterns of species richness (Peet 1978, de Lafontaine and Houle 2007).

Like SOC, the total nitrogen content of the soil decreased with soil depth. Similar results were also reported from temperate forests elsewhere (Berger et al. 2002, Sharma et al. 2009). This might be because in the top soil layer, there are more litter fall, fine roots, and soil microorganisms, and they can increase the content of nitrogen. Moreover, the nitrogen content increased with elevation. Zhang et al. (2009) and Zhang and Zhang (2011) also respectively reported an increase in total nitrogen with elevation and a reduction with depth at Quilian Mountain and Lishan Mountain Nature Reserve, China. There was also a seasonal variation in the soil total nitrogen content, with the maximum being recorded in the rainy season. Spatial and temporal variations in total nitrogen depend on many factors, like temperature, moisture, microbes etc. The vegetation can influence the spatial and temporal variability of soil nitrogen through the quality and quantity of litter fall as an input to soil nitrogen (Marinari et al. 2010, Roy et al. 2010). The distribution of fine roots of plants can affect the quantity of the soil total nitrogen and of other important nutrients in each soil layer. Moreover, when the soil depth increases, amounts of soil microorganisms decrease, and as a result, decomposition activity weakens, which ultimately leads to reduced nutrient contents in the soil (Berger et al. 2002).

Both available phosphorus and exchangeable potassium decreased with depth, and the highest values were recorded in the rainy season, but neither showed a definite elevational trend. In contrast, Sundriyal and Sharma (1996) reported an increasing trend of available phosphorus with soil depth in a temperate forest of the Mamlay watershed in Sikkim. As discussed above, variations in these 2 nutrients with depth and season are also mainly controlled by the quality and quantity of organic matter and microbial activity. The amounts of phosphorus and potassium recorded in the present study were very low, and the lowest value was recorded from the study site at the highest elevation. It was previously reported that almost all soils in Arunachal Pradesh are low in available phosphorus and high in organic carbon content compared to those in other neighboring states (Mishra et al. 2004). Nilsen et al. (2001) also reported very low contents of available phosphorus and exchangeable potassium in forests of northern red oak (*Quercus rubra*) with thickets of *R. maximum* in the sub-canopy. Although soil mineral particles are naturally rich in phosphorus and potassium, they are readily available to plants in trace amounts. Moreover, it was reported that the phosphorus and potassium in soils are commonly considered to be most available at pH values near 6.5, with the availability decreasing at both lower and higher pH values (Bates and Johnston 1991). The lower contents of soil available phosphorus and exchangeable potassium in the present study may have been due to the acidic nature of the soils.

The present study revealed that the growth in height and collar diameter of all selected rhododendrons was positively correlated with soil pH. Reiley (1995) stated that rhododendrons are best raised in environments where the soil pH is 4.5~5.5. With an increase in the pH, growth of the studied rhododendrons increased. Pausas and Austin (2001) also emphasized the importance of pH to nutrient availability in soils and growth of plant species. On the other hand, the soil moisture content, SOC, and total nitrogen content were negatively correlated with growth of all selected rhododendrons. As mentioned above, SOM has multiple effects on soils through affecting the moisture content and availability of nutrients for plant growth. Although the total nitrogen content in the soil increased with elevation, most of it was in organic forms. However, plants are able to use only very specific inorganic forms of nitrogen (NO_3, and NH_4). The reduced growth of all selected rhododendrons at higher elevations may have been due to depleted nutrient availability. Wilcke et al. (2008) also concluded that the reduced tree growth rate at higher elevations might be due to nutrient deficiencies, possibly caused by reduced turnover of organic matter. On the other hand, it was found that the growth of all selected rhododendrons was positively correlated with available phosphorus and exchangeable potassium. All selected rhododendrons showed higher growth at lower elevations. As in the lower elevation in the present study, organic matter accumulation was less due to rapid decomposition processes, and most of the nutrients required by plant species were readily available for uptake. Bot and Benites (2005) also emphasized the importance of organic matter decomposition and the release of nutrients in forms available to plants. Every plant species has some optimum requirements of nutrients and other growth conditions, and beyond this optimal level, growth and development are affected. The higher growth of *R. kendrickii* and *R. grande* at Shegong and Hanuman Camp, respectively, may have been due to the availability of optimal growth conditions such as moisture, temperature, and nutrients at these study sites. On the other hand, lower growth of these 2 species at the higher elevation may have been due to a lack of available nutrients for their growth and lower temperatures. Soethe et al. (2008) reported that there was reduced availability of nutrients to plants at higher elevations, in spite of higher nutrient stocks of organic matter present in a tropical montane forest of Ecuador, which may have been due to the lower soil pH, lower temperatures, and less oxygen availability. Many other workers also reported similar reduced nutrient availability for plant species at higher elevations (Wilcke et al. 2002, Wegner et al. 2003, McGroddy et al. 2004, Soethe et al. 2006). *Rhododendron mechukae* may require relatively low temperatures and nutrients for growth compared to the other 2 *Rhododendron* species; hence, it showed differential growth of height and collar diameter at Hanuman Camp and Yarlung.

CONCLUSIONS

From the above study, it was found that physicochemical properties of the soil varied along an elevational gradient. Moreover, the chemical properties of the soil significantly varied among the different seasons. The soil was more acidic at higher elevations, and the organic matter accumulation affected the availability of various nutrients required by the plants. Further, the growth of the selected *Rhododendron* species was affected by nutrient availability at different study sites. Moreover, it was found that the growth of rhododendrons is directly affected by the soil pH.

ACKNOWLEDGEMENTS

The authors thank the PCCF of Arunachal Pradesh for the research permit and the villagers for help and cooperation during the field surveys. The corresponding author thankfully acknowledges the financial support provided by Univ. Grant Commission, GOI, through the Rajiv Gandhi National Fellowship.

LITERATURE CITED

Allen SE, Grimshaw HM, Parkinson JA, Quarmby C. 1974. Chemical analysis of ecological materials. Oxford, UK: Blackwell Scientific Publications. 565 p.

Anderson JM, Ingram JSI. 1993. Tropical soil biology and fertility – a handbook of methods. 2nd edition. Wallingford, UK: CAB International. 221 p.

Aweto AO. 1981. Secondary succession and soil fertility restoration in south-western Nigeria. J Ecol 60(2):609-14.

Bates TE, Johnston RW. 1991. Soil acidity and liming. Ontario, Canada: Ontario Ministry of Agriculture and Food. 4 p.

Behera MD, Kushwaha SPS, Roy PS, Srivastava S, Singh TP, Dubey RC. 2002. Comparing structure and composition of coniferous forests in Subansiri District, Arunachal Pradesh. Curr Sci 82(1):70-6.

Berger TW, Neubauer C, Glatzel G. 2002.

Factors controlling soil carbon and nitrogen stores in pure stands of Norway spruce (*Picea abies*) and mixed species stands in Austria. For Ecol Manage 159(1/2):3-14.

Bhatnagar HP. 1965. Soils from different quality sal (*Shorea robusta*) forests of Uttar Pradesh. Trop Ecol 6:56-62.

Binkley D, Vitousek PM. 1989. Soil nutrient availability. In: Pearey RW, Ehleringer NA, Mooney, Rundel PW, editors. Plant physiological, field methods and instrumentation. London: Chapman and Hall. p 75-96.

Biswas TD, Mukherjee SK. 1994. Text book of soil science. 2nd edition. New Delhi: Tata McGraw-Hill Education. 433 p.

Bot A, Benites J. 2005. The importance of soil organic matter: key to drought resistant soil and sustained food production. FAO Soils Bulletins 80. Rome, Italy: Food and Agriculture Organization (FAO) of the United Nations. 78 p.

Bouyoucos GJ. 1962. Hydrometer method improved for making particle size analyses of soils. Agron J 54(5):464-5.

Bray RH, Kurtz LT. 1945. Determination of total organic and available forms of phosphorus in soils. Soil Sci 59(1):39-46.

Brown J. 2001. Mammals on mountainsides: elevational patterns of diversity. Global Ecol Biogeogr 10(1):101-9.

Brunner I, Rigling D, Egli S, Blaser P. 1999. Response of Norway spruce seedlings in relation to chemical properties of forest soils. For Ecol Manage 116(1-3):71-81.

Chapman JL, Reiss MJ. 1992. Ecology: principles and applications. Cambridge, UK: Cambridge Univ. Press. 294 p.

de Lafontaine G, Houle G. 2007. Species richness along a production gradient: a multivariate approach. Am J Bot 94(1):79-88.

Du YX, Wu CJ, Zhou SX, Huang L, Han SM, Xu XF, Ding Y. 2011. Forest soil organic carbon density and its distribution characteristics along an altitudinal gradient in Lushan Mountains of China. Chin J Appl Ecol 22(7):1675-81.

Esen D. 2000. Ecology and control of rhododendron (*Rhododendron ponticum* L.) in Turkish eastern beech (*Fagus orientalis* Lipsky) forests. PhD thesis. Blacksburg, VA: Virginia Polytechnic Institute and State Univ. 112 p.

Gupta RD, Arora S, Gupta GD, Sumberia NM. 2010. Soil physical variability in relation to soil erodibility under different land uses in foothills of Siwaliks in N-W India. Trop Ecol 51(2):183-97.

Holland PG, Steyn DG. 1975. Vegetational responses to latitudinal variations in slope angle and aspect. J Biogeogr 2(3):179-83.

Johnston AE. 1986. Soil organic matter; effects on soil and crops. Soil Use Manage 2(3): 97-105.

Kaisheva MV. 2006. The effect of metals and soil pH on the growth of *Rhododendron* and other alpine plants in limestone soil. PhD thesis. Edinburgh, UK: Univ. of Edinburgh. 360 p.

Latham RE, Thompson JE, Riley SA, Wibiralske AW. 1996. The Pocono till barrens: shrub savanna persisting on soils favoring forest. B Torrey Bot Club 123(4):330-49.

Likens GE, Bormann FH, Pierce RS, Reiners WA. 1978. Recovery of a deforested ecosystem. Science 199(4328):492-6.

Lomolino MV. 2001. Elevation gradients of species-density: historical and prospective views. Global Ecol Biogeogr 10(1):3-13.

Majila BS, Kala CP. 2010. Forest structure and regeneration along the altitudinal gradient in the Binsar Wildlife Sanctuary, Uttarakhand Himalaya, India. Russ J Ecol 41(1):75-83.

Marinari S, Lagomarsino A, Moscatelli MC, Di Tizio A, Campiglia E. 2010. Soil carbon and nitrogen mineralization kinetics in organic and conventional three-year cropping system. Soil Till Res 109(2):161-8.

Mcgroddy ME, Daufresne T, Hedin LO. 2004. Scaling of C:N:P stoichiometry in forests worldwide: implications of terrestrial red field-type ratios. Ecology 85(9):2390-401.

Mishra AK, Bundela DS, Satapathy KK. 2004. Analysis and characterization of rice environment of Arunachal Pradesh. ENVIS Bull Himal Ecol 12(1):12-24.

Molles MC. 2002. Ecology: concepts and applications. 2nd edition. Singapore: McGraw-Hill. 586 p.

Nilsen ET, Clinton BD, Lei TT, Miller OK, Semones SW, Walker JF. 2001. Does *Rhododendron maximum* L. (Ericaceae) reduce the availability of resources above and below ground for canopy tree seedlings? Am Midl Nat 145(2):325-43.

Paudel S, Sah JP. 2003. Physiochemical characteristics of soil in tropical sal (*Shorea robusta* Gaertn.) forests in eastern Nepal. Himal J Sci 1(2):107-10.

Paul A. 2008. Studies on diversity and regeneration ecology of rhododendrons in Arunachal Pradesh. PhD thesis. Assam, India: Assam Univ. 213 p.

Pausas JG, Austin MP. 2001. Patterns of plant species richness in relation to different environments: an appraisal. J Veg Sci 12(2):153-66.

Peet RK. 1978. Forest vegetation of Colorado Front Range – patterns of species diversity. Vegetatio 37(2):65-78.

Piper CS. 1942. Soil and plant analysis. New York: Inter Science Publishers. 368 p.

Pritchett WL, Fisher RF. 1987. Properties and management of forest soils. 2nd edition. New York: J Wiley. 494 p.

Ramsay PM, Oxley ERB. 1997. The growth form composition of plant communities in the Ecuadorian paramos. Plant Ecol 131(2):173-92.

Read DJ. 1984. Interactions between ericaceous plants and their competitors with special reference to soil toxicity. Aspects Appl Biol 5:195-209.

Reiley EH. 1995. Success with rhododendrons and azaleas. Portland, OR: Timber Press. 285 p.

Rey A, Jarvis PG. 1997. Growth response of young birch trees (*Betula pendula* Roth.) after four and a half years of CO_2 exposure. Ann Bot 80(6):809-16.

Roy PK, Samal NR, Roy MB, Mazumder A. 2010. Soil carbon and nutrient accumulation under forest plantations in Jharkhand state of India. Clean-Soil, Air, Water 38(8):706-12.

Ruess JO, Innis GS. 1977. A grassland nitrogen flow simulation mode. Ecology 58(2):379-88.

Saarsalmi A, Malkonen E, Piirainen S. 2001. Effects of wood ash fertilization on forest soil chemical properties. Silva Fenn 35(3):355-68.

Sands R. 1983. Physical changes to sandy soils planted to radiate pine. In: Ballurd L, Gessel SP, editors. IUFRO Symposium on Forest Site and Continuous Productivity. General Technical Report, PNW-163. Washington, DC: USDA Forest Service. p 146-52.

Sharma CM, Suyal S, Gairola S, Ghildiyal SK. 2009. Species richness and diversity along an altitudinal gradient in moist temperate forest of Garhwal Himalaya. J Am Sci 5(5):119-28.

Sheikh MA, Kumar M. 2010. Nutrient status and economic analysis of soils in oak and pine forests in Garhwal Himalaya. J Am Sci 6(2):117-22.

Sheikh MA, Kumar M, Bussmann RW. 2009. Altitudinal variation in soil organic carbon stock in coniferous subtropical and broadleaf temperate forests in Garhwal Himalaya. Carbon Balance Manage 4:6 doi: 10.1186/1750-0680-4-6.

Shrestha BB, Ghimire B, Lekhak HD, Jha PK. 2007. Regeneration of treeline birch (*Betula utilis* D. Don) forest in a trans-Himalayan dry valley in central Nepal. Mt Res Develop 27(3):259-67.

Singh SK, Pandey CB, Sidhu GS, Sarkar D, Sagar R. 2011. Concentration and stock of carbon in soil affected by land uses and climates in western Himalaya, India. Catena 87(1):78-89.

Singha LB. 2005. Site specificity, growth and productivity of Arundinaria maling gamble in Jang area of Arunachal Pradesh. PhD thesis. Shillong, India: North Eastern Hill Univ. 211 p.

Soethe N, Lehmann J, Engels C. 2006. The vertical pattern of rooting and nutrient uptake at different altitudes of a south Ecuadorian montane forest. Plant Soil 286(1-2):287-99.

Soethe N, Lehmann J, Engels C. 2008. Nutrient availability at different altitudes in a tropical montane forest in Ecuador. J Trop Ecol 24(4):397-406.

Squire RO. 1983. Review of second rotation silviculture of *Pinus radiata* plantations in southern Australia: establishment practices and expectations. Aust For 46(2):83-90.

StatSoft Inc. 2001. STATISTICA (data analysis software system), version 6. www.statsoft.com.

Sundriyal RC, Sharma E. 1996. Anthropogenic pressure on tree structure and biomass in the temperate forest of Mamlay watershed in Sikkim. For Ecol Manage 81(1):113-34.

Tate R. 1987. Soil organic matter: biological and ecological effects. New York: J Wiley.

Walkley A, Black I A. 1934. An examination of the Det jareff method for determining soil organic matter and a proposed modification of the chromic acid filtration method. Soil Sci 37(1):29-38.

Walter H. 1985. Vegetation of the earth and ecological systems of the geobiosphere. 3rd edition. New York: Springer-Verlag. 318 p.

Wang Y, Amundson R, Niu XF. 2000. Seasonal and altitudinal variation in decomposition of soil organic matter inferred from radiocarbon measurements of soil CO_2 flux. Glob Biogeochem Cycles 14(1):199-211.

Wegner C, Wunderlich M, Kessler M, Schawe M. 2003. Foliar C:N ratio of ferns along an Andean elevational gradient. Biotropica 35(4):486-90.

Whittaker RH. 1975. Communities and ecosystems. 2nd edition. New York: Macmillan Publisher. 352 p.

Wilcke W, Oelmann Y, Schmitt A, Valarezo C, Zech W, Homeier J. 2008. Soil properties and tree growth along an altitudinal transect in Ecuadorian tropical montane forest. J Plant Nutr Soil Sci 171(2):220-30.

Wilcke W, Yasin S, Abramowski U, Valarezo C, Zech W. 2002. Nutrient storage and turnover in organic layers under tropical montane rain forest in Ecuador. Eur J Soil Sci 53(1):15-27.

Witkamp M. 1971. Soils as components of ecosystems. Annu Rev Ecol Evol S 2:85-110.

Zhang JT, Zhang F. 2011. Ecological relations between forest communities and environmental variables in the Lishan Mountain Nature Reserve, China. Afr J Agric Res 6(2):248-59.

Zhang P, Zhang T, Chen N L. 2009. Vertical distribution patterns of soil organic carbon and total nitrogen and related affecting factors along northern slope of Qilian Mountains. Chin J Appl Ecol 20(3):518-24.