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Facing north or south: Does slope aspect impact forest stand characteristics and soil properties in a semiarid trans-Himalayan valley?

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ABSTRACT

An understanding of the differences in vegetation and soil characteristics between slope aspects in high altitude semiarid environments is fundamentally important for efficient management of these semi-natural systems; however, few studies have quantified these differences. Here, we analyzed forest stand characteristics, carbon stocks and soil properties of north- and south-facing slopes in a trans-Himalayan semiarid valley. *Pinus wallichiana* was the dominant and *Juniperus indica* the co-dominant species in both aspects, whereas *Betula utilis* and *Abies spectabilis* were only recorded in north-facing forests. *Pinus* regenerated in both aspects, whereas *Juniperus* did not. Carbon stocks did not differ between aspects; 33 t/ha in north-facing and 31 t/ha in south-facing forests. Similarly, soil properties did not vary between slope aspects, expect for potassium (highest in south-facing slopes). These results suggest that topographic factors affect mountain forests through their direct influence on radiation and moisture, but that human disturbance also plays a significant role affecting vegetation and soil characteristics in a semiarid environment. These natural and anthropogenic factors may play in harmony or in discord with each other. Here, the aridity of the region, parent material and land use history led to less pronounced differences between slope aspects, than commonly found in moister habitats.

1. Introduction

Mountain forests, occupying 23% of the Earth's forest cover (Price et al., 2011), is home to about 12% of the global human population (FAO, 2002). Consequently, sustainable management and conservation of mountain environments and their unique biological diversity are pertinent for maintaining the livelihoods of mountain communities. Forest diversity, composition and regeneration are affected by factors like climate, topography, aspect, inclination of slope soil type and land use. Differences in insolation period and intensity change with aspect, thereby forming a range of microclimates in multifaceted landscapes (Holland and Steyn, 1975). Several studies conclude that the variation between two contrasting aspects is the result of the differences in solar radiation received, e.g. in North America (Cantlon, 1953), the Middle East (Kutiel and Lavee, 1999), Australia (Kirkpatrick et al., 1988), in east Africa (Vetaas, 1992), the Himalaya (Ghimire et al., 2010; Paudel and Vetaas, 2014), and even within the same elevation (Shank and Noorie, 1950). Cantlon (1953) and Pook and Moore (1966) revealed that opposing slopes vary in their microclimate; light intensity, soil and air temperature, humidity, soil moisture and evaporation, and duration of growing periods, and that these differences are closely associated with differences in vegetation composition and structure. In general, for the northern hemisphere, south-facing slopes receive more sunlight and become more xeric and warmer, supporting drought-resistant vegetation and less conducive for tree growth, while north-facing slopes retain moisture and are cold and humid, supporting moisture-loving plants.

The trans-Himalayan region of central Asia is known for

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harboring permanent human settlements in cold arid environments at high elevations, typically ranging from 3000 to 4800 masl, as well as being home for many endangered plant and animal species. The region exhibits complex topographical structure, high intensity of solar radiation, high degree of seasonality, extreme weather conditions, low precipitation and low productivity (Miehe et al., 2001), but the influence of slope aspect on forest stand characteristics and soil physico-chemical properties in the semiarid inner valleys of the Himalaya are still lacking. The understanding of aspect is important for forest management and planning because of its influence on growth and forest productivity. Many studies have estimated high productivity potential, and hence high carbon sequestration potential, for temperate mid-elevation, community managed broad-leaved forests in the Himalaya (Chhetri, 1999), but little work has been carried out in high-altitude forests. In the Himalayan agro-ecological system, forests in the agricultural matrix landscape provide biomass based ecosystem services to the subsistence farmers (Måren and Vetaas, 2007; Måren et al., 2013). In Nepal, the majority of people; more than 80%, heavily depend on agriculture for their subsistence, and the study area of Manang is no exception; here people rely on agriculture and livestock rearing for subsistence survival. The farming system comprises a typical high altitude Himalayan system with valley cultivation and animal husbandry (Chaudhary et al., 2007); where *Pinus wallichiana* A. B. Jacks. (Himalayan Blue Pine) forests provide firewood, construction materials, edible plants and traditional medicine, and conifer needles mixed with manure provide natural fertilizer, a fundamental nutrient input to the agriculture. This interrelationship between forest and agriculture is age old and analyzing forest stand characteristics can inform land management; both agricultural and forested. In order to assess the relevance of slope aspect for forest stand characteristics, we analyzed vegetation parameters and soil chemical properties of northern and southern slopes under traditional land use regimes in the high altitude semiarid Manang Valley of Nepal. Our objectives were to answer: 1) is there a significant difference in tree species richness, structure and regeneration between slope aspects? 2) is there a significant difference in above ground tree biomass and carbon stocks between forests on northern and southern slopes?, 3) does soil chemical properties vary between slope aspects?, and 4) can pine needle color be linked to soil chemical properties?

2. Material and methods

2.1. Study area

The Manang district, Nepal, is located between latitudes 28° 27′ to 28° 54′ N and longitudes 83° 49′ to 84° 34′ E, with an elevation gradient from 1880 to 8136 m above sea level (Fig. 1). It borders China to the north, Lamjung and Gorkha districts to the east, Myagdi and Mustang districts to the west, and Kaski and Lamjung districts to the south. The U-shaped Manang Valley is glacially formed and surrounded by high mountains; the Annapurna range to the south, Choya and Himlung to the north, Manasalu to the east and Muktinath and Damodar to the west, and positioned in the rain shadow of the trans-Himalayan region. More than two thirds of the surface area is occupied by high mountains and dominated by land under snow or glaciers; Manang district covers an area of 2246 km^2, of which 66% is mountains and rocks, 8% cultivated area, 5% pasture, 9% forest, and 9% shrub land (DDPoN, 2012). The parent material of Manang contains quartzites with layers of hematite, slates and limestone with clays and marl (Hagen, 1969). Manang has semiarid cold, desert-like conditions, resembling that of the Tibetan plateau, and receives little of the monsoon rain from the southeast and the southwest as it lies north of the massive Annapurna range (Aase and Vetaas, 2007). Most of the rainfall occurs from June to September and snowfall is common in winter (November to March). Average annual precipitation is 279 mm (2008–2012) at Manang Bhot (3420 masl), the nearest meteorological station to the west, with maximum monthly rainfall in July (61 mm) and no rainfall in December (Department of Hydrology and Metrology). Average maximum temperature at Jomsom to the east (2744 masl, temperature data not available at Manang Bhot) is 22.8 °C for July and average minimum is −2 °C for January.

The great variation in climatic conditions in Manang district gives rise to a variety of vegetation types, ranging from subtropical, temperate, xerophyllous to alpine vegetation, and the district hosts a wide range of flora and fauna divided into three board ecological-cultural zones; 1) *Nar-Phoo*; mostly located above timberline with steppe communities of mainly *Juniperus indica* Bertol., *Berberis* L.-, *Rosa* Lindl.- and *Lonicera* Mill.-species, 2) *Nyeshang* (Upper Manang) with *Pinus wallichiana* forests with the upper belt of *Betula utilis* D.

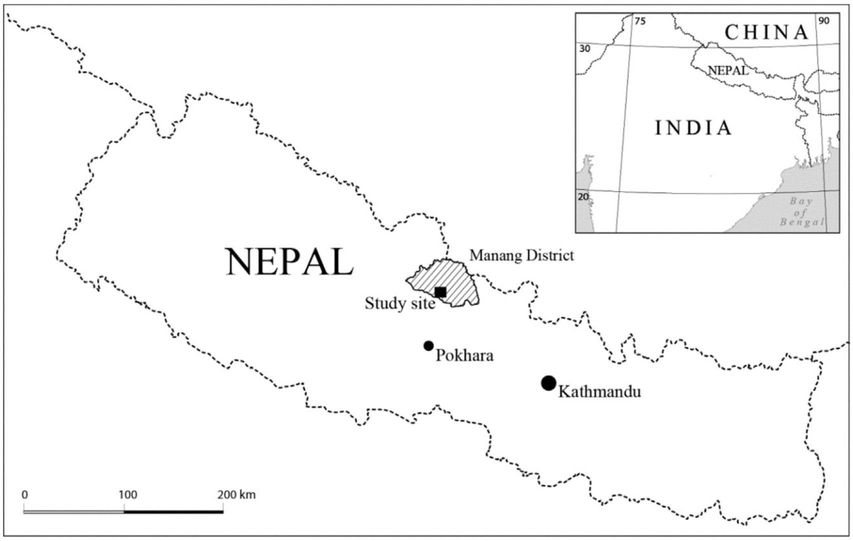
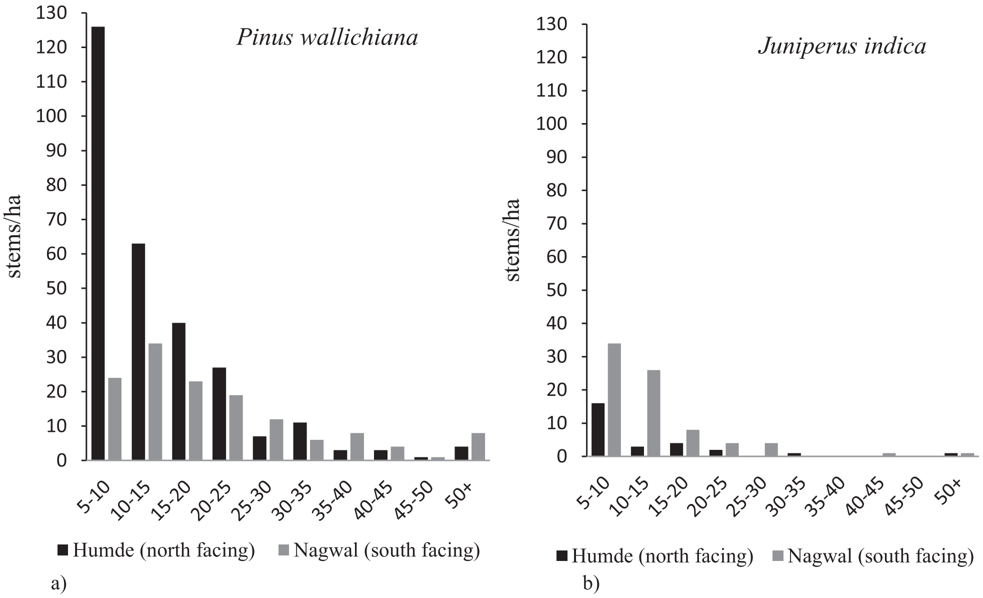


Fig. 1. Map of Nepal showing the study site in the Manang valley located within the Manang district.



a)

b)

Fig. 2. Size-class distributions (5 cm diameter at breast height classes) expressed in tree density (stems/ha) of a) *Pinus wallichiana* and b) *Juniperus indica*, in north-facing (black) and south-facing (grey) forests in the Manang Valley of Nepal.

Don and *Abies spectabilis* (D. Don) Mirb., and 3) *Gyasumdo* (Lower Manang); dominated by *B. utilis* and conifers (*P. wallichiana, Taxus baccata* L., *Tsuga dumosa* (D. Don) Eichler, *A. spectabilis* and *Picea smithiana* (Wall.) Boiss.) in the upper belt and with dense oak (mostly *Quercus semecarpifolia* Sm.) and rhododendron (*Rhododendron arboreum* Sm.) forest in the lower belt (NTNC, 2008). At our field site *Pinus wallchiana*, a subalpine conifer tree species native to the Himalaya, Karakoram and the Hindu Kush Mountains, was the dominant tree species, and it has an almost continuous distribution range along the Himalaya range at elevations between 1800 and 4300 masl (Schickhoff, 1996). These areas also serve as major wildlife habitats to a unique mountain fauna with blue sheep (*Pseudois nayaur* Hodgson), snow leopard (*Panthera uncia* Schreber), Himalayan tahr (*Hemitragus jemlahicus* Smith), serow (*Capricornis thar* Hodgson) and red panda (*Ailurus fulgens* F. Cuvier), as well as avifauna such as Himalayan griffon (*Gyps himalayensis* Hume), lammergeier (*Gypaetus barbatus* Linnaeus) and golden eagle (*Aquila chrysaetos* Linnaeus).

Table 1
Tree measurements and soil parameters, in plots sampled at the north-facing slopes of Humde and the south-facing slopes of Ngawal, Manang Valley, Nepal ($n = 90$). DBH = Diameter at Breast Height (1.37 m), Std.Error = Standard error. *Abies spectabilis* and *Betula utilis* occurred in very few numbers only on north-facing slopes and are not included.

Parameters	North-facing forests			South-facing forests			*p*-value
	Min	Max	Mean ± Std.Error	Min	Max	Mean ± Std.Error	
Tree measurements							
Total tree density (stems/ha)	200	3500	693 ± 84	200	1200	482 ± 32	<0.05
Basal area (m^2/ha)	0.19	58.08	1.65 ± 0.15	0.19	30.19	2.74 ± 0.25	<0.05
Tree height (m)	1.5	12	5.50 ± 0.10	2	11	5.14 ± 0.11	<0.05
Tree DBH (cm)	5	86	14.45 ± 0.59	5	62	18.72 ± 0.85	<0.05
Total seedling density	100	2600	1014 ± 107	100	1200	440 ± 45	<0.001
Total sapling density	100	3000	618 ± 84	100	600	263 ± 27	<0.01
Total biomass (tons/ha)	2.41	271.75	64.68 ± 9.6	5.27	221.04	59.9 ± 6.3	<0.05
Total carbon stock (tons/ha)	1.44	135.47	32.9 ± 4.1	3.13	111.5	30.5 ± 2.8	<0.05
Pinus wallichiana tree density	200	3500	633 ± 81	100	700	309 ± 21	<0.01
P. wallichiana seedling density	100	2600	947 ± 108	100	1100	379 ± 43	<0.001
P. wallichiana sapling density	100	1900	533 ± 59	100	500	193 ± 19	<0.01
Juniperus indica tree density	100	400	225 ± 39	100	700	244 ± 25	NS
J. indica seedling density	100	800	229 ± 47	100	300	161 ± 18	NS
J. indica sapling density	100	1900	272 ± 99	100	400	162 ± 18	NS
Soil parameters							
Soil pH	8.38	10.07	9.39 ± 0.05	8.12	10.04	9.43 ± 0.05	NS
Soil organic carbon (%)	0.42	5.24	2.00 ± 0.13	0.37	7.11	2.18 ± 0.22	NS
Total soil nitrogen (%)	0.03	0.17	0.09 ± 0.01	0.02	0.18	0.08 ± 0.01	NS
Soil available phosphorus (ppm)	17	60.7	33.80 ± 1.31	14.2	103.9	36.42 ± 3.05	NS
Soil available potassium (ppm)	23.18	153.9	63.05 ± 3.18	23.88	216.1	76.75 ± 5.85	<0.05
Clay (%)	6	19	11.56 ± 0.44	6	20	11.10 ± 0.41	NS
Sand (%)	21.37	87.84	52.68 ± 1.41	35.86	73.8	58.88 ± 1.28	<0.001
Silt (%)	3.16	68.63	35.76 ± 1.38	17.24	50.14	30.02 ± 1.15	<0.001

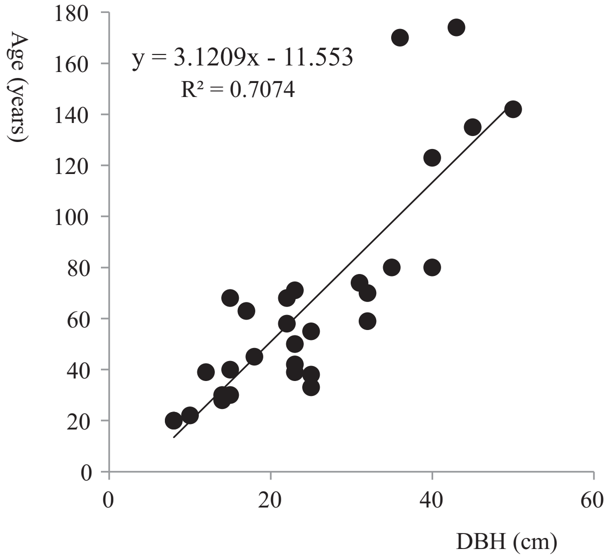


Fig. 3. Relationship between diameter at breast height (DBH) and age of *Pinus wallichiana* trees in the Manang Valley, Nepal ($n = 30$).

Table 2
Overview of environmental and disturbance variables measured in plots ($n = 90$) of north-facing and south-facing slopes in the Manang Valley in Nepal. RRI = Relative Radiation Index.

Variables	North-facing	South-facing	*t* value	*p*-value
Slope (degree)	24.6	29.6	$t\,(88) = -4.40$	<0.01
Tree cover (%)	44.4	41.9	$t\,(88) = 0.99$	NS
Bush cover (%)	17.1	30.2	$t\,(88) = -4.40$	<0.001
Exposed soil (%)	20.6	18.4	$t\,(88) = 0.84$	NS
Litter cover (%)	42.6	35.2	$t\,(88) = 2.60$	<0.01
Rock cover (%)	14.3	13.5	$t\,(88) = 0.44$	NS
Number of cut trees	1.6	0.9	$t\,(88) = -25.30$	<0.001
RRI	0.62	0.93	$t\,(88) = -25.30$	<0.001

2.2. Land use and human impact on the landscape

Manang is part of the Annapurna Conservation Area (ACA), the largest protected area in Nepal (NTNC, 2008). It belongs to the western development region and has 13 Village Development Committees and district headquarters at Chame. The official total population is 6527; 3664 males and 2863 females, residing in 1495 households (DDPoN, 2012). The average population density is 3 people per km^{-2} and the average annual growth rate is negative; −3.8%, and average household size is 4.4. The dominant land use is a combination of agriculture and transhumant pastoralism (Aase and Vetaas, 2007). The cultivated fields are found predominantly on south-facing slopes or in the valley bottom with an average growing season of 120 days. The fields are fertilized around the first week of November before snowfall starts. The main agricultural activities start with the ploughing by oxen in the first week of April and ends in the first week of October with harvesting and storing. Agriculture is possible, though the area is semiarid, due to a system of gravity irrigation where the irrigation channels are fed by glacier- and snowmelt fed streams. Fields are irrigated during sowing in April, and on some occasions during summer depending on the monsoon rain, and then again in September. The main crops include wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and buckwheat (*Fagopyrum esculentum* Moench and *F. tataricum* (L.) Gaertn.); the latter is cropped alternatively with the wheat (Chaudhary et al., 2007). Domesticated animals include yak, horse, mule, sheep and goats which are taken to alpine pastures during summer and down to the lower slopes in winter. When the valley is covered with snow, all animals are stall fed and manure is collected.

Forest resources are mainly used for three purposes; firstly, for construction and firewood. Pine and fir are used as construction materials whereas junipers, birch and pine are used for firewood, where pine is the least preferred. Secondly, pine needles and juniper branches are used as animal bedding (Chaudhary et al., 2007), and collected from the forest every six weeks in winter. After being used for bedding, it is mixed with dung and urine in a large manure heap, allowing it to ferment until spring. This acidic natural fertilizer produced by the mixture of conifer needles and manure is perfectly suitable for fertilizing the highly alkaline soils of Manang (Aase and Vetaas, 2007). Thirdly, forest resources are used in traditional medicine, incense and for subsistence income. Juniper, *J. indica* in particular, is considered the best incense and is in high demand and burned in every household in the morning. The district is rich in wild edible and medicinal plants which are collected for economic benefit (Bhattarai et al., 2006), e.g. the collection of

Table 3
Matrix of Pearson correlation coefficients (r) showing correlations between environmental variables and seedling and sapling densities measured in plots at north-facing and south-facing forests in the Manang Valley, Nepal ($n = 90$). SOC = Bu co = Bush cover, Li co = Litter cover, P seedl = *Pinus wallichiana* seedlings, P sapl = *P. wallichiana* saplings, J seedl = *Juniperus indica* seedlings, J sapl = *J. indica* saplings, RRI = Relative Radiation Index.

	North-facing slopes								South-facing slopes						
		Bu co	Li co	P seedl	P sapl	J seed	J sapl			Bu co	Li co	P seedl	P sapl	J seedl	J sapl
North-facing slopes	Bu co	1						South-facing slopes	Bu co	1					
	Li co	−0.31[a]	1						Li co	−0.51[b]	1				
	P seedl	0.15	−0.4	1					P seedl	0.35[a]	−0.4[a]	1			
	P sapl	0.05	−0.34[a]	0.42[a]	1				P sapl	0.2	−0.26	0.52[b]	1		
	J seedl	0.22	0.18	−0.31	−0.65[b]	1			J seed	−0.49	0.74	−0.19	−0.79	1	
	J sapl	0.25	0.37	−0.2	0.4	0.55[a]	1		J sapl	−0.06	−0.07	−0.42	−0.15	0.35	1
	RRI	0.45[b]	−2.2	0.4	0.4	0.5	−0.8[a]		RRI	−0.49[b]	0.19	−0.09	−0.2	−0.4	0.1

[a] Correlation is significant at the 0.05 level (2-tailed).
[b] Correlation is significant at the 0.01 level (2tailed).

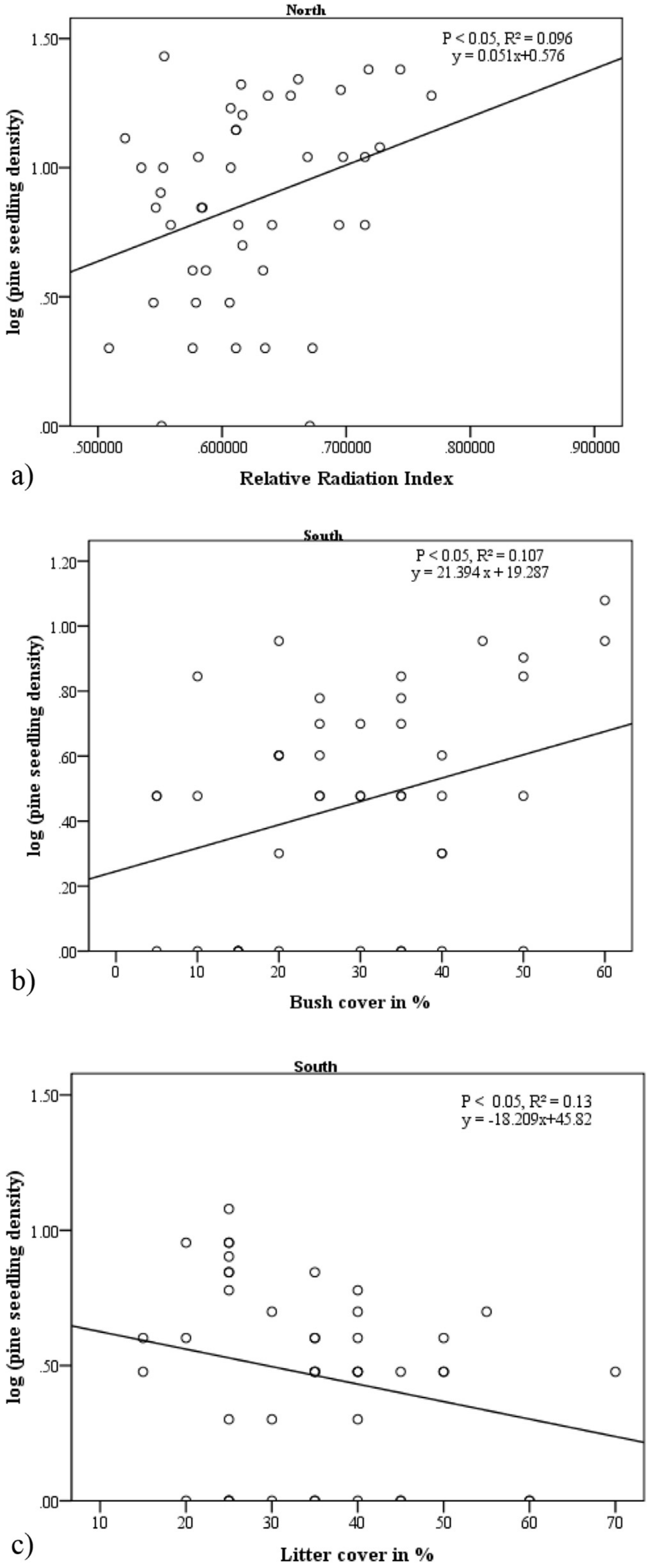


Fig. 4. Relationships between *Pinus wallichiana* seedling densities and a) Relative Radiation Index at north-facing slope, b) litter cover at south-facing slope, and c) bush cover at south-facing slope, ($n = 45$).

the Himalayan caterpillar fungus '*yarsagumba*' (*Ophiocordyceps sinensis* Berk.) which is highly valued in Chinese medicine and generates very high profits.

2.3. Sampling design

Data were collected in April and May of 2013 from two sites; north-facing Humde (28°37′57.5″N-28°38′2.29″N and 084°05′25.2″E −084°05′42.9″E), and south-facing Ngawal (28°38′27.0″N- 28°38′47.5″N and 084°05′57.4″E − 084°05′36.6″E), in the Manang Valley, northern Central Nepal (Fig. 1). The valley floor in this section of the valley is at 3380 masl. Systematic sampling was employed for vegetation, and environmental and soil parameters in altogether 90 plots (quadrats of 10 m × 10 m); 45 plots in each slope aspect. All plots were placed between 3400 and 3500 masl to avoid confounding effects of elevation, and placed at regular intervals, maintaining an inter-plot distance of 10 m. Plots were excluded if steeper than 45° slope, with more than 50% rock or exposed soil, having a water stream flowing or well-established trail passing through it, or without a single tree. Slope and aspect were measured from the center of the plot using a Silva compass. All woody species were identified in the field using Polunin and Stainton (1984). Vegetation- and ground cover were estimated subjectively as percentage cover by standing at the center of the plot. Ground cover was categorized into three categories; litter, exposed soil and rocks. Canopy cover; the proportion of the sky hemisphere obscured by vegetation when viewed from a single point, was visually estimated by sitting in the middle of the plot. Human disturbance was estimated by counting the number of cut stems, counted irrespective of whether they were dead or had re-sprouts from the base. The Relative Radiation Index (RRI), which is the relative measure of the substrate's annual exposure to radiation (Oke, 1987; Vetaas, 1992), was estimated as a function of latitude, aspect, and slope (the value ranges from −1 to +1 and is calculated as: $RRI = \cos(180° - \Omega)$ x $\sin\beta$ x $\sin\,'$ + $\cos\beta$ x $\cos\,'$, where Ω = aspect, β = slope, and $'$ = latitude, cf. Paudel and Vetaas, 2014).

The number of seedlings (height < 1.37 m) and saplings (height > 1.37 m, DBH < 5 cm) were counted and trees (height >1.37 m, DBH ≥ 5 cm) were measured at breast height (1.37 m) by a diameter tape in each plot. Height of the individual trees was calculated from the angle measured by a Sunto clinometer. In the absence of specific allometric equations developed for the mountain region, the total stem volume of each tree was calculated using the relationship developed by Sharma and Pukkala (1990), as we presumed it to be a suitable locally developed allometric equation. Over bark stem volume is calculated as; $\ln(V) = a + b \times \ln(d) \times c \times \ln(h)$, where V = over bark stem volume, d = diameter at breast height (1.37 m above the ground) (cm), h = tree height (m) and a, b, c = species-specific constants provided by Sharma and Pukkala (1990). For species without species-specific constants the values developed for miscellaneous Middle Hill species were used (Sharma and Pukkala, 1990). The over-bark volume of each tree obtained using the above equation was then multiplied by the dry wood density derived from Zanne et al. (2009) for individual species to obtain stem biomass. The biomass of branches, leaves and roots were estimated to be 45%, 11% and 46%, respectively, of the stem biomass (Sharma, 2003). The root-to-shoot ratio of 1:5 (20%) of above-ground (AG) biomass was used to estimate below-ground biomass (MacDicken, 1997). The total biomass was converted into carbon by multiplying by the default carbon fraction for temperate and boreal forests; 0.51 for conifer forests (Lamlom and Savidge, 2003).

For soil sampling altogether five sub-samples were taken from each plot; four from the center of each sub-plot (5 m × 5 m) and one from the center of the main plot, to a depth of 30 cm, and

Table 4
Matrix of Pearson correlation coefficients (r) showing correlations between the soil physico-chemical parameters measured in plots at north-facing and south-facing forests in the Manang Valley, Nepal ($n = 90$). SOC = Soil organic carbon, TN = Total Nitrogen, AP = Available Phosphorus, and AK = Available Potassium.

	North-facing slopes							South-facing slopes					
		pH	SOC	TN	AP	AK			pH	SOC	TN	AP	AK
North-facing slopes	pH	1					South-facing slopes	pH	1				
	SOC	−0.56[b]	1					SOC	−0.54[b]	1			
	TN	−0.23	0.33[a]	1				TN	−0.62[b]	0.64[b]	1		
	AP	0.08	−0.15	−0.22	1			AP	0.12	0.01	−0.07	1	
	AK	−0.21	0.66[b]	−0.01	0.06	1		AK	−0.68[b]	0.70[b]	0.61[b]	−0.21	1

[a] Correlation is significant at the 0.05 level (2-tailed).
[b] Correlation is significant at the 0.01 level (2-tailed).

bulked to one sample of *ca.* 200 g. Samples were analyzed at the Aquatic Ecology Centre, Soil and Water Analysis Laboratory at Kathmandu University, see Appendix A for details. The dominant color of the pine needles was evaluated visually on a subjective scale categorizing it into one of three subjective color categories; 1 for yellow color, 2 for yellow–green color, and 3 for green color. For the age determination of *P. wallichiana*, coring was done horizontally with a Pressler's borer of 0.4 cm diameter. A total of 30 tree-cores from each slope were collected and rings counted.

2.4. Data analyses

Descriptive statistics was applied to generate means, range and standard error. Before performing statistical analysis, data on tree density, seedlings and saplings of *P. wallichiana* and *J. indica* were subjected to a normality test (Shapiro–Wilk test of normality). The tree density value was normal ($p < 0.05$), but seedling and sapling density values were not ($p > 0.05$), and hence log-transformed. A t-test was used to compare the differences in means of parameters between slope aspects. Pearson correlation analysis was used to correlate the environmental variables and soil parameters observed to the seedling and sapling densities. Although correlation does not imply causation, if a significant correlation was found, it was tested by regression. Student t-test was performed to determine if there were significant differences in the soil parameters with respect to aspect. Multiple regression analysis was used to test whether measured soil variables affect the soil organic carbon or not. Multiple linear regressions were used to test if the variance in the response variable soil organic carbon was better explained, as indicated by increasing R^2, when more variables were added as predictors. A forward multiple regression was used, instead of backward elimination, as it does not require a 'complete model', involving all factors and variables as required by backward selection. Pearson's bivariate correlation (2-tailed) was applied to evaluate the relationship among the soil parameters. Generalized Additive Models (GAMs) were used to model the functional dependence of pine needle color on different soil parameters. All statistical analyses were performed in the statistical software package R (R Development Core Team, 2012).

3. Results

3.1. Influence of slope aspect on forest stand characteristics and carbon stocks

We found four tree species in total; four in the north-facing forest (NF) and only two in the south-facing forest (SF). The dominant tree species *P. wallichiana* was represented in all size-classes (Fig. 2a), showing an inverse J-shaped size-class distribution. The occurrence of larger individuals (DBH > 35 cm) was highest in the SF, while the smallest size-class (DBH 5–10 cm) was very well represented in the NF. *J. indica* showed an interrupted size-class distribution with no trees in size-classes 35–40 cm and 45–50 cm (Fig. 2b), and its density was higher in all size-class intervals in the SF compared to in the NF.

Pinus wallichiana in the NF was most abundant in the seedling stage (44.3%), followed by tree- (30.8%) and sapling stage (24.7%), (Table 1). In the SF trees were more abundant (43.1%) than seedlings (38.8%), followed by saplings (18.0%). *Juniperus indica* showed a different pattern; in the NF it was most abundant in the sapling stage (44.5%), followed by the seedling stage (35.4%) and least abundant as mature trees (20.0%). However, in the SF, we found that juniper trees compiled more than 50% (55.3%), followed by saplings (24.1%) and seedlings (20.5%). Total tree density was higher in the NF, but basal area was higher in the SF (Table 1). Tree DBH differed between slope aspects, and ranged from 5 to 86 cm with a mean of 14.5 cm in the NF, while it ranged from 5 to 62 cm with mean of 18.7 cm in the SF (Table 1). Tree height also differed; in the NF it ranged from 3 to 12 m, with a mean height of 5.5 m, and in the SF from 3 to 11 m with mean height of 5.1 m. The total biomass and carbon stocks did not differ between slope aspects. *P. wallichiana* had a mean age of 65.53 ± 7.76 years with maximum of 174 years and minimum of 20 years, and age was related to tree size (Fig. 3, $p < 0.001$). *P. wallichiana* trees were, on average, slightly older in the SF, but this difference was however not significant.

Bush cover was highest in the SF ($p < 0.001$) and litter cover was highest in the NF ($p < 0.01$), while tree cover, exposed soil and rock cover were not found to differ between slope aspects (Table 2). The human disturbance measured in terms of number of stumps was higher in the NF than in the SF (Table 2, $p < 0.001$). RRI is significantly higher in the SF than in the NF (Table 2, $p < 0.001$), as expected. In the NF, litter cover showed negative correlation with *Pinus* saplings, whereas RRI showed positive correlation with *Pinus* seedlings (Table 3). In the SF bush cover was positively correlated with *Pinus* seedlings, whereas litter cover was negatively correlated.

Regression analyses were run for environmental variables found to correlate with *Pinus* seedling density (the dependent variable) and seedling densities increased with increasing RRI at the NF, increased with increasing bush cover at the SF, and decreased with increasing litter cover at the SF (Fig. 4).

3.2. Influence of slope aspect on soil properties and pine needle color

The analyzed soil physio-chemical properties did not show significant differences between slope aspects, except for soil available potassium, which was higher in the SF (Table 1). The

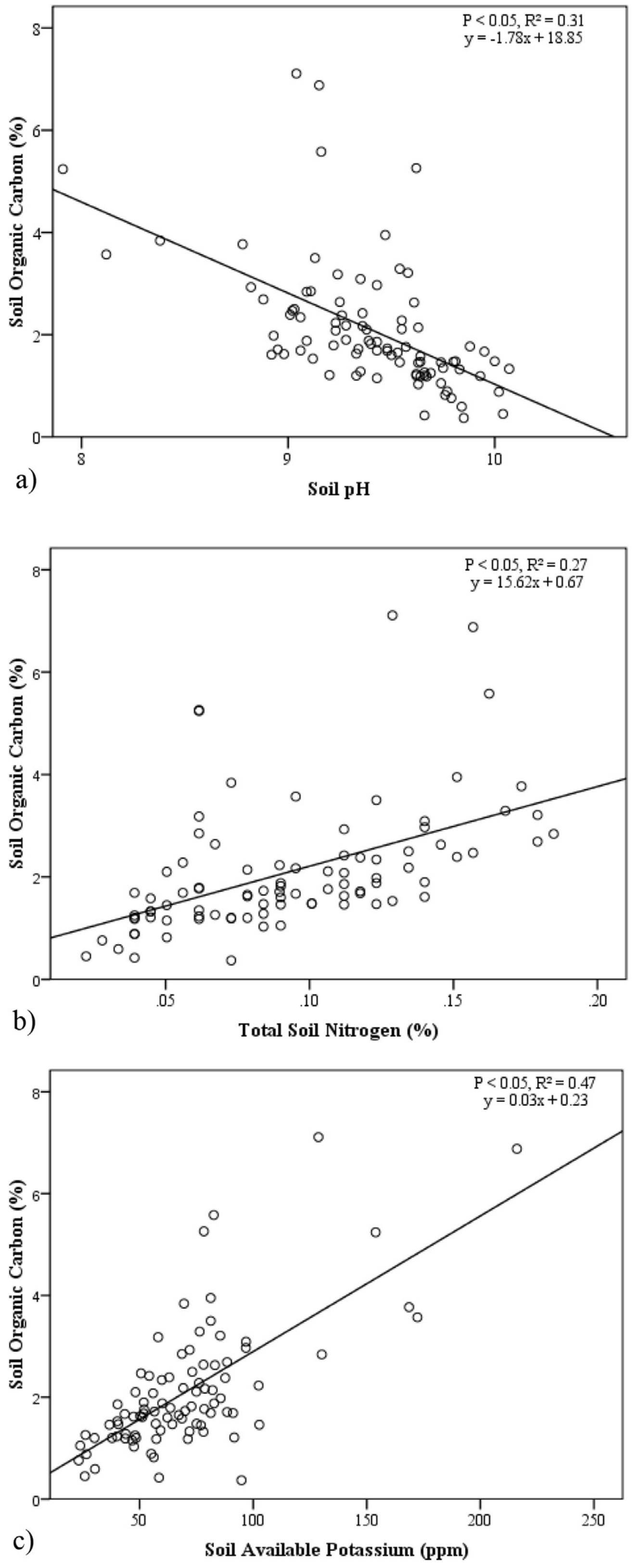


Fig. 5. Scatter plots of soil organic carbon as the response variable and a) soil pH, b) total soil nitrogen and c) soil available potassium as predictor variables in the Manang Valley, Nepal ($n = 90$) ($p < 0.05$).

sand and silt contents differed between slope aspects; sand content was higher in SF while silt content was higher in NF, whereas the content of clay did not vary (Table 1). Pearson correlation analysis revealed a significant positive correlation of soil organic carbon with total soil nitrogen and available potassium, and negative correlation of soil organic carbon with the soil pH in both aspects (Table 4). Soil pH, on the other hand, was negatively correlated with soil organic carbon, total soil nitrogen, and available potassium, but not for available phosphorus. Total soil nitrogen was positively correlated with soil organic carbon in both aspects (Table 4).

Multiple regression analysis showed that when all the variables were treated together, soil organic carbon was found to be best explained by soil pH, total soil nitrogen and soil available potassium; and the latter parameter contributed to explain a unique part of the variance (Fig. 5). Soil pH significantly predicted soil organic carbon ($\beta = -0.61$, $p < 0.05$), as did the total soil nitrogen ($\beta = 7.75$, $p < 0.05$) and soil available potassium ($\beta = 0.02$, $p < 0.05$). Using these three predictors in the model explained 57.0% of the variation in the data ($R^2 = 0\ 0.57$, $F_{3,\ 86} = 38.21$, $p < 0.05$).

All five edaphic predictor variables soil pH, total soil nitrogen, soil organic carbon, soil available phosphorus and soil available potassium individually showed significant effects on the color of the pine needles. However, when all variables were treated together, only two variables; total soil nitrogen and soil pH, showed effects on pine needle color (Fig. 6). The stepwise selection in the multiple GAM showed that the functional dependence of pine needle color was best explained by soil pH and total soil nitrogen ($p < 0.05$), which explained 21.4% of the variation (Fig. 7).

4. Discussion

4.1. Slope aspect, stand characteristics and carbon stocks

We found that north-facing forests had more tree species and higher tree density than the south-facing forests. The dominant species *Pinus wallichiana* and co-dominant *Juniperus indica* were present on both slope aspects, whereas *Betula utilis* and *Abies spectabilis* were only present in very low numbers in north-facing forests. These results concur with other findings, both from Nepal (Ghimire et al., 2010) and other parts of the world (Olivero and Hix, 1998; Schinkhoff, 1996). Along with total tree density, seedling and sapling densities were significantly higher in north-facing forests than in south-facing forests. This result may be attributable to the pronounced aridity of the area (Mong and Vetaas, 2006), where higher solar radiation and less available snow melt water dries out the south-facing forests faster, hence reducing tree growth. It has long been assumed that insolation affects plant species composition greatly, especially in semiarid and arid regions at low latitudes, through its influence on the water balance (Boyko, 1947). Radiation co-varies with many features of the plants' environment, especially physiological processes, and is thus a relevant variable for species composition and forest characteristics. In the present study the significantly higher RRI in the SF shows the clear difference in insolation between the two opposing slope aspects. In areas with less than 600 mm annual precipitation, moisture plays a deterministic role in the composition, structure and density of plant communities (Kutiel and Lavee, 1999) and in the Manang Valley Panthi et al. (2007) argued that moisture was the main environmental factor governing plant species composition and richness. Snow melt

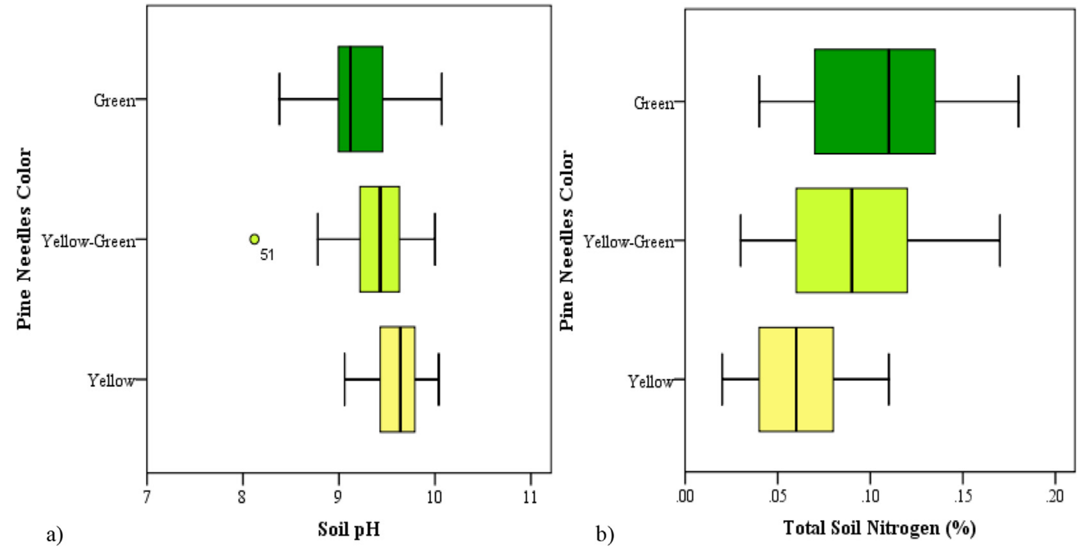


Fig. 6. Horizontal box plots of the three different pine needle color classes; yellow, yellow–green and green, for different values of a) soil pH and b) total soil nitrogen, from both north-facing and south-facing forests in Manang Valley, Nepal ($n = 90$). The box contains the middle 50% of the data, the upper edge of the box indicates 75th percentile of the data and the lower edge indicated 25th percentile. The black line inside the box is the median and the ends of the horizontal lines, the "whiskers", represent minimum and maximum values. The green round circle in the left figure indicates an outlier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water is the major source of moisture for the vegetation in dry parts of the Himalaya where annual precipitation is very low (Miehe et al., 2001), and in the study area, as permanent snow cover is absent on mountain tops of the south-facing slope, soil moisture recharge from snow melt water during growing season is low. Additionally, high evapotranspiration on the south-facing slopes may cause drought stress during the growing season. Contrastingly, the mountains on the north-facing slopes suffer

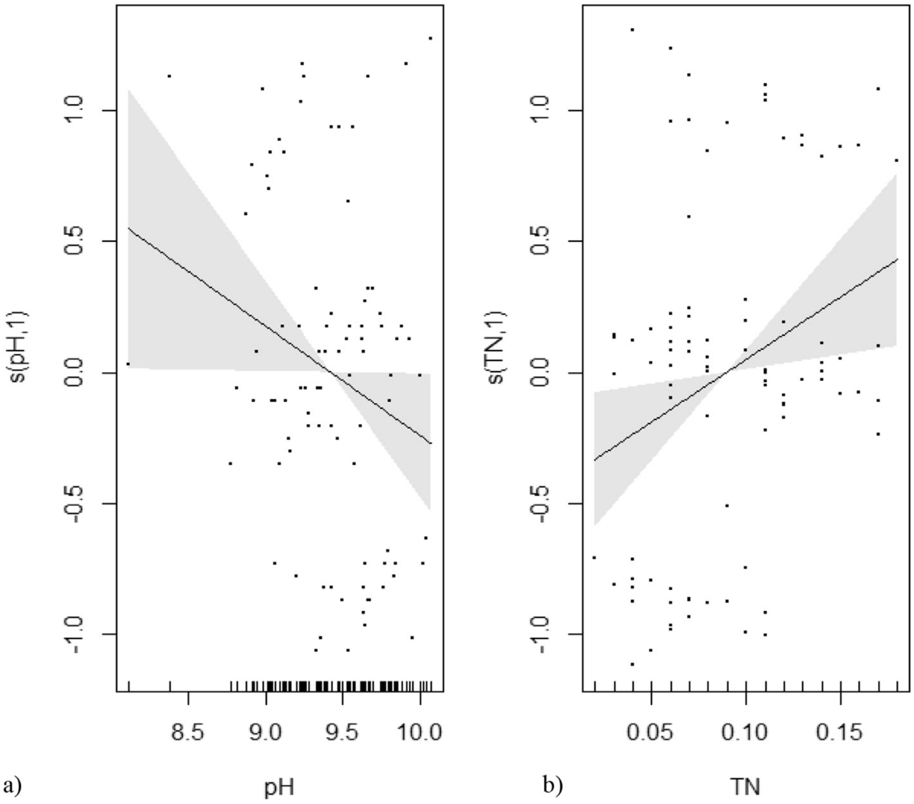


Fig. 7. The relationship between pine needle color and a) soil pH ("pH" to the left) and b) total soil nitrogen ("TN" to the right), plotted by a General Additive Model (GAM). The solid line represents the predicted value of the dependent variable (pine needle color) as a function of the x-axis, and the shaded region represents point wise 95% upper and lower confidence intervals. The tick marks along the x-axis represents the distribution of observed values, and the number "1" in s(pH,1) and s(TN,1) on the y-axis are the effective degrees of freedom for each smooth function.

lower evaporation from reduced insolation and have large amounts of perennial snow cover, a major source of moisture supporting forest growth on these slopes. This is evident by the occurrence of dense *A. spectabilis* and *B. utilis* forests on the north-facing slopes at higher elevation than at the present study site (Shrestha et al., 2007) within the Manang Valley. In contrast to *P. wallichiana*, the *J. indica* density was higher in the south-facing forest and this may be explained by the xerophytic properties of this species.

Seedlings are generally light demanding and grow best in sunny areas and we found seedlings to be negatively related to litter cover in south-facing forests. The litter mat may inhibit the emergence of seedlings or sprouts as it constitutes a physical barrier and impedes or retards seeds reaching the soil (Facelli and Pickett, 1991). This site was also far from settlements and was subject to infrequent litter collection. Seedlings were positively related to bush cover in the south-facing slope, and the bush cover may facilitate seedling survival under the present grazing regime. Similarly, Shrestha et al. (2007) reported the survival of *B. utilis* seedlings due to protection from browsing by the thicket of thorny *Caragana* spp. Both *P. wallichiana* and *J. indica* showed higher seedling densities in the north-facing forest, indicating good regeneration here, whereas the south-facing forest showed fair regeneration of *P. wallichiana* but poor regeneration of *J. indica*. The failing regeneration in the south-facing forest may also be partly due to more human disturbance in the form of livestock grazing and the collection of incense. Grazing is a major ecological factor influencing vegetation dynamics in the trans-Himalaya (Omer et al., 2006), limiting the regeneration of several tree species (Måren and Vetaas, 2007). South-facing forests are also preferred by livestock due to warmer temperature, and we found livestock droppings in most of the plots here, a phenomenon also observed by Chaudhary et al. (2007) and Shrestha et al. (2007) in the Manang district. Other human disturbances include the collection of firewood and timber and we observed the negative impacts of forest biomass outtake on forests along the trekking corridor on the north-facing slopes in Manang Valley, as did Chettri et al. (2002) in Sikkim, India. An increase in distance from the settlements gradually decreased human disturbance in the forest. However, by talking to many of the locals, it is clear that forest degradation has been more prominent in the past than at present, as many Manangis have migrated out of the valley.

Måren and Vetaas (2007) argue that interpretations of forest regeneration may better be portrayed by size-class distributions than seedling counts because the former represents longer time spans. The size-class curve of *P. wallichiana* in north-facing forest resembles an inverse J-shape (Fig. 2a), indicating sustainable regeneration (Shimano, 2000), opposed to at the south-facing site. The size-class curve of *J. indica* resembles an inverse J-shape in south-facing forests, with interrupted distribution (no trees in DBH classes 30–40 and 45–50, Fig. 2b), whereas it shows an erratic size-class distribution in north-facing forests, where the absence of middle girth classes may be explained by old deforestation episodes and the fact that *J. indica* is preferred over *P. wallichiana* for firewood (Chaudhary et al., 2007). We found no significant differences in biomass or carbon stocks between slope aspects. Highest tree biomass was found on the north-facing slope (65 t/ha), compared to the south-facing slope (60 t/ha), and this is in congruence with other studies showing higher biomass in shaded aspects (Gong et al., 2008; Uclés et al., 2015), and Tewari and Karky (2007) found tree biomass of 66.4 t/ha in a community forest at a comparable altitude of 3500–4200 masl in Nepal. Without the logging incident right before the formation of ACAP in the NF we figure this slope aspect would harbor even more tree biomass, hence carbon stocks, than today, and there is still potential for enhanced carbon sequestration at this slope aspect. We attribute the lack of a clear difference in carbon stocks between slope aspects to the differential management history and distance to settlements of the two sampled sites. High altitude forests seem not to be attractive for the study of carbon storage as these forests tend to have less forest density, and hence, store less carbon. However, they do cover extensive areas and should not be overlooked.

4.2. Slope aspect, soil properties and pine needle color

With no significant differences in soil properties between the north-facing and south-facing slopes, except for soil available potassium, the present study is not consistent with most of the previous findings or with the general pattern usually reported for soil properties pertaining to slope aspect, where soil properties are typically reported to be more fertile in north-facing aspect (Begum et al., 2010). This deviance in findings is explained by the arid nature of the study region and according to Kutiel and Lavee (1999) no significant differences in soil properties between the opposing aspects can be expected in arid zones (<400 mm of annual precipitation) due to low rainfall and high potential evaporation. Our finding is in line with Burke's (2002) study from Namibia's arid Nama Karoo inselbergs where slope aspect affected only the potassium content as well.

The north-facing forests are claimed to have undergone massive deforestation before the area was declared as a Conservation Area in 1986 (Karky, 2008). If this is the case, the similar soil conditions in north- and south-facing slopes can be attributed to the successional stage of the forest recovery, as suggested Liu et al. (2010). Another plausible cause may be the closeness of the sampled sites to the valley floor and as we move up-slope significant differences in soil parameters may be detected.

The soil pH at both slope aspects was extremely alkaline, with 9.39 and 9.43 as mean values for north-facing and south-facing aspects, respectively. This is common in semiarid and arid areas formed of limestone where the alkalinity of the soil can be attributed to its parent material and where water from both rain and snow is insufficient to leach the base-forming cations (Cardenas-Manriquez et al., 2006). Change in soil pH has large effect on the availability of ions to the plants and sufficient quantities of bicarbonates (HCO_3^-) are usually observed at higher pH and interfere with the normal uptake of other ions and could be unfavorable for optimum growth. Soil pH greater than 7.5 leads to a reduced availability of micronutrients; copper, iron, and manganese, which are important for plant growth. Soil pH greater than 8.5, as in this area, is indicative of sodic soils having more than 15% of exchangeable Sodium (Na) and a high content of salt.

Soil nitrogen is generally the most limiting nutrient in a majority of ecosystems. The total nitrogen in both slope aspects was low (based on the NARC standard for soil fertility; NARC, 1998/1999). The nitrogen content in semiarid and arid regions is often low due to the low content of organic matter (Tisdale et al., 1995), thus the location of the current study in a semiarid region with scanty vegetation could explain the low nitrogen levels found here. Furthermore, alkaline soils with high pH have been shown to be deficient in total soil and available nitrogen content (Bose and Sengupta, 1990). The mean values of soil available phosphorus in both slope aspects (101.40 kg/ha in the NF and 109.26 kg/ha in the SF) were high and higher than those reported for subalpine birch forest (11–92 kg/ha) by Shrestha et al. (2007) and for pure and mixed Sal forests (77 and 79 kg/ha) by Paudel and Sah (2003). At high values of pH (>8.5), the availability of phosphorus is high because of sodium phosphates' high solubility (Foth, 1990). Soil organic matter content did not differ between slope aspects, and correlated negatively with increasing pH, and positively with increasing total soil nitrogen and increasing soil available potassium. This explains why local land use practices have developed methods for reducing pH and increasing organic content by composting acidic pine needles and organic material later used as natural fertilizer in the soils of their crop fields.

When there is a certain nutrient deficiency in a forest, symptoms are generally seen uniformly in a cluster of trees instead of in individual trees (as this is usually caused by disease, mechanical damage or damage by animals). Conifers, including pines, have relatively low nutrient requirements in comparison with broadleaved trees, and this has enabled conifers to dominate vast portions of world's cold, boreal regions with limited nitrogen availability. We show that the yellowing of the pine needles observed in the Manang Valley can be related to low nitrogen content and high pH of the soil. This result is consistent with the results from a study conducted in the Upper Manang where seedling leaf color was used as an indicator of stress level (Mong and Vetaas, 2006), where the discoloration of the leaves in seedlings occurred in soils with low nitrogen content and high pH. Nitrogen is essential for the production of the pigment chlorophyll which is responsible for making the plant tissues green. Hence, its deficiency results in yellowing of the leaves. The yellowish foliage was also observed in several other tree species that are generally late successional; and which had recently established on the deglaciated moraines as seedlings. We also observed that the tree seedlings had blue green foliage when they grew close to sources of nitrogen such as faeces or animal bones, as also observed by Lawrence (1958).

5. Conclusions

We did not find the general relationships between opposing slope aspects, and forest stand characteristics and soil properties as seen in many other studies. *P. wallichiana* was dominant on both slope aspects, followed by *J. indica* predominantly in south-facing forests, while *A. spectabilis* and *B. utilis* were only recorded in small numbers in the north-facing forests. Tree density, along with seedling and sapling densities, was significantly higher in the north-facing forests. Forest structure was affected by human disturbance regimes integrated in the traditional land use system of the valley. The moist north-facing forest, deforested in earlier days, had higher tree density and smaller basal area. The south-facing forest harbored old mature trees with less density and larger basal area, but also with less seedling density, as seedling establishment was adversely affected by grazing and litter cover. There was no difference between slope aspects with regards to above-ground tree biomass and carbon stocks, explained by management history and regeneration structure. In spite of considerably higher insolation received by soils on the south-facing slopes, both aspects share the same physical variables (precipitation, elevation and parent material) that dictate much of the soil development. There was no or little difference in soil properties between slope aspects, explained by the origin of soil formation and water scarcity, in combination with management history. For forest management, north-facing forests can offer better yields by having slightly greater tree growth rate and a good regeneration potential. In the south-facing forest natural regeneration can be aided by moderate litter collection and by minimizing grazing impacts. We conclude that the combined effects of topographical variability, slope aspect and human disturbance regime determine the forest stand characteristics, along with above-ground biomass and carbon stock in this semiarid region. Additional research is needed to investigate if similar findings between slope aspects can be observed at larger scales in dry regions. Additionally, for carbon estimation, there is an urgent need for developing allometric equations for mountain forests.

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Appendix A. Soil analyses carried out on soils from north and south-facing slopes in the Manang Valley, Nepal.

The air dried soil was manually ground and passed through a 2 mm mesh sieve prior to the analyses. Soil pH was measured with the help of pH probe with a glass-calomel electrode keeping 1:1 soil: water ratio (McLean, 1982). Equal weights of air dried soil sample and distilled water (10 g: 10 ml) were mixed and stirred. Soil texture was determined by the soil hydrometer method (Gee and Bauder, 1986) where air dried soil samples (51 g) were weighed and placed in a 500 ml plastic bottle, then 50 ml of sodium hexa-metaphosphate (Na-HMP, as dispersing agent) and 100 ml tap water were added. The samples were soaked in sodium hexa-meta phosphate overnight. The bottles were placed and shaken in mechanical shaker for 2 h. The samples were then poured into 1000 ml cylinders and filled to 1000 ml scale on the cylinder with tap water, after that another 100 ml tap water was added to it. The cylinders were inverted and left for 2 h. The soil hydrometer was inserted carefully to let it float in the suspension and once it had stabilized the reading was noted, in order to determine the amount of clay. The contents of the cylinder were then poured into a 300 mesh sieve and washed with tap water until all the fine materials passes through the sieve. The sand left on the sieve was transferred to a beaker and then oven dried at 105 °C for 24 h. The oven dried sand was weighed to get the total sand content (as %). The silt content = 100 - %clay - %sand.

The total soil nitrogen was determined by Kjeldahl method (Bremner and Mulvaney, 1982) which is a wet oxidation method of total nitrogen determination. The sample was digested with concentrated Sulphuric acid (H_2SO_4) containing substance (which promotes the conversion) to convert organic-nitrogen to ammonium-nitrogen (NH_4^+-N). The ammonium-nitrogen is determined from the amount of ammonia (NH_3) liberated by distillation of the digest with alkali. Potassium sulfate (K_2SO_4) or sodium sulfate (Na_2SO_4) is used to raise the temperature of digestion and the oxidation of organic matter is promoted with the help of catalyst such as selenium (Se), mercury (Hg) or copper (Cu). Five gm of air-dried and sieved (2 mm) soil was weighed and transferred to a digestion tube, then 7 g anhydrous potassium sulfate and 5 mg of selenium powder was added. The entire content was mixed thoroughly by shaking the tube. Similarly, 7 ml of conc. Sulphuric acid (98%) and 5 ml of hydrogen peroxide (35%) was added. The sample was digested by heating (420 °C) for 30 min and then cooled to 50–60 °C. The digested tube was placed in a distillation unit where 50 ml distilled water and 50 ml NaOH (10N) was added and sample collection in Erlenmeyer flask after distillation is 100 ml. The sample was then titrated with 0.1N HCl after adding 10 drops of boric acid indicator solution. The color change at the endpoint was from green to pink: %TN in soil = ml HCl * 1.402 mg N × 100/5000 mg soil, = ml HCl * 0.02804, where, TN = Soil Total Nitrogen.

Soil available phosphorus was determined using modified Olsen's method (Olsen and Sommer, 1982). In order to compare phosphorus and potassium values (in ppm) with corresponding values in other studies, the values of other studies (in kg/hg) were converted to ppm by dividing it by 3 (Poon and Schmidt, 2010) and then compared with the present study. Based on this method, phosphorous was extracted from the soil with 0.5 M sodium bicarbonate ($NaHCO_3$) which can repress the concentration of calcium ions by precipitation as calcium carbonate and of aluminum and ferric ions by precipitation as hydroxides. Five g of soil was weighed in Erlenmeyer flask and one teaspoon of carbon black was added. Then, 100 ml of 0.5 M $NaHCO_3$ solution was added and shaken for 30 min. Ten ml of filtrate was pipetted out into a 50 ml volumetric flask and 30 ml of water and 3 drops of dinitro-phenol added into the volumetric flask and the pH was adjusted to 3 by adding H_2SO_4 drops. The volume was made up to 50 ml by adding water and 2 ml of ammonium molybdate-H_2SO_4 solution was added in it. Blue color was developed by adding 3 drops of stannous chloride. After 5 min, the absorbance was taken in spectrophotometer at a wavelength of 660 nm ppm P in soil = ppm in test solution * 100/5 * 50/10, = ppm P in test solution * 100, where, ppm = Parts per Million, P = Phosphorus.

Soil available potassium was determined by extracting with ammonium acetate where soil was leached with excess of neutral, 1N ammonium acetate solution to remove the exchangeable cations and saturate the exchange material with ammonium (Rhoades, 1982). After removal of the excess of ammonium present in the soil by salt solution as the acetate, the exchangeable ammonium is determined by distillation and then potassium was determined with the help of Atomic Absorption Spectrophotometer. Ten g of air-dried soil was weighed into a 50 ml beaker and 20 ml of ammonium acetate added and stirred. The liquid content was transferred quantitatively on a filter paper p1aced in buchner funnel fitted on a 500 ml suction flask, then 25 ml ammonium acetate was added to the beaker and stirred well. Then the liquid content was transferred on the filter paper again, and repeated 4 times to get a total 100 ml. The filter paper was then discarded and all the content was transferred in a bottle and soil available potassium was determined with the help of Atomic Absorption Spectrophotometer.

Soil organic matter followed by soil organic carbon was determined by the dry combustion method (Nelson and Sommers, 1982). The ground and sieved (through 0.5 mm mesh) 20–25 g soil were weighed into porcelain crucible. The crucible with soil was placed in hot air oven (105 °C) to remove moisture overnight, and then weighed using a 4 digit balance. The sample was then placed into muffle furnace (400° C) for 60 min; then placed in glass desiccators to cool for 20–30 min, and then weighed using 4-digit balance. Then soil organic matter and soil organic carbon were calculated as follows: Soil Organic Matter (%) = (Wcs - Wf)/(Wcs - Wc)*100, where, Wcs = Wt. of oven dried soil, Wf = Wt. of furnace fired soil, Wc = Wt. of crucible. In order to convert organic matter into organic carbon a conversion factor of 1.724 was used; as soil organic matter is assumed to contain 58% of organic carbon (Nelson and Sommers, 1982); Soil Organic Carbon (%) = 0.58 * Soil Organic Matter %.

Fig. A1. Each of the plots were categorized and assigned a color category according to three different colors of the pine needles; a) yellow, b) yellow–green, and c) green color of the pine needles. The close-up pictures below show the respective pine needle colors in more detail.

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