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ORIGINAL PAPER

Elevational gradients of terricolous lichen species richness in the Western Himalaya

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Abstract Elevation confers limitations on distribution of organisms through correlated variations in temperature, moisture, radiations and precipitation. The elevation gradients of terricolous lichen species richness in Garhwal, western Himalaya were assessed using generalized additive models, in order to compare distribution patterns of different growth-forms, photobiont types, and dominant families. A total of 148 terricolous lichen species belonging to 42 genera and 19 families were recorded. The total species richness showed unimodal relationship with elevation, where the highest species richness was observed at mid elevations (3,200 m). The species richness of lichens with green algae (chlorolichens) and of lichens with cyanobacteria (cyanolichens) also exhibited significant unimodal elevational patterns with cyanolichens peaked at somewhat lower (2,800–2,900 m) elevation than chlorolichens (3,200 m). Growth forms showed statistically significant relationship of species richness to elevation, with crustose and squamulose lichens reaching their maxima at higher elevation than foliose, fruticose and dimorphic terricolous lichens. Unimodal pattern of species richness was also followed by six dominant families, with these families reaching maximum richness at different elevations. Elevational variation in topography, climate, and competition from vascular plant communities, together with the tolerance of specific growth forms to zoo-anthropogenic pressures, shape the distribution of terricolous lichens in the Garhwal Himalaya.

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Introduction

Organisms occur in a characteristic, limited range of habitats and within this range they are found to be most abundant indicating their environmental optima (Körner 2003). The diversity and distributions of organisms are shaped by their physiological tolerance and context-specific competitive ability in response to environmental variables such as elevation, topography, moisture, temperature, precipitation, exposure to radiation and substrate attributes (i.e. stability, nutrients, and chemistry) (John and Dale 1990; Eldridge and Tozer 1997; Belnap and Gillette 1998; Ponzetti and McCune 2001). Elevational gradients in several of these environmental variables, are especially influential in determining the distribution patterns of animals and plants in mountainous areas (Hunter and Yonzon 1993; Vetaas and Grytnes 2002; Bhattarai et al. 2004; McCain 2004; Grau et al. 2007; Baniya 2010; Baniya et al. 2012).

Elevational gradients are among the most powerful drivers of the ecological and evolutionary responses of biota to geophysical influences (Körner 2003, 2007). Lichens, one of the most successful symbiotic associations of a fungus, a green and/or blue green alga, are known to inhabit nearly all the terrestrial domains of the planet (Galloway 1992). Although the distribution range of lichens is influenced by a diversity of environmental variables at multiple scales (Lalley et al. 2006), elevation is a key factor influencing lichen distribution and diversity in the mountainous landscape of Himalaya (Bruun et al. 2006; Pinokiyo et al. 2008; Baniya et al. 2010; Huang 2010; Baniya et al. 2012; Rai et al. 2012b).

The western Himalaya constitutes of diverse eco-climatic zones, ranging from subtropical (≤2,000 m), at foot hills through temperate (≤3,000 m) at intermediate elevations to alpine at higher elevations (≥3,000 m) (Singh and Singh 1987). Himalayan habitats harbor a rich diversity of lichens, which appears to display altitudinal zonation by growth form, with foliose lichens dominating at lower to mid elevations and by fruticose and dimorphic lichens at higher elevations within the alpine zone (Upreti 1998; Singh and Sinha 2010).

Among the various habitat subsets of lichens (i.e. epiphytic-corticolous, soil inhabiting-terricolous and rock inhabiting- saxicolous) soil inhabiting (terricolous) lichens are among the excellent indicators of ecosystem conditions and environmental quality (Will-Wolf et al. 2002). In contrast to dominant epiphytic lichens and mosses, terricolous lichens, due to their small size (low biomass) and very slow growth rates, face strong competition from flowering plants (Zedda et al. 2010). However the poikilohydric physiology of lichens, help them to sustain drought, heat or cold much better than vascular plants. Terricolous lichens can thus flourish in habitats where the flowering plants grow poorly or not at all, and so are unable to cover the ground completely. Such habitats are characterized by nutrient scarcity, harsh climate (e.g. wind exposed ridges, alpine tundra and alpine permafrost) and unsustainable edaphic conditions. Thus the soil lichens are specialists which flourish in habitats that are usually not very conducive for other vascular and cryptogamic plants.

Terricolous lichens are found to be good indicators of habitat heterogeneity and suitable indicators of zoo-anthropogenic pressures in alpine grasslands of the western Himalaya (Rai et al. 2012a, b). Except few sporadic mention of altitudinal distribution of some terricolous lichen taxa in Himalaya, there is no broad scale study dealing with the overall elevation patterns of soil lichens in the region (Rai et al. 2014a). The upward shift of snowline and the glacial melting, due to global warming provide new habitats for lichens which increases their elevational range (Insarov and Schroeter 2002; Pounds et al. 2005; Ellis and Yahr 2011). The rapid extension of elevation range of lichen species poses threat to adaptability of lichens and increases the probability of their extinction (Van Herk et al. 2002; Ellis et al. 2007; Price et al. 2013). Therefore there is urgent need to acquire baseline data on the elevational distributions of sensitive lichen groups such as terricolous lichens, for monitoring future changes and developing appropriate conservation measures.

Here we describe and interpret the elevational distribution of terricolous lichen species richness, with reference to their photobiont types, growth forms and taxonomic affinities in the Garhwal region of the western Himalaya.

Materials and methods

Study area

With a total area of 14,580 km^2, Garhwal is the north-western region and administrative division of the northern Indian state of Uttarakhand. The region lies in the western Himalaya and is bounded on the north by Tibet, on the east by the Kumaon region of Uttarakhand, on the south by Uttar Pradesh state, and on the west by Himachal Pradesh (Fig. 1). Garhwal region is comprised of seven districts: Chamoli, Dehradun, Haridwar, Pauri Garhwal, Rudraprayag, Tehri Garhwal, and Uttarkashi (Fig. 1). Topography of the area is mountainous ranging from 315 to 7,816 m. The terrain of the region consists almost entirely of rugged mountain ranges running in all directions, and separated by narrow valleys ravines and deep gorges. The Himalaya in this region is represented by the outer Himalaya/Shiwalik Range (500–1,200 m elevation) in Dehradun, Haridwar and southern area Pauri; the Lesser or Middle Himalaya (3,700–4,500 m) in Uttarkashi, Northern Pauri,

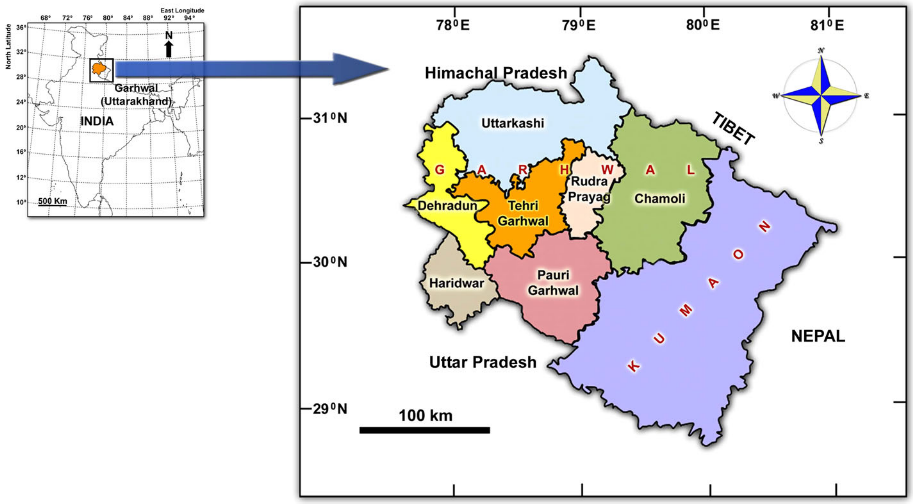

Fig. 1 Location map of Garhwal and its constituent districts in state of Uttarakhand (Maps and their grid over lay are based on the 1:1,000,000 State map of Uttarakhand, First edition, Survey of India, Department of science and technology, Government of India, 2001)

Tehri, Rudraprayag and Chamoli; and the Greater or Inner Himalaya (>4,500 m) in Uttarkashi, Rudraprayag and Chamoli.

The climate of Garhwal ranges from subtropical (i.e. Haridwar) to temperate (i.e. Dehradun) in foothills to temperate-alpine in higher elevations (i.e. Tehri, Pauri, Rudraprayag, Uttarkashi, Chamoli). Precipitation is mainly monsoonal, in the months of June to August. Average annual precipitation of the region is 1,550 mm, which ranges from 600 to 2,350 mm (Sharma et al. 2010). Though there is regular orographic precipitation at higher elevations (>2,700 m), maximum rainfall is received in the months of June to September (Nautiyal et al. 2001). Average annual temperature ranges from 19 to 37 °C (Rai et al. 2012b). Minimum temperature easily dips to subzero levels at higher elevations (up to −19 °C) during November-February (Rai et al. 2012b). Higher elevations receive maximum snowfall during November to April. Snowmelt is the major source of soil water prior to monsoons (Nautiyal et al. 2001, Rai et al. 2012b). The surface geology is of crystalline and metamorphic weathered bedrock with sedimentary deposits formed during the Paleozoic. Soils of the region are generally acidic (pH 4–5), coarse textured loam to sandy-loam at lower elevations to sandy at higher elevation (Sundriyal 1992; Rai et al. 2012b).

Garhwal Himalaya is the constituent component of the Central Himalayan Botanical region (Singh and Singh 1987). The vegetation in Garhwal Himalaya shows an elevational zonation leading from tropical deciduous forests and savannas to alpine grasslands and tundra along increasing altitudinal gradient. At foothills (450–1,000 m) the vegetation is deciduous type and main trees are Sal (*Shorea robusta*) and *Mallotus philippensis*. Between 1,000 and 2,000 m the dominant vegetation is sub-temperate consisting of Oaks (*Quercus* spp.). The elevational span of 2,000–3,000 m is dominated by moist temperate forests and main trees are Oaks (*Quercus* spp.), Pines (*Pinus* spp.), spruce (*Picea* spp.), *Rhododendron*, Bhojpatra/birch (*Betula* spp.) and Deodar/cedar (*Cedrus* spp.). Above 3,000 m, there is transition to alpine pastures and tundra characterized by shrubby *Rhododendron* coppices, *Anthopogon* and *Juniperus* and herbaceous species of *Anemone*, *Potentilla*, *Aster*, *Geranium*, *Meconopsis*, *Primula* and *Polemonium* (Singh and Singh 1987).

The Garhwal Himalaya harbor a rich diversity of lichens in the terms of both species and growth forms, which occupy all available relevés of a habitat (Upreti 1998; Upreti and Negi 1998). Terricolous lichens constitute about 9 % of total lichen species recorded from India and their major distribution ranges from temperate (1,500–3,000 m) to alpine (>3,000 m) habitats (Rai et al. 2012a, b). In Garhwal, terricolous lichens though constitute about 1.2–6.8 % of total lichen biota, their role in soil stabilization, as indicators of habitat and climate variability and anthropogenic pressures is far greater (Negi 2000; Rai et al. 2012a, b; Rai et al. 2014a).

Floristic studies

The present study is based on 912 terricolous lichen specimens collected from the Garhwal region of Uttarakhand, lodged in lichenology herbarium (LWG) of CSIR-National Botanical Research Institute, Lucknow, Uttar Pradesh, India. The circumscription of terricolous lichens followed Scheidegger and Clerc (2002), and included lichens growing directly on the ground, on ground over mosses, on soil accumulated on rocks, on mosses rooted in accumulated soil or organic debris on rocks, and on the ground over plant remains (Rai et al. 2014c). Lichen samples were examined and identified up to species level morpho-anatomically using a stereomicroscope (LEICA™ S8 APO), light microscope (LEICA™ DM 500), and chemically with the help of spot tests, UV light and standardized thin-layer chromatography (Elix and Ernst-Russel 1993; Orange et al. 2001). All the samples thus studied were compared with relevant literature for taxonomic determinations (Rai et al. 2014b).

The study provided elevation distribution data for 148 taxa (including species, subspecies, and varieties). For the purpose of this study, all the taxa were treated as 'species' (Baniya 2010; Baniya et al. 2010). In addition, data about growth forms, photobiont types (green algae and blue-green algae) and dominant families were also recorded. Lichens with green algae as sole photobiont were treated as chlorolichens, whereas lichens either with single blue green algal photobiont (i.e. bipartite) or having both a green alga and a blue-green alga (i.e. tripartite), were treated as cyanolichens.

Data analysis

Elevational patterns-generalized additive models (GAM)

The altitudinal range of terricolous lichens in Garhwal Himalaya, from 600 to 4,600 m, was divided into 41 elevational bands each of 100 m, and a complete set of a presence/absence of lichen species data matrix through altitude was prepared (Baniya 2010; Baniya et al. 2010). The presence of an individual terricolous lichen species to a particular altitude means that either the species has been collected in the past from that elevation or is housed somewhere in the lichen herbarium or it has the potentiality to occur. Absence means either that the species does not occur or it has previously not been collected from that elevation, e.g. the species "*Cladonia awasthiana* Ahti and Upreti" has found to be distributed from 2,097; 2,150; 2,286 and 3,500 m elevations according to exact herbarium data. In our treatment this species comes at all 15 elevation bands from 2,100 to 3,500 m. This also applies for its algal component and the lichen growth forms. This is a macro-scale study (gamma diversity, sensu Whittaker 1972) where the definition of species richness applies for the total number of terricolous lichen species occurring in each 100 m altitudinal band covering the entire altitudinal range of Garhwal Himalaya.

Patterns related to the total richness of terricolous lichen species, growth forms, photobiont type and the dominant lichen families represented were regarded as response variables and their elevations as predictor variable. Each of their patterns was extracted through application of cubic smooth spline (s) within the framework of generalized additive models (GAM) with default of ca. 8° of freedom (Hastie and Tibshirani 1990; Heegaard 2004).

Response variables are counts; thus, the variance changes with the mean and negative predictions are meaningless. Over-dispersion in data was found, therefore Quasi-poisson family error distribution with a logarithmic link function was applied (Crawley 2006). The change in deviance followed F-distribution. Open source programming language and software environment R 2.14.1 (R Development Core Team 2011) was used to analyze our data and cubic smooth spline was fitted through application of library GAM (Hastie and Tibshirani 1990). GAM was used because it is a non-parametric approach that does not make a priori assumptions about the species-elevational relationship (Baniya et al. 2010).

Results

The study revealed occurrence of 148 terricolous lichen species belonging to 42 genera and 19 families in the area (Table 1). *Cladoniaceae* was the most diverse family with 35 species, followed by *Parmeliaceae* (27 species), *Collemataceae* (18 species),

Table 1 Elevational ranges of terricolous lichens of Garhwal Himalayas, their family and growth forms

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
1	*Acarospora schleicheri*	*Acarosporaceae*	Gr	Cr	3,200	3,871	3
2	*Allocetraria ambigua*	*Parmeliaceae*	Gr	Fl	3,840	–	2
3	*A. flavonigrescens*	*Parmeliaceae*	Gr	Fl	3,700	3,810	2
4	*A. stracheyi*	*Parmeliaceae*	Gr	Fl	3,840	–	2
5	*Bryoria confusa*	*Parmeliaceae*	Gr	Fr	3,000	–	1
6	*Bulbothrix meizospora*	*Parmeliaceae*	Gr	Fl	1,280	–	1
7	*Cetraria aculeata*	*Parmeliaceae*	Gr	Fl	3,840	3,841	3
8	*C. islandica*	*Parmeliaceae*	Gr	Fl	3,871	–	1
9	*C. laevigata*	*Parmeliaceae*	Gr	Fl	3,340	–	1
10	*C. nigricans*	*Parmeliaceae*	Gr	Fl	3,350	3,871	2
11	*C. odontella.*	*Parmeliaceae*	Gr	Fl	3,600	3,810	2
12	*Cetrelia olivetorum*	*Parmeliaceae*	Gr	Fl	2,850	–	1
13	*Cladia aggregata*	*Cladoniaceae*	Gr	Fr	4,200	–	1
14	*Cladonia awasthiana*	*Cladoniaceae*	Gr	Dm	2,097	3,500	4
15	*C. borealis*	*Cladoniaceae*	Gr	Dm	4,000	4,050	2
16	*C. cariosa*	*Cladoniaceae*	Gr	Dm	2,324	–	1
17	*C. cartilaginea*	*Cladoniaceae*	Gr	Dm	1,067	3,400	24
18	*C. ceratophyllina*	*Cladoniaceae*	Gr	Dm	3,000	–	1
19	*C. chlorophaea*	*Cladoniaceae*	Gr	Dm	2,324	3,901	43
20	*C. coccifera*	*Cladoniaceae*	Gr	Dm	3,400	3,750	15
21	*C. coniocraea*	*Cladoniaceae*	Gr	Dm	2,052	3,123	7
22	*C. corniculata*	*Cladoniaceae*	Gr	Dm	1,200	3,901	28
23	*C. corymbescens*	*Cladoniaceae*	Gr	Dm	1,400	3,900	24
24	*C. crispata* var. *cetrariiformis*	*Cladoniaceae*	Gr	Dm	3,250	–	1

Table 1 continued

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
25	*C. delavayi*	*Cladoniaceae*	Gr	Dm	4,050	–	1
26	*C. fenestralis*	*Cladoniaceae*	Gr	Dm	2,100	3,900	4
27	*C. fimbriata*	*Cladoniaceae*	Gr	Dm	2,900	3,962	16
28	*C. fruticulosa*	*Cladoniaceae*	Gr	Dm	1,379	3,300	13
29	*C. furcata*	*Cladoniaceae*	Gr	Dm	560	2,881	12
30	*C. humilis*	*Cladoniaceae*	Gr	Dm	2,850	–	1
31	*C. laii*	*Cladoniaceae*	Gr	Dm	2,700	3,900	2
32	*C. macilenta*	*Cladoniaceae*	Gr	Dm	2,150	–	1
33	*C. macroceras*	*Cladoniaceae*	Gr	Dm	4,200	–	1
34	*C. macroptera*	*Cladoniaceae*	Gr	Dm	2,743	–	1
35	*C. mongolica*	*Cladoniaceae*	Gr	Dm	3,150	3,750	2
36	*C. ochrochlora*	*Cladoniaceae*	Gr	Dm	1,829	3,650	18
37	*C. pocillum*	*Cladoniaceae*	Gr	Dm	2,743	4,115	41
38	*C. pyxidata*	*Cladoniaceae*	Gr	Dm	2,200	4,200	85
39	*C. ramulosa*	*Cladoniaceae*	Gr	Dm	1,800	3,000	6
40	*C. rangiferina*	*Cladoniaceae*	Gr	Dm	3,128	–	1
41	*C. rei.*	*Cladoniaceae*	Gr	Dm	3,200	–	1
42	*C. scabriuscula*	*Cladoniaceae*	Gr	Dm	1,776	3,400	11
43	*C. singhii*	*Cladoniaceae*	Gr	Dm	1,200	2,238	2
44	*C. squamosa*	*Cladoniaceae*	Gr	Dm	1,524	3,123	6
45	*C. subradiata*	*Cladoniaceae*	Gr	Dm	1,379	3,137	15
46	*C. subulata*	*Cladoniaceae*	Gr	Dm	2,850	3,000	2
47	*C. verticillata*	*Cladoniaceae*	Gr	Dm	1,401	2,134	3
48	*Coccocarpia erythroxyli*	*Coccocarpiaceae*	Bg	Fr	3,000	4,115	10

Table 1 continued

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
49	*C. palmicola*	*Coccocarpiaceae*	Bg	Fl	1,200	1,300	3
50	*C. pellita*	*Coccocarpiaceae*	Bg	Fl	1,286	1,300	2
51	*Collema furfuraceum*	*Collemataceae*	Bg	Fl	3,100	–	1
52	*C. furfureolum*	*Collemataceae*	Bg	Fl	2,804	–	1
53	*C. polycarpon*	*Collemataceae*	Bg	Fl	3,660	–	2
54	*C. pulchellum* var. *subnigrescens*	*Collemataceae*	Bg	Fl	1,100	2,300	11
55	*C. ryssoleum*	*Collemataceae*	Bg	Fl	1,798	1,890	2
56	*C. subconveniens*	*Collemataceae*	Bg	Fl	1,000	1,890	2
57	*C. subflaccidum*	*Collemataceae*	Bg	Fl	2,804	–	1
58	*C. tenax*	*Collemataceae*	Bg	Fl	1,200	2,804	5
59	*C. tenax* var. *corallinum*	*Collemataceae*	Bg	Fl	3,000	–	1
60	*Dermatocarpon vellereum*	*Verrucariaceae*	Gr	Fl	3,000	–	1
61	*Endocarpon subrosettum*	*Verrucariaceae*	Gr	Sq	3,340	3,871	2
62	*Evernia mesomorpha*	*Parmeliaceae*	Gr	Fr	3,104	3,901	8
63	*Everniastrum cirrhatum*	*Parmeliaceae*	Gr	Fl	2,390	3,400	5
64	*Flavocetraria cucullata*	*Parmeliaceae*	Gr	Fl	3,840	–	1
65	*Flavoparmelia caperata*	*Parmeliaceae*	Gr	Fl	3,118	–	1
66	*Flavopunctelia soredica*	*Parmeliaceae*	Gr	Fl	3,104	–	1
67	*Fuscopannaria saltuensis*	*Pannariaceae*	Bg	Sq	3,648	–	1
68	*Heterodermia angustiloba*	*Physciaceae*	Gr	Fl	1,500	3,005	2
69	*H. diademata*	*Physciaceae*	Gr	Fl	1,550	4,267	6
70	*H. firmula*	*Physciaceae*	Gr	Fl	1,300	1,360	4
71	*H. hypocaesia*	*Physciaceae*	Gr	Fl	3,000	–	3
72	*H. japonica*	*Physciaceae*	Gr	Fl	2,850	3,100	2

Table 1 continued

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
73	*H. leucomelos*	*Physciaceae*	Gr	Fl	3,340	–	2
74	*H. microphylla*	*Physciaceae*	Gr	Fl	3,100	–	1
75	*H. obscurata*	*Physciaceae*	Gr	Fl	3,400	–	1
76	*H. pseudospeciosa*	*Physciaceae*	Gr	Fl	1,800	1,871	2
77	*H. rubescens*	*Physciaceae*	Gr	Fl	2,134	–	1
78	*H. speciosa*	*Physciaceae*	Gr	Fl	2,200	–	2
79	*Hypogymnia enteromorpha*	*Parmeliaceae*	Gr	Fl	3,128	–	1
80	*Hypotrachyna adducta*	*Parmeliaceae*	Gr	Fl	3,137	–	1
81	*H. crenata*	*Parmeliaceae*	Gr	Fl	1,911	–	1
82	*Lempholemma chalazanum*	*Lichinaceae*	Bg	Sq	1,036	–	1
83	*Lepraria caesioalba* var. *groenlandica*	*Sterocaulaceae*	Gr	Cr	2,850	3,133	2
84	*L. lobificans*	*Sterocaulaceae*	Gr	Cr	1,835	–	1
85	*L. neglecta*	*Sterocaulaceae*	Gr	Cr	3,400	–	2
86	*Leptogium askotense*	*Collemataceae*	Bg	Fl	1,000	3,200	5
87	*L. burnetiae*	*Collemataceae*	Bg	Fl	1,650	3,550	20
88	*L. cyanescens*	*Collemataceae*	Bg	Fl	1,890	3,650	7
89	*L. denticulatum*	*Collemataceae*	Bg	Fl	1,300	–	1
90	*L. pedicellatum*	*Collemataceae*	Bg	Fl	1,524	3,900	34
91	*L. phyllocarpum*	*Collemataceae*	Bg	Fl	1,350	1,820	2
92	*L. saturninum*	*Collemataceae*	Bg	Fl	1,700	3,100	6
93	*L. teretiusculum*	*Collemataceae*	Bg	Fl	2,760	–	1
94	*L. trichophorum*	*Collemataceae*	Bg	Fl	2,250	3,900	4
95	*Melanelia hepatizon*	*Parmeliaceae*	Gr	Fl	3,500	3,840	3
96	*M. stygia*	*Parmeliaceae*	Gr	Fl	3,500	–	1

Table 1 continued

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
97	*M. panniformis*	*Parmeliaceae*	Gr	Fl	3,340	–	1
98	*M. tominii*	*Parmeliaceae*	Gr	Fl	3,660	–	1
99	*Melanelixia villosella*	*Parmeliaceae*	Gr	Fl	3,100	3,340	5
100	*Mycobilimbia hunana*	*Lecideaceae*	Gr	Cr	1,350	–	1
101	*M. philippina*	*Lecideaceae*	Gr	Cr	2,438	–	1
102	*Nephroma helveticum*	*Nephromataceae*	Bg	Fl	1,850	3,600	7
103	*N. parile*	*Nephromataceae*	Bg	Fl	3,200	3,650	3
104	*Parmelia masonii*	*Parmeliaceae*	Gr	Fl	2,200	–	1
105	*P. sulcata*	*Parmeliaceae*	Gr	Fl	3,104	3,340	5
106	*Parmelinella wallichiana*	*Parmeliaceae*	Gr	Fl	2,200	–	1
107	*Peccania synalliza*	*Lichinaceae*	Bg	Cr	3,505	–	1
108	*Peltigera canina*	*Peltigeraceae*	Bg	Fl	1,400	3,962	27
109	*P. didactyla*	*Peltigeraceae*	Bg	Fl	2,134	3,658	5
110	*P. dolichorrhiza*	*Peltigeraceae*	Bg	Fl	2,134	2,590	3
111	*P. elisabethae*	*Peltigeraceae*	Bg	Fl	1,700	3,450	4
112	*P. horizontalis*	*Peltigeraceae*	Bg	Fl	3,505	3,700	4
113	*P. lepidophora*	*Peltigeraceae*	Bg	Fl	3,617	–	1
114	*P. malacea*	*Peltigeraceae*	Bg	Fl	4,500	–	1
115	*P. membranacea*	*Peltigeraceae*	Bg	Fl	3,300	–	1
116	*P. pindarensis*	*Peltigeraceae*	Bg	Fl	3,300	–	1
117	*P. polydactylon*	*Peltigeraceae*	Bg	Fl	1,890	3,962	34
118	*P. polydactylon* var. *pruinosa*	*Peltigeraceae*	Bg	Fl	2,150	2,700	2
119	*P. praetextata*	*Peltigeraceae*	Bg	Fl	1,590	3,840	49
120	*P. rufescens*	*Peltigeraceae*	Bg	Fl	1,829	4,500	60

Table 1 continued

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
121	*Phaeophyscia hispidula*	*Physciaceae*	Gr	Fl	1,796	3,200	2
122	*Physcia adscendens*	*Physciaceae*	Gr	Fl	3,840	–	1
123	*P. caesia*	*Physciaceae*	Gr	Fl	3,841	–	1
124	*P. dilatata*	*Physciaceae*	Gr	Fl	3,505	–	1
125	*Physconia detersa*	*Physciaceae*	Gr	Fl	3,133	–	1
126	*P. grisea*	*Physciaceae*	Gr	Fl	3,400	–	1
127	*Ramalina hossei*	*Ramalinaceae*	Gr	Fr	2,850	3,400	2
128	*Rhizoplaca chrysoleuca*	*Lecanoraceae*	Gr	Sq	3,152	–	1
129	*R. melanophthalma* var. *obscura*	*Lecanoraceae*	Gr	Sq	3,452	–	1
130	*Stereocaulon alpinum*	*Sterocaulaceae*	Gr/Bg	Dm	3,400	3,800	2
131	*S. foliolosum*	*Sterocaulaceae*	Gr/Bg	Dm	1,800	3,900	8
132	*S. foliolosum* var. *botryophorum*	*Sterocaulaceae*	Gr/Bg	Dm	3,123	–	1
133	*S. foliolosum* var. *strictum*	*Sterocaulaceae*	Gr/Bg	Dm	2,850	3,400	9
134	*S. massartianum*	*Sterocaulaceae*	Gr/Bg	Dm	2,900	–	1
135	*S. myriocarpum*	*Sterocaulaceae*	Gr/Bg	Dm	3,340	4,200	31
136	*S. pomiferum*	*Sterocaulaceae*	Gr/Bg	Dm	2,850	–	1
137	*Sticta henryana*	*Lobariaceae*	Gr	Fl	2,400	4,500	3
138	*S. indica*	*Lobariaceae*	Gr	Fl	2,700	–	1
139	*S. limbata*	*Lobariaceae*	Bg	Fl	1,860	3,200	2
140	*S. nylanderiana*	*Lobariaceae*	Gr	Fl	3,000	–	1
141	*S. platyphylloides*	*Lobariaceae*	Gr	Fl	2,850	3,000	2
142	*S. praetextata*	*Lobariaceae*	Gr	Fl	3,150	3,300	2
143	*Toninia tristis* ssp. *asiae-centralis*	*Ramalinaceae*	Gr	Sq	3,340	3,900	3
144	*T. tristis* ssp. *scholanderii*	*Ramalinaceae*	Gr	Sq	3,900	4,000	2

Table 1 continued

S. No.	Name of lichen species	Family	Algal photobiont	Growth Form	Altitudinal range (m)		Number of specimens examined
					Min.	Max.	
145	*T. vermicularis* var. *subuliformis*	*Icmadophilaceae*	Gr	Fr	3,840	–	3
146	*T. vermicularis* var. *vermicularis*	*Icmadophilaceae*	Gr	Fr	2,200	4,572	11
147	*Umbilicaria indica*	*Umbilicariaceae*	Gr	Fl	3,700	–	1
148	*Xanthoparmelia terricola*	*Parmeliaceae*	Gr	Fl	3,204	–	1

Gr green algae, *Bg* blue green algae, *Gr*/*Bg* both green algae and blue green algae

Cr crustose, *Fl* foliose, *Fr* fruticose, *Sq* squamulose, *Dm* dimorphic

Peltigeraceae (13 species), *Stereocaulaceae* (10 species) and *Physciaceae* (6 species) (Table 1). Lichens with green algae as the photobiont included 103 taxa; 39 species had blue green algae as the photobiont, and seven species had both green algae and blue green algae as photobiont (Table 1).

The total terricolous lichen species richness showed a significant curvilinear (unimodal) relationship with elevation (Table 2; Fig. 2a). The maximum modelled total species richness of 48 species occurred at 3,200 m (Fig. 2a). Similar significant unimodal relation of species richness occurred in chlorolichens and cyanolichens, with a maximum modeled richness of 19 cyanolichen species between 2,800 and 2,900 m (Table 2; Fig. 2b), and 33 chlorolichen species at 3,200 m (Table 2; Fig. 2c).

Five growth forms were recorded: crustose, squamulose, foliose, fruticose and dimorphic (squamules as primary thallus bearing erect fruticose body as secondary thallus). Among these, foliose lichens were taxonomically more diverse (86 species), followed by dimorphic (41 species) and crustose (7 species) lichens (Table 1). All growth forms showed significant statistical results with altitude, but clear significant curvilinear unimodal relationship was found between foliose, fruticose and dimorphic terricolous lichens (Table 2; Fig. 3). Among the growth-forms recorded, the crustose and squamulose taxa peaked at higher altitudes (1.4 spp. at 3,400–3,500 m for crustose taxa; 3.0 spp. at 3,600 m for squamulose forms), while foliose had their maximum predicted richness at lower altitudes (25 spp. at 2,900 m) (Fig. 3a–c). Fruticose (4 spp.) and dimorphic (21 spp.) growth forms peaked at intermediate (3,100 m) elevation (Fig. 3d, e).

Among the dominant families, primary six dominant families (i.e. *Cladoniaceae*, *Collemataceae*, *Parmeliaceae*, *Peltigeraceae*, *Physciaceae* and *Stereocaulaceae*) showed significant curvilinear (unimodal) relationship (Fig. 4; Table 2). *Cladoniaceae* peaked with

Table 2 The regression analyses results modelled after different species richness variables as response variables and each of their elevation as predictor variable

Response variables	Null *df*	Res. *df*	D^2	Deviance	*F*	Pr (>*F*)
Total richness	40	32	0.9798	594.56	208.13	<0.001
Blue green algal lichen	35	26	0.9821	153.19	164.84	<0.001
Green algal lichen	40	33	0.961	389.9	126.38	<0.001
Crustose	25	22	0.46947	9.9	6.2	<0.001
Squamulose	30	24	0.974667	47.17	146.4	<0.001
Foliose	35	26	0.9613	187.8	75.9	<0.001
Fruticose	24	16	0.942463	16.3	36.5	<0.001
Dimorphic	36	27	0.98025	174.6	153.8	<0.001
Cladoniaceae	36	27	0.98317	150	178.3	<0.001
Collemataceae	29	23	0.88268	21.9	31.7	<0.001
Parmeliaceae	26	23	0.7320	56.378	23.76	<0.001
Peltigeraceae	31	22	0.96851	48.146	48.146	<0.001
Physciaceae	30	24	0.7621	15.79	13.249	<0.001
Stereocaulaceae	24	19	0.72584	13.374	11.196	<0.001

The Quasi-poisson family of error fitted by the GAM model after the cubic spline (s) with approximately 8° of freedom. ($P \leq 0.05$)

df degrees of freedom, D^2 coefficient of determination, *Res.* residual deviance, *F* Fischer value, *Pr* (>*F*) probability of test statistics

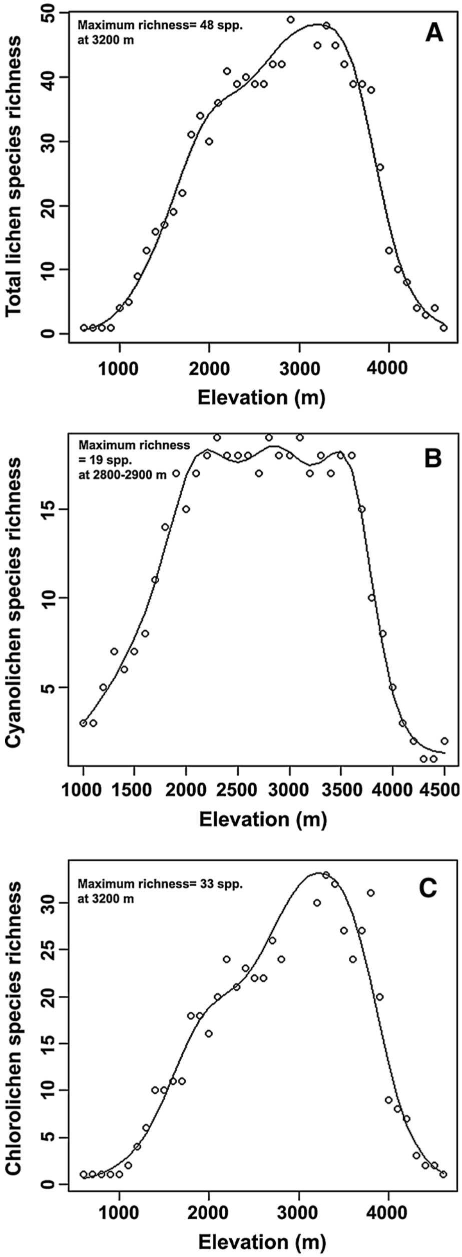

Fig. 2 Relationship between elevation and terricolous lichen species richness from Garhwal Himalaya. **a** Total terricolous lichen species richness; **b** Cyanolichen species richness; **c** Chlorolichen species richness. The fitted regression line represents the statistically significant (P ≤ 0.001) smooth spline (s) after using GAM with approximately 8° of freedom

maximum species richness of 19 species at 3,000 m (Fig. 4a), followed by *Collemataceae* and *Peltigeraceae* (with maximum species richness of 8 spp. at 1,900–2,000 m and 2,400 m respectively) (Fig. 4b, c), *Parmeliaceae* (maximum species richness of 6 spp. at 3,900 m) (Fig. 4d), *Physciaceae* and *Stereocaulaceae* (with maximum species richness of 4 spp. at 3,000–3,100 m and 3,200–3,500 m respectively) (Fig. 4e, f).

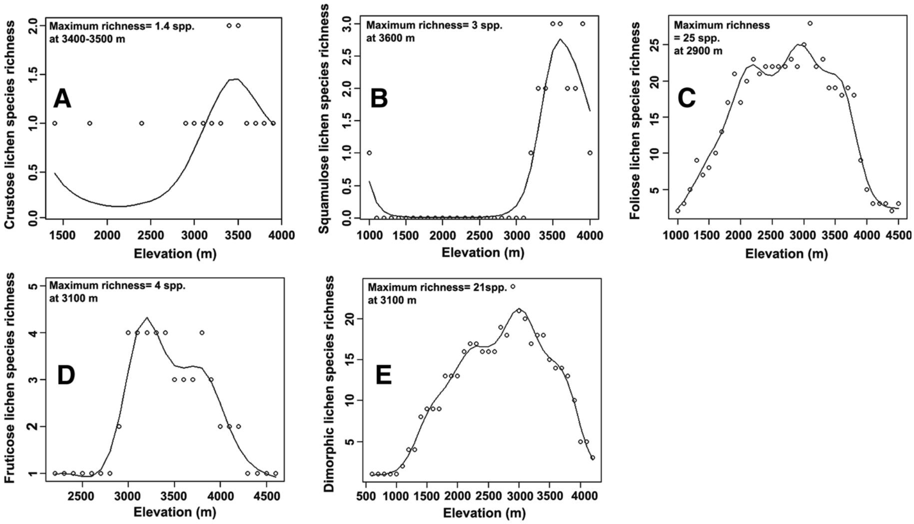

Fig. 3 Relationship between elevation and terricolous lichen species richness from Garhwal Himalaya. **a** Crustose terricolous lichen species richness; **b** Squamulose terricolous lichen species richness; **c** Foliose terricolous lichen species richness; **d** Fruticose terricolous lichen species richness; **e** Dimorphic terricolous lichen species richness. The fitted regression line represents the statistically significant ($P \leq 0.001$) smooth spline (s) after using GAM with approximately 8° of freedom

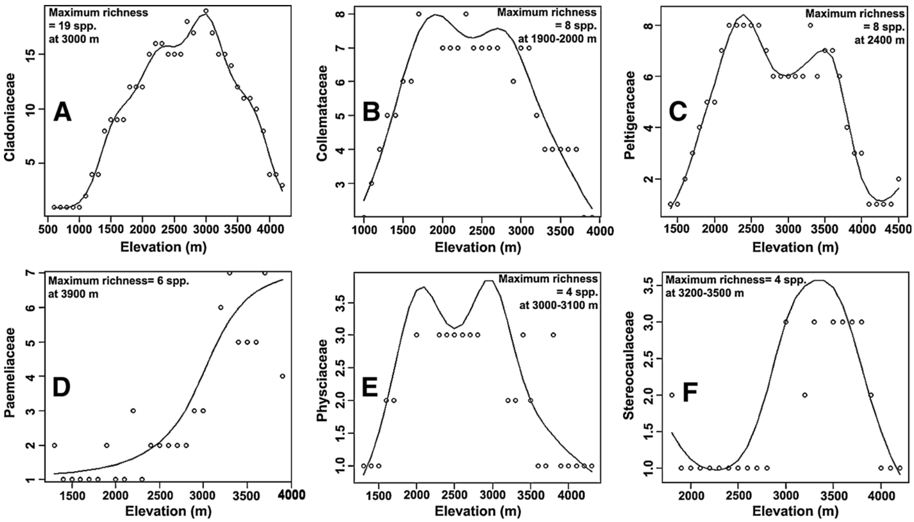

Fig. 4 Elevational richness pattern showed by dominant terricolous lichen families in Garhwal Himalaya. **a** *Cladoniaceae*; **b** *Collemataceae*; **c** *Peltigeraceae*; **d** *Parmeliaceae*; **e** *Physciaceae* and **f** *Stereocaulaceae*. The fitted regression line represents the statistically significant ($P \leq 0.001$) smooth spline (s) after using GAM with approximately 8° of freedom

Discussion

The total species richness of terricolous lichen varies strongly with elevation (Fig. 2a), peaking at mid elevations, in parallel with vascular plants (Grytnes and Vetaas 2002;

Vetaas and Grytnes 2002; Bhattarai and Vetaas 2003; Bhattarai et al. 2004), bryophytes (Grau et al. 2007) and all other lichens (Grytnes et al. 2006) in Himalayan and similar habitats. Terricolous lichen species richness tends to peak at intermediate elevations i.e. 3,200 m (Fig. 2a), which is in accordance with other similar studies worldwide (Wolf 1993; Wolseley and Aguirre-Hudson 1997; Negi 2000; Wolf and Alejandro 2003; Pinokiyo et al. 2008; Baniya et al. 2010; Rai et al. 2012a, b). The mid elevations represents the upper temperate zone in the Himalaya, which receives highest rainfall in monsoon (>4,000 mm), which decreases from southernmost slopes to northernmost slopes, due to local drying by Himalayan föhn (Miehe 1989). The high atmospheric moisture and cooler summer temperatures at mid elevations is likely to favor terricolous lichens. Phytosociological factors such as decrease in competition from vascular plants also contribute to the mid-elevational peak species richness of terricolous lichens, as at these heights the tree canopy starts to thin out in Himalaya (Baniya et al. 2010; Rawat 2011). The decrease in terricolous lichen species richness beyond mid elevations can be attributed to decrease in overall soil cover, as the landscape at higher elevations is dominated by exposed rocks, and soil crusts are limited to rock crevices and some flat faces of rocks (Rai et al. 2012a, b).

The lower peak altitudinal distribution of cyanolichens than that of chlorolichens is in accordance with the different physiological needs of hydration by the two groups respectively, where cyanolichens need liquid water for positive net photosynthesis, chlorolichens are able to achieve net photosynthetic carbon gain through water vapour uptake alone (Lange et al. 1986; Lange 2003). The elevations at which cyanolichens reach peak richness (i.e. 2,800–2,900 m) in the Garhwal Himalayas receive more moisture than of higher elevations, through orographic as well as seasonal monsoon precipitation (Bhattarai et al. 2004). Further upslope, the frigid soil temperature regimes at higher elevations limit the water availability to cyanolichens, which negatively affects the net photosynthesis and respiration of thallus (Kershaw 1977; MacFarlane and Kershaw 1980; Brown and Kershaw 1984). The physiological constraints posed by subzero soil temperature at higher elevation (>3,500 m) restrain cyanolichens extension to alpine elevations (Belnap et al. 2001; Rosentreter et al. 2014). Thus in temperate-alpine habitats the stress-gradients produced by the abiotic factors influence the spatial co-occurrence and segregation of chlorolichens and cyanolichens (Maestre et al. 2009).

Among the growth forms, the higher peak altitudinal distribution and low species turnout of crustose and squamulose growth forms is in accordance to other such studies in Himalayan habitats (Baniya 2010; Baniya et al. 2012), which can be attributed to decreasing soil cover, low atmospheric humidity and poor soil nutrients (carbon and nitrogen) at higher elevations (Baniya et al. 2012; Rai et al. 2012a, b). Mid altitudinal distribution of fruticose and dimorphic growth forms can be explained by the tolerant nature of these forms to harsh climate extremes, acidic soils and deterrence to disturbance induced by grazing, which is the major land use at mid altitudes in Himalaya (Sheard 1968; Nautiyal et al. 2004; Rai et al. 2012a, b). Fruticose growth forms, in well-lit higher elevations have the advantage of being able to utilize light from all direction than foliose lichens, which can maximize the harvest of more or less unidirectional light (Gauslaa et al. 2009). Further the dissected fruticose lichens have high surface area: volume ratio (Purvis 2000), making them more closely coupled to ambient atmosphere than flat foliose lichens and absorb moisture more readily from air (Jonsson et al. 2008; Baniya et al. 2010).

The comparative tolerant nature of various growth forms is also exemplified in the elevational distribution of species of six dominant families of terricolous lichens in Garhwal Himalaya. The highest elevational distribution (3,900 m; 6 species) achieved in *Parmeliaceae* appears due to the presence of tussock forming species (i.e. *Allocetraria* *ambigua*). Such cushion forming habitus is favoured in both vascular and cryptogamic vegetation at these altitudes (Körner 2003; Baniya et al. 2012). *Cladoniaceae* (3,000 m; 19 species) and *Stereocaulaceae* (3,200–3,500 m; 4 spp.) reached maximum species richness at mid elevations, most likely due to their lower palatability, and greater structural robustness of their dimorphic growth forms, which provides deterrence to grazing and resistance to trampling (Ahti et al. 1973; Grabherr 1982; Rai et al. 2012a, b). The higher species turnover of dimorphic growth form harboring families (*Cladoniaceae* and *Stereocaulaceae*) at their peak elevation, can be attributed to the tolerance of these species to acidic soil pH and frigid atmospheric temperature in the Garhwal Himalaya (Ahti 1964; Rai et al. 2012b). The lower altitudinal distribution of terricolous cyanolichen families—*Collemataceae* and *Peltigeraceae* is in accordance with the physiological hydration needs of constituent species and comparatively lower grazing pressures at these altitudes, where open grasslands are not very common in Himalaya (Rai et al. 2012a, b).

Conclusion

The study revealed a strong influence of elevation on distribution of terricolous lichens in Garhwal Himalaya, where they show unimodal patterns, similar to those seen in other taxonomic groups (i.e. vascular plants, mosses and ferns), but at higher elevations. The maximum terricolous richness at mid elevations includes regions in the Himalaya with high diversity of ecological niches in terms of habitat heterogeneity, reduced vegetative competition, suitable climate (i.e. rainfall, temperature), and soil cover. The study identifies the altitudinal optimums for terricolous lichens in western Himalaya. Terricolous lichens are a major component of ground vegetation at these elevations and play a vital role in maintaining the stability of soil crusts. The mid elevations where major concentration of terricolous lichens occur are predominately used as alpine pastures (*Bugyals*), which expose them to grazing induced zoo-anthropogenic pressures. Our findings highlights the vulnerability of terricolous lichen rich habitats in Himalaya, which should be taken into account for formulation of conservation and management practices. These habitats can be conserved through sustainable management measures, such as checks on frequency and span of grazing by livestock and formation of approach paths in areas where tourism based movement exists.

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