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CONTEMPORARY AND POST-GLACIAL RATES OF AEOLIAN DEPOSITION IN THE COAST MOUNTAINS OF BRITISH COLUMBIA, CANADA

BY
PHILIP N. OWENS[1] AND OLAV SLAYMAKER[2]

[1]Department of Geography, University of Exeter, Exeter, UK
[2]Department of Geography, University of British Columbia, Vancouver, Canada

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ABSTRACT. Contemporary and post-glacial rates of aeolian deposition are determined for three small catchments that straddle the alpine–subalpine ecotone in the Pacific Ranges of the Coast Mountains of British Columbia. From process measurement over a single year, the mean annual regional (allochthonous) rate of aeolian deposition for the catchments is estimated to be approximately 11 g m^{-2}. The average rate of annual deposition over the post-glacial period is calculated from the soil profiles to be c. 6 g m^{-2}, although fallout rates are likely to have varied significantly over the Holocene epoch due to changes in climate and catchment conditions. It would appear that the vegetated ground strata in these catchments are net receivers of aeolian dust fallout. Consequently, many of the soils are cumulic in nature and protect the bedrock in these catchments from subaerial weathering. These results have implications for sediment transfers in alpine and subalpine environments in southwestern British Columbia.

Key words: aeolian deposition, atmospheric dust fallout, alpine environment, cumulic soils, sediment supply, British Columbia.

Introduction

Recent studies have shown that contemporary rates of aeolian dust fallout may be relatively high both below (Franzén and Hjelmroos 1988; Franzén 1989; Nihlén and Mattsson 1989) and above (Izmailow 1984; Darmody and Thorn 1987; Dahms and Rawlins 1996) the tree-line. Reported annual rates of continental dust deposition vary from <10 to about 200 g m^{-2} (Pye 1987). Present-day aeolian infall to the alpine zone of many mountain ranges has been identified as an important pedogenic and geomorphic process (Birkeland 1973; Burns 1980; Dumanski *et al.* 1980; Kotarba 1987; Litaor 1987; Dahms 1993), although there is still some controversy surrounding this issue (cf. Litaor 1987, 1988; Munn 1988, 1992; Munn and Spackman 1990; Dahms 1992). Similarities in the grain size distribution of aeolian material and sediments in alpine and subalpine lakes have convinced several authors (e.g. Caine 1974; Andrews *et al.* 1984, 1985; Harbor 1985) that aeolian infall is the dominant source of the sediment contained within these lakes. Some studies have also been concerned with identifying the source areas of aeolian dust (Dahms 1993; Orange *et al.* 1993; Franzén *et al.* 1994; Wasklewicz and Meek 1995).

Little information currently exists on the importance of aeolian deposition in British Columbia, particularly in alpine and subalpine environments. Furthermore, virtually all existing data on rates of aeolian fallout have been estimated from short-term process studies and few studies have attempted to examine fallout rates over longer periods of time. This paper presents data on both contemporary and post-glacial rates of aeolian deposition in three small catchments that straddle the alpine–subalpine ecotone in the Pacific Ranges of the Coast Mountains of British Columbia. The alpine zone is defined here as the altitudinal zone above the upper limit of continuous forest (Löve 1970).

Study area and research methodology

Study area

The study area is located 120 km north of Vancouver, southwestern British Columbia, Canada (Fig. 1). Catchment characteristics are given in Table 1. The study catchments are not glacierised, although active alpine glaciers are locally common (as the Pacific Ranges are oceanic) and present glaciers extend downslope to elevations of 1500 m above sea level. The three study catchments each contain a small oligotrophic lake that defines the lower limit of the basin (Fig. 2). The present mesoscale climate is cold perhumid. There are limited data on air temperature, although Gallie (1983) found that temperatures in the study area ranged between

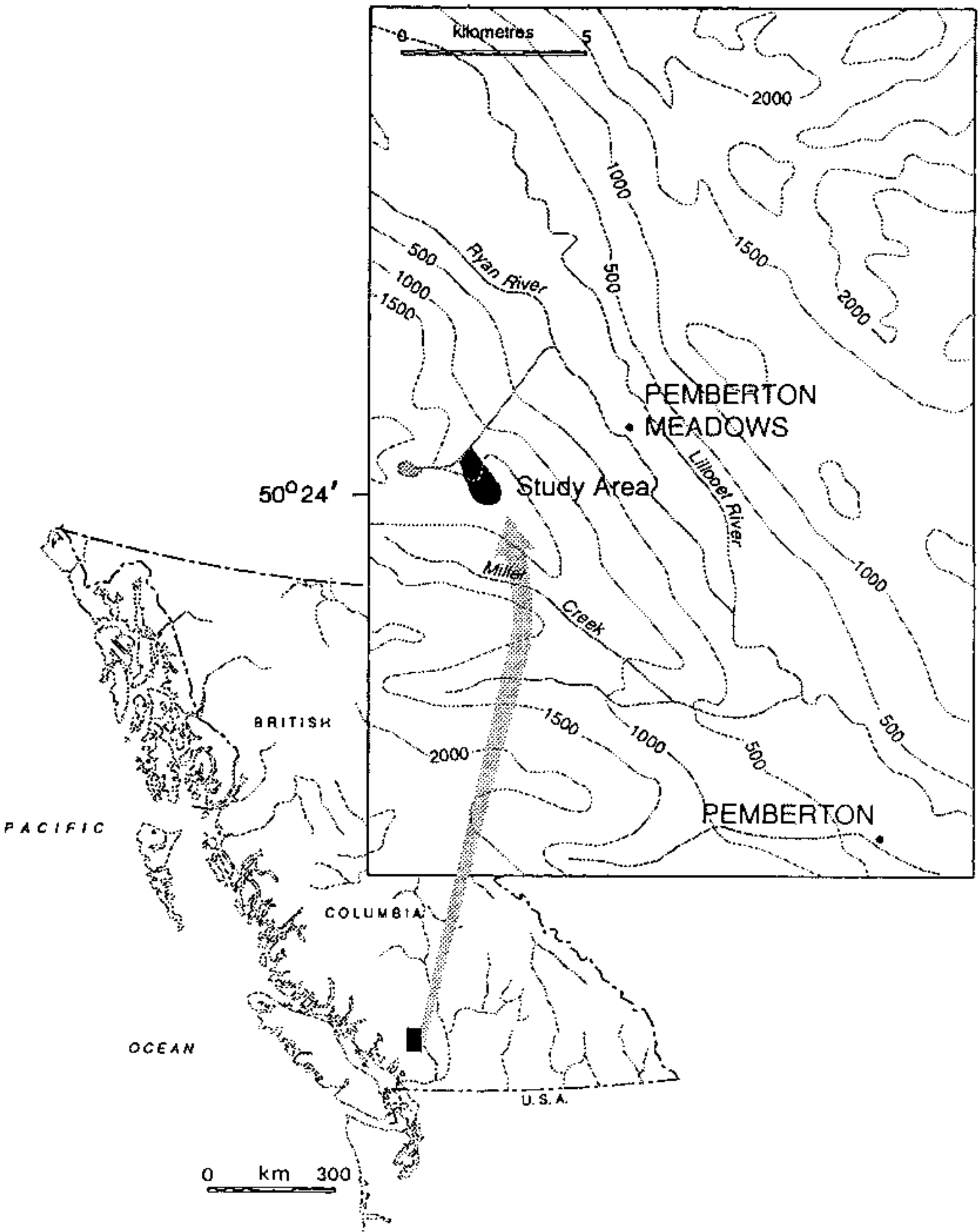

Fig. 1. Location of the catchments in British Columbia. Altitudes are metres above sea level.

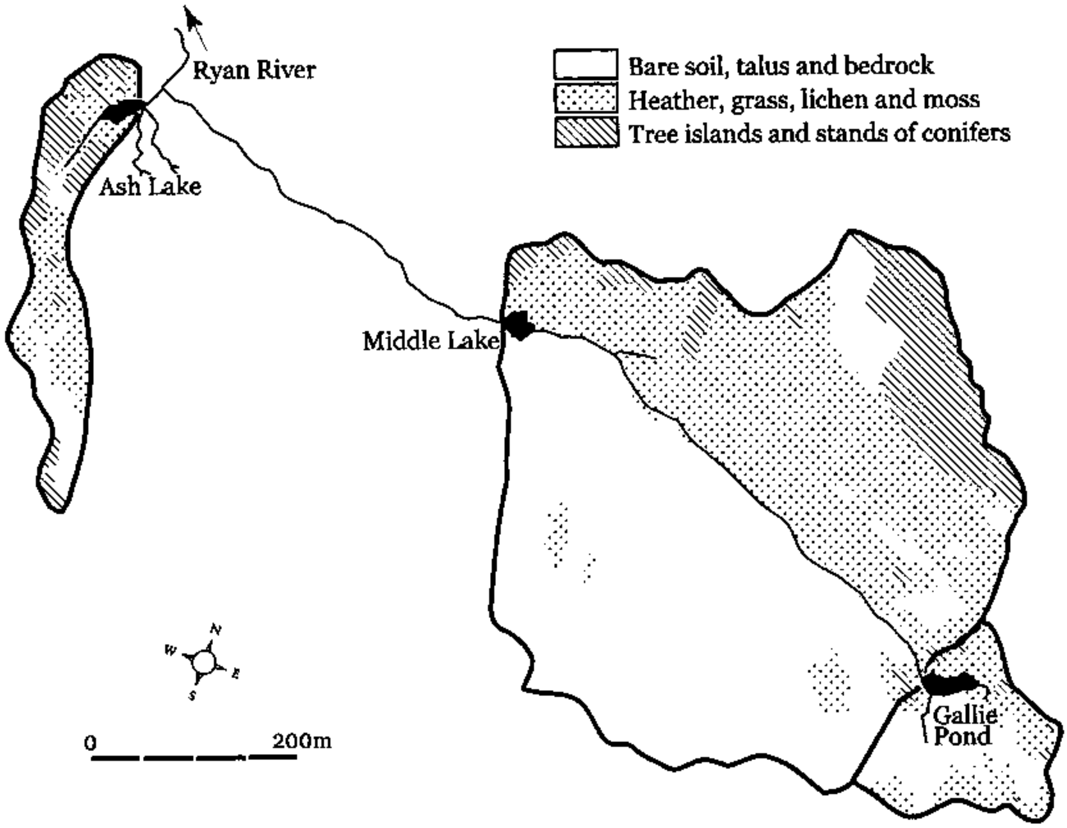

Fig. 2. Vegetation cover of the study catchments. The catchments are named after the lake which defines the lower limit of each basin, except in the case of the Goat Meadows catchment which contains Gallie Pond.

–40°C and +23°C during the period 1979 and 1980, and the annual mean for these years was about 0°C. Annual precipitation exceeds 1800 mm, of which 70 to 80% falls as snow. The local bedrock consists of an association of metasediments, which were mapped by Woodsworth (1977) as the Late Cretaceous Gambier Group, forming a roof pendant in the quartz diorite of the Coast Plutonic Complex (Roddick 1976). The bedrock in the catchments is discontinuously covered by a stony dioritic Pleistocene till. This, in turn, is overlain by a variety of brunisols, gleysols, podzols and cumulic regosols which incorporate Holocene loess and two tephra layers, of which the lower is Mount Mazama (*c.*

Table 1. Characteristics of the study catchments.

Characteristics	Goat Meadows	Middle Lake	Ash Lake
Altitudinal range (m a.s.l.)	1850–1900	1710–1970	1624–1850
Catchment area (km^2)	0.023	0.202	0.022
Vegetation cover (%)			
bedrock/talus/bare soil	49	55	23
tundra	45	34	43
trees	3	10	32
lake	3	1	2

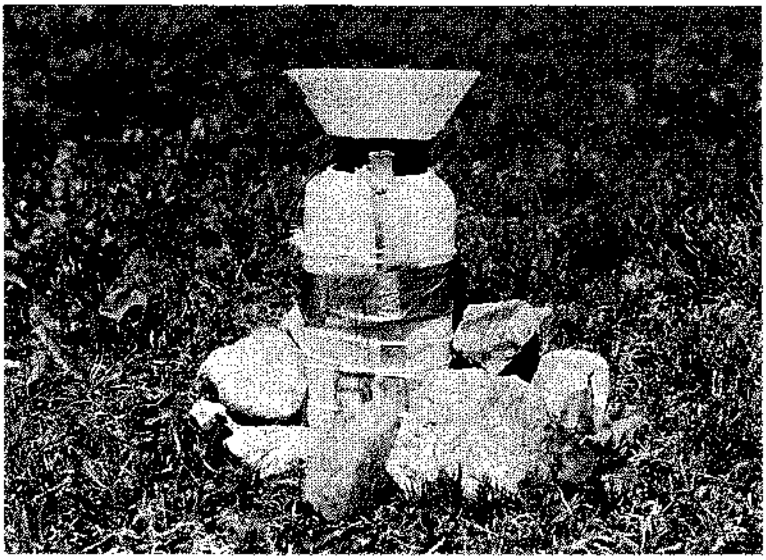

Fig. 3. A bulk dust collector (wet and dry) located in alpine tundra in the Goat Meadows catchment.

6750 years BP) and the upper is Bridge River (*c.* 2350 years BP) (cf. Gallie 1983; Souch 1989; Owens and Slaymaker 1994). In active sites, colluvium overlies the basal till, especially along glacially oversteepened cliffs which run along the southern margin of the catchments (Fig. 2). In the Middle Lake catchment, talus on the north-facing slopes extends to the valley bottom. The catchments are located near the upper altitudinal limit of parkland subzone at the alpine–subalpine ecotone (Brooke 1965). In the Goat Meadows catchment, discontinuous tree islands grade into krummholz life-forms 100 m further upslope. The limit of arboreal species occurs at about 2100 m above sea level. The local vegetative mosaic is heterogeneous due to steep microclimatic gradients and a variety of geomorphic processes in this environment. It is dominated by heath, sedge, forb, moss, Lutkea, lichen, Cassiope and grass, in addition to tree islands and, in the lower two catchments, stands of coniferous trees.

Methodology

In order to estimate the contemporary aeolian input of material to the catchments, a sampling framework was established based on vegetation/ground cover strata. Vegetation/ground cover strata were used as these have been identified as causing spatial variations in rates of aeolian accumulation (Darmody and Thorn 1987; Dahms 1993). Non-vegetated, alpine tundra, and tree (tree islands and stands of coniferous trees) strata were present in each of the three catchments (Fig. 2). Three sites were selected from each stratum in each catchment, yielding a total of 27 sites.

Aeolian input was separately assessed for the snow-covered and for the snow-free periods. For the snow-covered period, a Mount Rose snow corer was used to assess the amount of material contained in the snowpack. In brief, the metal core tube (of diameter 7.4 cm, surface area 0.0044 m^2) was inserted into the snow to the depth of the soil/ground cover. The tube was then rotated, removed from the snowpack and the snow (and aeolian material contained within it) extruded from the core tube and melted. This assumes that no snow in the pack is derived from previous years, an assumption which was supported by observations in the field. Four cores were taken at each of the 27 sites. Due to logistical problems in the field, cores were not taken in the tree stratum in the Goat Meadows catchment and additional sites were added to other strata in order to account for this. Also, snow cores were not collected at physically inaccessible sites; therefore, in some cases, the sites chosen were not strictly random, but are considered to be spatially representative of the study area. In total, 108 (27×4) cores were collected. For the snow-free period, a bulk dust collector (which collected both dry and wet fallout) was installed at each of the 27 sites. The collectors consisted of polyethylene funnels

Table 2. Average ($n = 3$) aeolian material collected in each stratum for each of the three catchments. Due to problems in the field, there are no data for the tree island stratum during the snow-covered period in the Goat Meadows catchment. The bulk collectors were left in the field for *c.* 60 days during the snow-free period.

		Deposited aeolian material (g m^{-2})					
		Snow-covered		Snow-free[1]		One year[2]	
Catchment	Vegetation	mineral	organic	mineral	organic	mineral	organic
Goat Meadows	non-veg.	26.73	4.30	12.42	1.53	39.15	5.83
	tundra	5.24	7.76	0.59	1.03	5.83	8.79
	tree	–	–	0.53	1.61	–	–
Middle Lake	non-veg.	41.98	3.30	1.03	0.51	43.02	3.81
	tundra	6.75	11.65	0.37	0.84	7.12	12.49
	tree	2.90	13.83	0.33	0.48	3.23	14.31
Ash Lake	non-veg.	8.01	6.19	0.47	0.67	8.48	6.86
	tundra	7.61	47.38	0.19	0.38	7.80	47.76
	tree	2.61	41.05	0.29	0.86	2.90	41.91

[1] <1 mm material only.

[2] One year is the sum of the snow-covered and snow-free deposited aeolian material and it is assumed that this constitutes one year.

(surface area 0.0266 m^2) attached to 4 l polyethylene containers (Fig. 3). In order to reduce contamination by other forms of sediment transport such as grain saltation and rainsplash (cf. Bagnold 1941), the height of the top of the funnel above the ground surface was 36 cm. Furthermore, at the base of the funnel stem, 1 mm mesh netting was attached so as to prevent large organic material, such as insects and seeds, from entering the collectors. The >1 mm material trapped by this mesh was retained for separate analysis. The containers were installed as soon as the sites became snow-free and emptied at the end of the field season (3 months later), before the first snowfall. Both sets of samples were filtered through 0.45 μm cellulose nitrate membrane filter papers. The oven-dried mass of the samples was determined at 105°C, while the organic matter content was determined by loss-on-ignition at 550°C for 3 hours (the flash-point of the filter papers was 170°C and the mass of the residue was 0.0001 g).

Rates of aeolian deposition over the post-glacial period were based on the analysis of soil characteristics at 50 sites in the study area. At each site, soil samples (of mass 20 to 100 g, mean = 55 g) were collected from the wall of a soil pit dug to till or bedrock. Organic matter content was determined by loss-on-ignition at 550°C for 3 to 4 hours. The particle size composition of the mineral fraction was determined by wet sieving.

Rates of aeolian deposition

Contemporary fallout

The aeolian material collected by the bulk traps during the snow-free period was separated into material >1 mm and <1 mm by wire mesh. This is an arbitrarily derived separation and the wire mesh was originally used in order to stop insects and seeds from entering the traps, and not to define the upper limit of aeolian material. Consequently, the >1 mm fraction is dominated by organic material, which consists mainly of insects which had fallen into the bulk collectors and been retained on the 1 mm mesh. However, at two non-vegetated sites in the Goat Meadows catchment, mineral grains >1 mm were also retained by the mesh and, because of their size, these grains had probably been derived locally and transported by saltation (cf. Bagnold 1941). Thus, it is assumed that both the mineral and organic material >1 mm is locally derived and does not represent regional aeolian fallout. Therefore, only material <1 mm is considered below. The <63 μm fraction of collected mineral material typically ranges from *c.* 20 to 60% (by mass) and variations partly reflect the distance to unvegetated source areas.

Table 2 presents summary statistics for each vegetation stratum for each of the three catchments. In general, the total amount of aeolian fallout collected during the snow-covered period is greater by an order of magnitude than for the snow-free period. This partly reflects the difference in the length of time associated with each period. The ratio of mineral to organic material collected for each stratum is consistent: non-vegetated sites are dominated by mineral material (although the magnitude of this difference is reduced in the case of Ash Lake, which may reflect the reduced availability of local fine mineral material at these sites), while organic material dominates at vegetated (alpine tundra and tree) sites.

Yearly rates of aeolian deposition could be calculated by the addition of mineral and organic material for each of the two time periods. Such estimates, however, would be misleading because aeolian material can be derived from a number of sources both within and outside of the study catchments. Areas of limited vegetation cover, in particular, have been shown to favour aeolian erosion (e.g. Chepil 1951; Woodruff and Siddoway 1965; Thorn and Darmody 1985). Therefore, the non-vegetated sites are likely to contain mineral material derived from within the catchment (autochthonous) and organic and mineral material derived from outside the catchment (allochthonous). The other sites are located in areas of well developed vegetation cover, with little or no local mineral sediment sources, and the material collected at these sites is probably organic matter derived from within the catchment and organic and mineral material derived from outside the catchment. Consequently, it may be possible to separate the deposited material into two sources. Here, the regional or allochthonous rate of aeolian fallout is calculated as the sum of the mean mineral material collected at the vegetated sites (including tundra and tree island sites) and the mean organic material collected at non-vegetated sites. Thus, annual rates of aeolian fallout are 11.66, 8.99 and 12.21 g m^{-2} (mean = 10.95 g m^{-2}) for the catchments of Goat Meadows, Middle Lake and Ash Lake, respectively. The similarity between catchments lends support to the argument above.

Although this estimation may appear rather crude, it is supported by the work of Jones (1984), who used X-ray diffraction in order to determine the mineralogy of contemporary aeolian material in the Goat Meadows catchment. She concluded that the mineral aeolian material collected in areas of well developed vegetation cover was derived from a regional source as opposed to within the catchment. The two dominant rock units in this catchment are quartz diorite and quartz–actinolite–chlorite schist, of which the former is the main regional rock type (Woodsworth 1977). Table 3 gives the relative mineral abundances in the <63 μm fraction of aeolian material and that of the two major rock units. Jones (1984) inferred that the quartz diorite appears to be the major source of plagioclase (which is the largest component of the aeolian material) and kaolinite, an alteration product, and that the quartz diorite is probably the major source of the windblown quartz (based on the distribution of quartz in the different size fractions of source rocks and aeolian material). Thus, it can be seen from Table 3 that relative mineral abundances in the <63 μm fraction of collected aeolian mineral material suggest that the regional quartz diorite is the dominant source of the aeolian material.

Table 3. Mineral abundances in collected aeolian material and the two dominant rock units in the study area based on X-ray diffraction (from Jones (1984). Quartz diorite is the main regional rock type.

Aeolian material	Quartz–actinolite–chlorite schist rock type	Quartz diorite rock type
Plagioclase (largest component)	Quartz (30%)	Quartz (30%)
Muscovite	Actinolite (30%)	Plagioclase (30%)
Kaolinite	Chlorite (20%)	Hornblende (15%)
Amphibole	Epidote (5%)	Epidote (10%)
Vermiculite	Diopside (2%)	K-spar (5%)
Chlorite	Sphene (2%)	Sericite (3%)
Orthoclase	Biotite (1%)	Opaques (2%)
Quartz (smallest component)	Plagioclase (trace)	Chlorite,muscovite, clinopyroxene (5%)

The rates of contemporary aeolian fallout agree well with those presented in the literature for the study area and for other study sites. Jones (1982) collected aeolian fallout during the snow-free and snow-covered time periods in the study area in 1981 and calculated that mineral fallout rates ranged between 0.9 and 6.9 g m^{-2} $year^{-1}$. The difference between the two data sets probably reflects the known variation in fallout rates which may vary annually by a factor of two or three (Reheis and Kihl 1995). Franzén *et al.* (1994) reported rates of deposition of *c.* 0.2 g m^{-2} for a single dustfall episode in Sweden and Finland on 10 March 1991. Nihlén and Mattsson (1989) calculated an annual deposition rate of 11.4 g m^{-2} for southern Greece, based on material collected in aeolian traps. The annual input to the Green Lakes valley in the Colorado Rocky Mountains has been estimated at

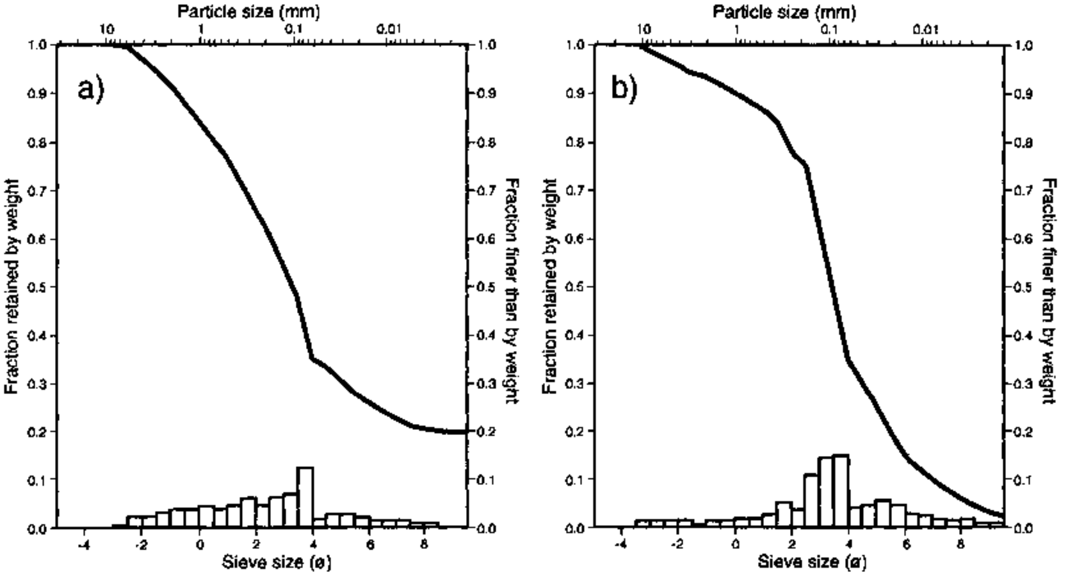

Fig. 4. Particle size composition of two representative soil samples: a) clay-rich (>15% clay) and b) clay-poor (<8% clay). Both samples were collected from cumulic soils within the alpine tundra vegetation stratum. Although the clay contents for both soils differ, the proportion of material <63 μm is similar for both (>30% of the total mass).

14 g m^{-2} (Caine 1986), while that calculated for the Polish Tatra Mountains ranges between 1 and 265 g m^{-2} (Izmailow 1984). More recently, Dahms and Rawlins (1996) used both snow and rain collectors to estimate that the contemporary average total influx of aeolian material to three sites in the Wind River Mountains, Wyoming was *c.* 5 g m^{-2} year^{-1} (mineral flux *c.* 3 g m^{-2} year^{-1}). McGowan *et al.* (1996) documented dust deposition rates ranging from 102 to 614 g m^{-2} year^{-1} (sample period 177 days) based on bulk collectors around Lake Tekapo, in the Southern Alps of New Zealand, with the magnitude of deposition reflecting the prevailing wind direction and the distance to source areas of fine material, such as sparsely vegetated proglacial river systems and degraded alpine tussock grasslands.

Post-glacial fallout

It is possible to calculate the magnitude of aeolian deposition over the post-glacial period from the accumulation of aeolian material in the soil profiles. The sampled soils in the study area can be grouped into two distinct types based on the clay content: those with a clay content >15% (by mass) and those with a clay content <8% (none of the samples had a clay content between 8 and 15%). Table 4 gives summary information on these two soil types and Fig. 4 gives the particle size composition of a representative sample from each type. A mean soil depth from the 50 soil pits in the study area is 18 cm. Here, it is assumed that the silt and clay fraction of the mineral soil is aeolian material mainly derived from regional sources as opposed to sources from within the catchment. However, it is likely that some of the clay-sized material is derived from in situ weathering of the bedrock, and thus the estimates of Holocene aeolian fallout calculated below may be slight overestimates of the true amount. From Table 4 the <63 μm fraction represents 33% of the soil mass, which equates to a maximum of *c.*

Table 4. Summary particle size information on the mineral fraction of the two soil types found in the study area based on the analysis of samples from 50 soil pits. None of the samples had a clay content between 8 and 15%.

Soil types	*n*	Total mass (g) (for all samples)	Silt %	Clay %	<63 μm %
A (>15% clay)	11	563.7	17	20	37
B (<8% clay)	39	2201.6	28	3	31
Both	50	2765.3	26	7	33

6 cm of aeolian deposition over the post-glacial period. The two tephra layers, whose depth is highly variable, but averages 2 cm, thus leave about 4 cm of Holocene aeolian deposits. An average bulk density of 1.6 g cm^{-3} (unpublished data) may be used to convert this to an average accumulation of about 6.1 g m^{-2} $year^{-1}$ (deglaciation occurred before 10,500 years BP (Souch 1989)). Given the assumptions made for both estimates, this figure is not significantly different from that calculated earlier based on process measurement over a single year period.

Palaeoenvironmental reconstruction based on the lacustrine sedimentary record in the small lake at the downstream limit of the Goat Meadows catchment, suggests that there have been changes in both the climate and the altitudinal position of the tree-line over the post-glacial period, with both the xerothermic interval and Neoglacial conditions identified (Souch 1989; Owens and Slaymaker 1994). Consequently, even though the order of magnitude of aeolian deposition over the post-glacial period is similar to the contemporary figure, fallout rates are likely to have varied over the longer period in association with changes in climate and catchment conditions. The analysis of the stratigraphy of the soil profiles in the Goat Meadows catchment indicates that there has been an increase in the rate of aeolian deposition over the second half of the Holocene epoch (Souch 1989), which contrasts with that documented for other parts of British Columbia (cf. Alley 1976). The increased rate of aeolian fallout associated with the present day may be due to anthropogenic activities and relate to an increase in atmospheric dust derived from regional agricultural, industrial and urban sources. However, the higher values of aeolian fallout associated with the present day in this study area are more likely to be the result of glacier retreat from Neoglacial maximum ice positions. Larger areas of recently exposed fine materials are available today than at any time since the paraglacial episode of 13,500 to 9000 years BP.

Implications

The rate of regional aeolian deposition calculated over both a single year and the Holocene epoch are of a similar order of magnitude and agree with other figures published for similar environments. It would appear that the vegetated strata in these catchments are net receivers of aeolian dust fallout. Consequently, most of the soils are cumulic in nature and protect the bedrock in these catchments from subaerial weathering. This has implications for establishing rates of local denudation. Although the fallout rates reported here are at the lower end of the global range mentioned earlier (Pye 1987), these rates are considerably greater than the estimated sediment yield for each catchment based on lake sedimentation (Owens and Slaymaker 1992, 1993). Furthermore, given the nature of the soils, it is likely that much of the fine particulate material eroded from the hillslopes and transported to the lake basins is essentially remobilised aeolian fallout and tephra.

It is interesting to note that recent lake sediment studies by Evans (1997) in Cathedral Park, northern Cascade Mountains of British Columbia, about 240 km southeast of the area examined in this paper, show insignificant aeolian components (median = c. 1g m^{-2} $year^{-1}$) within the alpine–subalpine ecotone. It is hypothesised that our results are representative of locations in the immediate vicinity of glacier forelands, where abundant fine material is available from Neoglacial moraines. The regional distribution of significant long-term aeolian contributions to sediment supply in British Columbia's alpine and subalpine environments would thus be restricted to mountain areas above 1600 m above sea level in the Coast, Columbia and Rocky Mountains. We would encourage attempts to examine this hypothesis more closely.

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Dr Philip N. Owens, Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter, Devon, EX4 4RJ, UK.

Professor Olav Slaymaker, Department of Geography, University of British Columbia, 1984 West Mall, Vancouver, British Columbia, V6T 1Z2, Canada.

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