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Impacts of Road Disturbance on Soil Properties and on Exotic Plant Occurrence in Subalpine Areas of the Australian Alps

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Abstract

The construction and maintenance of roads in the Australian Alps has caused profound disturbance to the natural existing soil and vegetation, as well as the introduction and proliferation of exotic plant species. This study examined three ecotypes associated with roads. These ecotypes were tested for differences in soil characteristics and occurrence of different plant species. Differences in chemical and physical soil properties were found between road verges and adjacent native vegetation areas. Soils from natural areas had higher humus levels, less gravel and sand, higher levels of nutrients, and higher pH and electrical conductivity than road verges. A relationship was found between soil properties and the occurrence of different exotic plant species along roadsides. Exotics dominated in areas along the road verge and road drainage lines. The dominant exotic found in these ecotypes was *Achillea millefolium* (yarrow). These ecotypes were characterized by high water and sediment wash off, which had significantly higher soil pH and exchangeable levels of calcium and potassium than natural areas and disturbed areas without yarrow.

Introduction

The dominant soil type found in the subalpine and alpine areas of the Australian Alps is the alpine humus soil (Kirkpatrick, 1994; Charman and Murphy, 1996). These soils are organo-mineral soils, in which the deep organic profile shows no elevation of sesquioxides and is acid to strongly acid. Alpine humus soil is derived from physical weathering processes and typically displays an upward fining structure, with a high sand fraction and high levels of stable clay minerals (kaolinite, illite) (Costin et al., 1959; Keane, 1977; Good, 1992; Johnston, 2001). In addition to physical weathering, the decomposition of organic matter, bioturbation, and aeolian deposition all represent important processes in its formation (Costin et al., 1954; Good, 1992; Johnston, 2001). The stability of alpine humus soil and its associated vegetation communities is completely reliant upon an intact surface organic horizon and the existence of a closed vegetation cover (Costin, 1954; Costin et al., 1959; Keane, 1977; Good, 1992). These alpine humus soils support tall alpine herbfield, sod tussock grassland, and heath vegetation communities (Costin, 1954). Many of these unique soil characteristics, combined with the critical interrelationship between soil-vegetation components, give rise to the inherent susceptibility of alpine environments to the impacts of disturbance (Buckley and Pannell, 1990).

Human activities within a landscape often result in fragmentation of the land with the division of the landscape by elements such as roads contributing to the loss of habitat and proliferation of exotic species (Reed et al., 1996; Saunders et al., 2002). A major form of disturbance in the Australian Alps is the construction and maintenance of roads and access tracks. One of the impacts of roadside disturbance is changes to the physical properties of the soil, for example to its structure, stability, erodibility, porosity, and permeability. However, the effects of roadside disturbance can also indirectly influence biological and chemical properties of soil, including organic content, soil biota, chemical conditions, and soil microclimatic conditions (Kuss et al., 1990). Many of these impacts have the potential to compromise primary ecosystem function, hydrological cycles, nutrient movement and availability, and surface stability. These soil-induced changes can affect plant growth and species diversity and composition, and create an environment conducive to colonization by exotic species (Frenkel, 1970; Reiners, 1983; Kuss et al., 1990; Forman and Alexander, 1998; Johnston, 1998; Spellerberg, 1998; Tyser et al., 1998; Forman, 2000; Jones et al., 2000).

The impact of road disturbance on the introduction, spread and proliferation of exotic plant species is well documented (e.g., Forman and Alexander, 1998; Lugo and Gucinsk, 2000; Trombulak and Frissell, 2000). The importance of disturbance in exotic plant invasion and in changing ecosystem dynamics has been examined in a large number of papers (e.g., Adair and Groves, 1988; Humphries et al., 1991; Cronk and Fuller, 1995; Amor and Piggins, 1997; Auerbach et al., 1997; Fox and Adamson, 1999; Groves and Willis, 1999). In general, disturbance increases the numerical abundance of exotic plants (Hobbs, 1987, 1989; Kotanen, 1997; Mack and D'Antonio, 1998). Exotic plants can have different effects on the environment, such as the displacement of native species and modification of ecosystem dynamics (Groves and Willis, 1999; Prieur-Richard and Lavorel, 2000). In the Australian Alps most of the exotic species are found in disturbed areas, for example along road verges, paths, and walkways and adjacent to surrounding infrastructures (Mallen-Cooper, 1990; Johnston and Pickering, 2001a). In Kosciuszko National Park (KNP), the largest park within the Australian Alps, there is a large number of both sealed and unsealed roads, access tracks, and walking tracks (Mallen-Cooper, 1990; Pickering et al., 2003. Eighty percent of the 140 exotic plant species found in KNP are recorded along roadsides and paths (Johnston and Pickering, 2001a).

Relatively few studies have examined patterns of invasion by non-native species within natural communities, or the processes contributing to invasion (Kolb et al., 2002). In our study in subalpine areas of KNP we examined three ecotypes associated with road ecosystems: the road verge, road drainage areas, and adjacent natural vegetation. We tested each of these ecotypes for differences in soil characteristics, including nutrient availability and the associated occurrence of different plant species.

Methods

This study was conducted at six road sites in subalpine areas of Kosciuszko National Park, the largest park in the Australian Alps,

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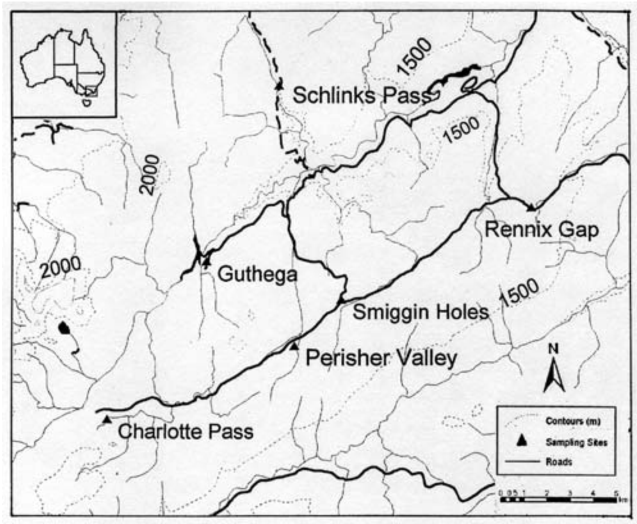

FIGURE 1. The location of the six study sites: Schlinks Pass (1634 m a.s.l), Guthega (1627 m a.s.l), Smiggins Holes (1650 m a.s.l), Charlotte Pass (1800 m a.s.l), Rennix Gap (1450 m a.s.l), and Perisher Valley (1700 m a.s.l).

southeastern Australia (Fig. 1). The road sites were constructed during the late 1950s to early 1960s as part of the Snowy Mountains Scheme, except for Kosciuszko Road which was originally constructed in 1906. All these roads are maintained annually or biannually. The altitudes of the road sites ranged from 1460 to 1800 m a.s.l. The six sites are in either woodland or open grassland/herbfield, on alpine humus soil. The dominant plant species at each site were recorded prior to the removal of the soil samples. Taxonomy was based on *Kosciuszko Alpine Flora* (Costin et al., 2000) and *Flora of NSW 1990–1992* (Harden, 1993).

Three replicate 1-m quadrats were randomly located at each site, in natural (undisturbed), road verge, and road drainage areas. The natural undisturbed area was typically 10 m from the edge of the road; the drainage area was approximately 2 to 5 m from the road edge; and the road verge area was directly alongside the road (0–2 m) (Fig. 2). For the purposes of this study the three ecotypes are defined as: natural areas not disturbed by road construction or maintenance; road drainage areas are natural or constructed water diversions from the road edge; and road verge is the area directly adjacent to the road. From each area five soil samples were collected from the top 10 cm of the soil profile and pooled. Soil samples were air dried, rolled, and sieved (5 mm) to remove coarse material such as rock and roots. After sieving the soil for the gravel content (>2 mm), further particle size composition was determined using the Bouyoucos hydrometer method. The divisions between the sand, silt, and clay fractions were 0.05 and 0.002 mm (Corbett, 1969).

Electrical conductivity and pH were determined in a 1:5 distilled water dilution (Rayment and Higginson, 1992). Organic carbon levels were determined using the Walkley and Black method (Rayment and Higginson, 1992). Extractable phosphorus was determined using a bicarbonate extraction modified from Olsen et al. (1954), extractable nitrogen using method 7C1c from Rayment and Higginson (1992), and exchangeable cations (potassium, manganese, magnesium, calcium, and sodium) using an ammonium acetate extraction (Lambert, 1978).

Soil characteristics were compared using one way ANOVA (SPSS Version 10.0 for Windows) (Coakes and Steed, 2000), with site as a block, ecotype as treatment and each soil character as the dependant variable. Mean, standard deviation, F ratio and level of significance (P) were calculated for all soil data and are presented in Table 1. The significance level was corrected using Bonforroni correction ($P = 0.0026$).

Plant cover abundance was measured using an adapted Braun-Blanquet method, as a percentage of the proportion of ground covered by the vertical projection of foliage (Mueller-Dombois and Ellenberg, 1974). Plant composition was compared using one way ANOVA (SPSS Version 10.0 for Windows) (Coakes and Steed, 2000), with site as a block. Mean and standard deviation for individual species and species type were calculated and are presented in Tables 2 and 3.

FIGURE 2. Photograph of typical study sites (Schlinks Pass) showing the three ecotypes examined: natural undisturbed area, road drainage area, and road verge.

TABLE 1

Summary of some chemical and physical properties for soil samples taken from six sites in Kosciuszko National Park. Five replicates (each replicate representing a pooled sample of five) were taken for each treatment. Mean ± Standard deviation (standard error) tabulated. Units for total and exchangeable minerals are mg kg^{-1}. Units for electrical conductivity (Ec) are mircosiemens

				Soil condition	
	Natural area	Road verge	Road drainage area	F	Significance
pH	4.70 ± 0.22 (0.06)	5.36 ± 0.21 (0.06)	6.29 ± 0.24 (0.07)	153.86	**0.00**
Ec	87.76 ± 13.24 (3.67)	49.76 ± 18.96 (5.26)	263.07 ± 58.20 (16.14)	127.11	**0.00**
Total nitrogen	7229.69 ± 892.70 (247.59)	1350.53 ± 376.16 (104.32)	3219.53 ± 1506.45 (417.81)	142.05	**0.00**
Total phosphorous	1307.23 ± 97.71 (27.10)	537.23 ± 97.71 (27.10)	726.00 ± 136.16 (37.76)	256.13	**0.00**
Total calcium	1294.54 ± 241.48 (66.97)	3111.35 ± 1098.56 (304.68)	10081.29 ± 2932.89 (813.43)	6.85	**0.01**
Total manganese	1074.89 ± 204.61 (56.74)	511.90 ± 68.82 (19.08)	550.35 ± 32.78 (90.09)	35.56	**0.00**
Total Sodium	172.14 ± 20.65 (5.72)	234.78 ± 44.07 (12.22)	219.81 ± 34.93 (9.68)	13.44	**0.00**
Total magnesium	7455.41 ± 686.87 (190.50)	10692.23 ± 1534.67 (425.64)	8648.16 ± 2158.44 (598.64)	21.77	**0.00**
Total potassium	7603.60 ± 303.50 (84.17)	9525.21 ± 1520.14 (421.61)	9978.93 ± 2380.88 (660.33)	6.85	**0.01**
Exchangeable calcium	401.92 ± 112.39 (31.17)	735.74 ± 154.83 (42.94)	7150.69 ± 1584.76 (432.53)	218.91	**0.00**
Exchangeable manganese	55.66 ± 16.85 (4.67)	17.89 ± 5.39 (1.49)	22.50 ± 10.11 (2.80)	45.90	**0.00**
Exchangeable sodium	6.54 ± 1.97 (0.54)	3.38 ± 1.11 (0.30)	7.92 ± 3.95 (1.09)	10.33	**0.00**
Exchangeable magnesium	185.14 ± 92.95 (25.78)	51.41 ± 15.49 (4.29)	106.86 ± 66.80 (18.52)	23.57	**0.00**
Exchangeable potassium	270.23 ± 47.15 (13.07)	118.25 ± 15.35 (4.25)	356.58 ± 94.05 (26.08)	62.41	**0.00**
Percentage organic matter	8.18 ± 1.25 (0.34)	0.61 ± 0.39 (0.10)	2.26 ± 1.16 (0.32)	300.73	**0.00**
Percentage slit	11.00 ± 2.70 (0.85)	11.20 ± 3.22 (1.01)	12.60 ± 2.95 (0.93)	0.73	0.49
Percentage clay	18.00 ± 2.26 (0.71)	7.10 ± 1.37 (0.43)	11.80 ± 1.98 (0.62)	152.45	**0.00**
Percentage course sand	26.40 ± 4.94 (1.56)	54.00 ± 8.23 (2.60)	39.40 ± 6.44 (20.39)	71.17	**0.00**
Percentage fine sand	44.60 ± 3.43 (1.08)	27.70 ± 7.08 (2.24)	36.20 ± 6.52 (2.06)	31.88	**0.00**

F values and significance (P) are corrected with Bonforroni correction to give the significance value of 0.0026. These are given for soil condition (d.f. = 2) and site (d.f. = 5).

Results

CHEMICAL AND PHYSICAL SOIL PROPERTIES

Three chemically and physically distinct soils were found to occur in the subalpine environment of Kosciuszko National Park following road disturbance. A significant trend (ANOVA F = 153.8, $P = 0.000$) was found for pH. The natural soil was the most acidic (4.7 ± 0.2), the road verge less acidic (5.3 ± 0.2), and the road drainage soil the most basic (6.3 ± 0.24) (Table 1). There are statistically significant differences across the soils in all of the measured total and exchangeable cations (calcium, manganese, sodium, magnesium, and potassium). For example, the soil in the road drainage area contained 8 times the amount of total calcium and 18 times the amount of exchangeable calcium compared to the undisturbed natural soil (ANOVA F = 6.85, $P = 0.000$, F = 218.9, $P = 0.000$, respectively) (Table 1).

For the major nutrients, nitrogen and phosphorus, concentrations are significantly different between the road verge, road drainage, and natural soil ecotypes (ANOVA F = 142, $P = 0.000$, F = 256.1, $P = 0.000$, respectively). The natural soil had the highest concentrations of the major nutrients, followed by the soil of the road drainage area and then the road verge soil. Road disturbance reduced the amount of organic matter in the soil. The natural soil had significantly higher amounts of organic matter (8.2% ± 1.3%) compared to the soil found on both the road verge (0.6% ± 0.4%) and drainage areas (2.3% ± 1.1%) (ANOVA F = 300.7, $P = 0.000$) (Table 1).

The physical composition of the soil reflects the levels of disturbance to the three soil types. There was a graduated transition from the finer natural undisturbed soil, to the road drainage soil, to the coarser road verge soil. The natural undisturbed soil had an overall finer texture, with a higher percentage of clay (18% ± 2.2%) and fine sand (44.6% ± 3.4%) and less coarse sand (26.4% ± 4.9%) compared to both other soils. The road verge soil had a high proportion of coarse material (54% ± 8.2%) and less fine material. The drainage area soil had intermediate amounts of both coarse (39.4% ± 6.4%) and fine material (16.6 % ± 2.9% silt and 11.8% ± 1.9% clay) (Table 1).

VEGETATION

There is a significant difference between the degree of exotic invasion occurring in the three road ecotypes (ANOVA F = 4.122, $P = 0.022$). The undisturbed natural soil was found to support a rich and diverse array of native vegetation types including trees, shrubs, forbs, and grasses. Over 30 native species were recorded in the natural areas (Table 2). Native species such as *Grevillea australis*, *Poa fawcettiae*, *Poa helmsii*, *Oreomyrrhis eriopoda*, *Craspedia aurantia*, *Helichrysum scorpioides*, *Olearia phlogopappa*, *Hovea montana*, *Asperula gunnii*, and *Aceaena novae-zelandiae* dominate the vegetation cover (91.78% ± 1.49%) (Table 2). A small percentage of the plants were exotic species (6.15% ± 2.86%). In contrast, the road verge ecotype was found to be dominated by exotic species (63.7% ± 5.31%), with only a small percentage of native species (7.5% ± 3.61%). A high proportion of the ground was also bare (28.8% ± 5.49%) along the road verge and there were only two native species: *Poa* sp. and *Luzula* sp. (Table 3). The road drainage area was again dominated by exotics (91.3% ± 5.86%). There was, however, a significant difference in the species present. The drainage ecotype vegetation cover was predominantly made up of a monoculture of *Achillea millefolium* (77.0% ± 13.89%), with only a small percentage of four other exotics and two native species (Table 2).

Discussion

This study demonstrates that the alpine humus soils found in the Australian Alps subalpine environment are physically and chemically altered due to road-induced disturbance. Road disturbance has reduced the amount of organic matter in the road verge and road drainage areas, due to its physical removal during road construction and maintenance (Forman and Alexander, 1998). Along with the removal of organic matter, roads were found to be associated with the importation of coarse material and removal of fine soil material. The coarse-grained mineral soils of the road verge had a lower total and available nutrient status than the finer grained drainage area soils. Disturbance to the

TABLE 2

Percentage cover (mean and standard deviation) of the common species found in the three road ecotypes studies: natural, road verge, and road drainage areas

Species name	Common name	Percentage cover (mean and standard deviation)		
		Natural	Road verge	Road drainage
Acaena novae-zelandiae	Bidgee-widgee	3.08 ± 1.28	—	—
*Acetosella vulgaris**	Sheep Sorrel	2.63 ± 1.09	19.70 ± 3.14	—
*Achillea millefolium**	Yarrow	2.16 ± 1.89	6.33 ± 2.87	77.00 ± 13.89
Aciphylla simplicifolia	Mountain Aciphyll	2.13 ± 0.56	—	—
*Anthoxanthum odoratum**	Sweet Vernal Grass	1.35 ± 2.05	28.30 ± 6.65	4.25 ± 3.25
Asperula gunnii	Mountain Woodruff	3.03 ± 1.25	—	—
Cardamine astoniae	Aston's Bitter-cress	0.98 ± 0.93	—	—
Carex appressa	Sedge	2.28 ± 1.26	—	—
Carnex breviculmis	Shortflowered Dryland Sedge	0.65 ± 0.71	—	—
Cassinia uncata	Sticky Cassinia	1.25 ± 1.06	—	—
Craspedia aurantia	Orange Billy-button	3.63 ± 1.19	—	—
Crapedia jamesii	Billy-button	1.18 ± 0.69	—	—
Deyeuxia quadriseta	Bent-grass	1.83 ± 1.00	—	—
*Echium plantagineum**	Paterson's Curse	—	—	1.83 ± 1.03
Eucalyptus sp.	Snow Gum	1.03 ± 0.76	—	—
Euphrasia collina	Eye Bright	1.98 ± 1.56	—	—
Geranium potentilloides	Alpine Swamp Crane's Bill	0.68 ± 0.57	—	—
Grevillea australis	Alpine Grevillea	12.6 ± 5.16	—	—
Helichrysum	Button Everlesting	2.28 ± 1.48	—	—
Hovea montana	Alpine Hovea	6.23 ± 2.04	—	—
Hymenanthera dentata	Wood Rush	1.63 ± 1.51	—	—
*Hypochoeris radicata**	Cat's Ear	—	4.67 ± 3.07	1.95 ± 1.78
Luzula novae cambriae	Rock Woodrush	2.15 ± 1.16	—	—
Luzula sp.	Woodrush	—	3.00 ± 1.67	—
Mircroseris lanceolata	Native Dendelion	1.80 ± 0.55	—	—
Oleria algida	Alpine Daisy Bush	2.55 ± 1.53	—	—
Olearia phlogopappa	Dusty Daisy Bush	3.37 ± 1.48	—	—
Oreomyrrhis eriopoda	Australian Caraway	2.77 ± 1.24	—	0.83 ± 0.92
Pimelea alpina	Alpine Rice-flower	1.95 ± 1.09	—	—
Poa fawcettiae	Smooth-blue Snow Grass	12.61 ± 4.22	—	—
Poa helmsii	Broad-leaved Snow Grass	2.36 ± 1.70	—	—
Poa hiemata	Soft Snow Grass	7.97 ± 2.40	—	—
Poa sp.	Snow Grass	—	4.50 ± 3.98	6.33 ± 3.83
Poranthera microphylla	Mint Bush	0.90 ± 0.81	—	—
Parsophyllum alpestre	Highland Leek-orchid	0.57 ± 0.76	—	—
Ranunculus graniticola	Granite Buttercup	1.68 ± 1.29	—	—
Scleranthus biflorus	Twin-flower Knawel	1.43 ± 0.86	—	—
Stellaria pungens	Prickly Startwort	3.11 ± 0.78	—	—
*Trifolium repens**	White Clover	—	4.67 ± 2.50	6.29 ± 5.96
Total Number of Species		34	7	7

* denotes exotic plant species

— denotes species is not present

natural soil also caused a significant change in pH, with the pH of disturbed soil being less acidic. This change is due to differences in the concentrations of total and exchangeable cations. The higher soil pH near the road has been attributed by others (Auerbach et al., 1997) to calcareous road dust deposition and leachate. This finding is supported here, in the significantly higher amounts of total and available calcium (as well as other cations) found in the disturbed soil, particularly in drainage soil. In a study (McDougall, 2001) examining colonization of alpine native plants in the Bogong High Plains (Victorian Alps, Australia), soil from the road verge was found to have higher levels of phosphorus than the adjoining native vegetation. These results are consistent with the results found here, with native areas having higher amounts of phosphorus compared to road verge and road drainage areas. In contrast, however, McDougall (2001) found there was no difference in pH or nitrogen content between the verge and native vegetation. In our study significant differences were observed, with the natural areas having considerably higher amounts of nitrogen and more acidic soil compared to the road verge. The levels of nitrogen and phosphorus reflect the amounts of organic matter found in the soils of the three ecotypes. The lowest amounts were found in the most disturbed soil, that of the road verge, and the highest in the natural, undisturbed soil. This study supports published research (e.g., Riley and Bank, 1996; Trombulak and Frissell, 2000) which shows that road disturbance has a significant impact on natural soil and the associated vegetation suite. Studies of soils next to roads in the arctic tundra also found similar results, with disturbance shown to increase pH, reduce organic matter and reduce the amount of fine material, while increasing coarse material as well as changing nutrient status (Auerbach et al., 1997). A change to a single soil factor can have a significant impact on a number of other environmental factors (Dupre and Ehrlen, 2002). In a study on herbaceous species growing in deciduous forest in south Sweden local factors, especially pH, were found to be more important for the incidence of certain plant species than the habitat as a whole configuration (Dupre and Ehrlen, 2002).

The road ecosystem has been defined as having two zones: the roadside and the surrounding ecotypes (Lugo and Gucinski, 2000). This definition highlights the differences between vegetation growing along the roadside and vegetation in the zone at the interface of the road with natural vegetation. That interface can be sharp or gradual, forming several ecotypes that differ from both the roadside and the natural vegetation (Lugo and Gucinski, 2000). In the current study, three ecotypes associated with road disturbance were examined: the road verge; the adjacent natural vegetation; and an intermediate ecotype, the road drainage area. Changes to the soil in these areas significantly affected the configuration of plant species growing in a given area. The natural soil, with its complete undisturbed profile, supports a wide range of vegetation life forms and species. However, a small percentage of exotics are still found in this area, probably due to seed input, into natural gaps, from the exotic plants growing near by. In contrast to these florally rich areas, the subalpine road verge soil supports only a limited array of (predominantly exotic) species. In general, the presence of disturbance reduces natural vegetation in terms of number and diversity, while conversely increasing exotic species (Humphries et al., 1991). This predominance of exotics along the roadside reflects the adaptation of exotic species to the properties (including changes to soil) of disturbed habitats (Amor and Stevens, 1975; Humphries et al., 1991; Fox and Adamson, 1999; Johnston and Pickering, 2001a). Species found along the road verge, such as *Acetosella vulgaris*, *Anthoxanthum odoratum*, *Echium plantagineum*, and *Mircroseris lanceolata* are commonly found associated with human induced disturbance in the Australian Alps (Johnston and Pickering, 2001a; Pickering et al., 2003). These findings are comparable to similar research conducted in North America. In these forest studies road disturbance caused changes to community composition in relation to distance from the road edge. Roadside vegetation was different to that of the forest interior with the exotic species more prominent near roads in terms of both frequency and abundance. In contrast to the exotics, the native species richness was the lowest where the disturbance was the greatest, i.e., road verge (Buckley et al., 2003; Watkins et al., 2003).

In addition to the direct effects on the soil, roads are also associated with changes to water flow and drainage systems (Cale and Hobbs, 1991; Forman and Alexander, 1998). Surface water carried by roadside ditches to streams or culverts will form gullies into natural habitats. Sediment and nutrient rich water from the road and upper slopes will be transported down the slope and deposited on existing soil and vegetation (Forman and Alexander, 1998). Alpine humus soils are naturally highly acidic, but with the addition of basic cations such as calcium the pH of the system has risen. This change in pH makes nitrogen, phosphorus, and other minor cations more available for plant use. These habitat changes are known to enhance the growth of aggressive exotics and can be a major stress on a roadside native plant community, particularly in ecosystems with predominantly nutrient-poor soils, as here. (Hobbs and Huenneke, 1992; McIntyre and Lavorel, 1994; Forman and Alexander, 1998). Henneke et al. (1990). Henneke et al. (1990) found that, with the addition of nitrogen and phosphorus, native vegetation could be transformed into vegetation dominated by non-native plants. Other roadside studies (e.g., Cale and Hobbs, 1991; Forman, 2000; Jones et al., 2000; Lugo and Gucinski, 2000; Trombulak and Frissell, 2000) have also shown a strong relationship between the degree of invasion by non-native species and soil nutrient levels, particularly of phosphorus. The greatest cause, however, of the establishment and growth of non-native plants is the combination of soil disturbance and nutrient addition (Hobbs and Huenneke, 1992; Ullmann et al., 1995, 1998; Kolb et al., 2002). The road drainage soil in our study has been affected by disturbance and high amounts of nutrient, sediment, and water wash off. The characteristics of runoff soil (increased water availability; increased amounts of fine sediment; increased amounts of nutrients, especially calcium; and increased organic matter) have been particularly favorable to the initial germination of one exotic species, *Achillea millefolium* (yarrow), and its establishment and finally domination of this subalpine roadside habitat.

TABLE 3

Percentage cover (mean and standard deviation) distribution of exotics, natives and bare ground in natural areas, road verges, and road drainage areas over the six sites along roadways in the Australian Alps

	Percentage cover in ecotype		
Plant category	Natural	Road verge	Road drainage area
Natives	91.78 ± 1.49	7.5 ± 3.61	7.17 ± 4.51
Exotics	6.15 ± 2.85	63.67 ± 5.31	91.30 ± 5.86
Bare ground	2.07 ± 1.92	28.83 ± 5.49	1.50 ± 1.55

Yarrow's presence in these road drainage areas is ecologically significant, as this exotic is a serious threat to the surrounding vegetation (New South Wales National Parks and Wildlife Service, pers. comm., 2001) It has been observed (Johnston and Pickering, 2001b; F. M. Johnston, pers. obs.) that once yarrow is well established in these drainage areas it will, in many cases, become dominant (70–100% cover), to the exclusion of both other exotic species and natives. Yarrow, with its high seed output and rhizome growth, has been observed to spread from the disturbed roadside environments into the surrounding undisturbed subalpine vegetation (Johnston and Pickering, 2001b; Johnston and Johnston, 2003). This threat is increased if the native vegetation lies downslope from the yarrow infestation, as seed and vegetative material can be transported, via water and sediment, further into uninfested areas (F. M. Johnston, pers. obs.). As well as the three ecotypes studied, a fourth ecotype was identified—the interface between the yarrow-dominated drainage area and the natural area (Fig. 2). However, exotic species invasion of roadsides is an ecological process that can be managed and minimized (Cale and Hobbs, 1991; Lugo and Gucinski, 2000). The occurrence of exotics is a symptom of an ecosystem in unbalance. In our study, changes to soils following disturbance have a direct effect on the type of vegetation growing on these soils. Both minimization of disturbance (as along the road verge) and reduction in nutrient enrichment (in drainage areas), as well as selective herbicide application, are needed for effective exotic plant control. The overall condition of the road ecosystem needs to favor the development and growth of native species and to promote vegetation complexity at the ecotone between the road ecosystem and adjacent vegetation (Lugo and Gucinski, 2000; Watkins et al., 2003). Re-assessment of construction materials and techniques, as well as improved drainage systems with collection points to reduce sediment and nutrient run off, are needed to minimize changes in soil composition, pH, and nutrient levels. The management of current road drainage areas infested with yarrow, especially downslope, needs special attention to prevent any further spread of this extremely competitive exotic into native vegetation.

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