Ecosystem-based conservation strategy for Central Otago's saline patches

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Ecosystem-based conservation strategy for Central Otago's saline patches

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ABSTRACT

Otago's inland saline ecosystem ranks with the worst examples of ecosystem loss in New Zealand. In a strict geomorphic and functional sense, salt pans are nearly extinct in Otago, salt meanders and salt plains are much reduced and heavily infested with weeds, while salt knolls and aprons dominate the relicts of the ecosystem. Fine-scale habitat variability is reflected in high within- and between-patch distinctiveness in the native halophytic flora and in soil morphology and chemistry. We exclude Sutton salt lake from our ecosystem definition, assigning it to a separate ecosystem. Fifteen native halophytes are recorded. Some have narrow soil and landform tolerances, while others have wider ranges. The segregate distributions of many of these species along salinity and tidal inundation gradients in salt marshes are mirrored in their habitats in the inland saline ecosystem. We consider the depauperate native halophytic flora and the low degree of plant endemism of this ecosystem points to its recent geological origin or to its discontinuous presence during the Quaternary. The inland habitats of all the native halophytes have weed problems, although those occupying salt knolls and aprons are least threatened. The large number of soil chemical parameters analysed to understand landform-soil-plant relationships can be reduced to two sets that separate out three broad soil types: saline, sodic, and saline-sodic. The three currently protected areas cover only a narrow range of the geographic, geomorphic, and biological variability in this ecosystem. We propose a geomorphic framework to understand the evolution of salinity in Central Otago's intermontane basins and as a basis for an ecosystem taxonomy. Electrical conductivity (salinity) and exchangeable sodium percentage (sodicity) of soils are useful gradients to typify ecosystem function, weed vulnerability, and to identify priorities to meet pressing conservation needs.

Keywords: conservation, indicators, geomorphology, edaphic factors.

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1. Introduction

This report presents an ecosystem-based conservation strategy for Central Otago saline patches.

1.1 BACKGROUND

Otago's inland saline ecosystem has received much research attention, particularly the ecology of its rare indigenous *Lepidium* species (Hewitt & Balks 1988; Allen & McIntosh 1993, 1994, 1997; Allen 1998), along with many reports of soil-plant relationships on individual sites (for references see Allen 2000). The survey and inventory of the inland saline ecosystem is approaching comprehensiveness, thanks to the unpublished soil-vegetation-animal inventories of McIntosh et al. (1990, 1992) and the earlier foundations of Partridge (1981) and Patrick (1989). Olrig Station, Galloway has not been comprehensively surveyed.

Saline ecosystem protection, on the other hand, has advanced slowly despite continuing contraction of the patchily distributed inland halophytic (salt-tolerant) (see Appendix 1 for Glossary) flora and fauna habitat. Possible reasons are that most sites are in private tenure, continued grazing of sites by farm stock is perceived as a useful suppression of weeds and, until recently, there has been a lack of key personnel charged with saline ecosystem management. Allen (2000) estimates less than 100 ha exist of the poorly-vegetated or bare-earth patches of apparently extreme saltiness. These are the remaining habitats for the native halophytic flora. About 40 000 ha of saline soils were mapped in 1960s and 1970s surveys (McCraw 1964, 1966; Raeside et al. 1966, Leamy & Saunders 1967; Orbell 1974), and now support improved pasture, or horticulture. The 100 ha remaining represents only about 0.025% of the former habitat area that would have once supported saline native vegetation. Also surveyed were extensive areas of partially to fully vegetated soils of low to intermediate saltiness, and these have dramatically reduced with agricultural improvement, particularly by irrigation. Whatever the true figures for total losses, it seems likely that the contraction and fragmentation of Otago's inland saline ecosystem represents the most dramatic reduction in any indigenous system in New Zealand.

1.2 ECOSYSTEM TERMINOLOGY

Terminological imprecision has clouded a full appreciation of the geomorphic and chemical variability and significance of the inland saline ecosystem. Saline soils, salt pans, sodicity, and alkalinity need careful definition at the outset. Salty soils have developed on a range of topographic units: alluvial plains, toe-slopes, terraces, and weathered bedrock (Fig. 1; Table 1). The manner in which salts have accumulated, their distribution, and their effects on soils on different topographical units are important components of an ecosystem approach to salty-soil conservation. A summary of previous contributions to saline terminology is useful.

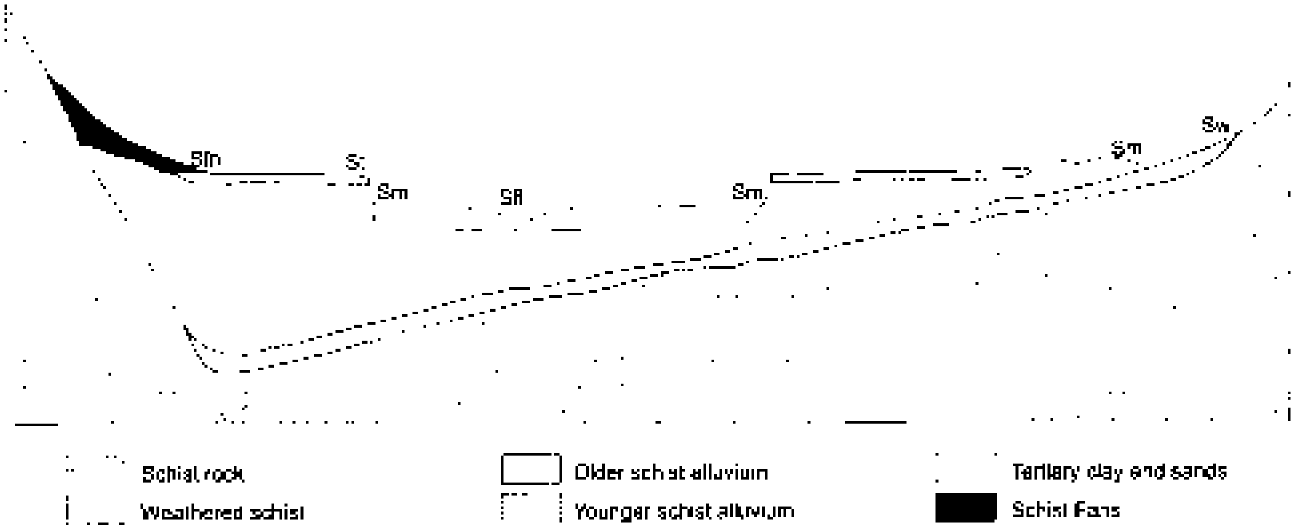

Figure 1. A diagrammatic cross section of the Ida Valley, modified from McCraw (1966), showing the location of saline and saline-sodic soils in relation to landforms. The relationships are typical of those in Central Otago's inland saline ecosystem.

Sw	Salinity directly derived from weathered schist.
Sm	Salinity in Tertiary clay and sands, ultimately derived from weathered schist.
St	Salinity on terraces derived from groundwater in contact with Tertiary clay and sands.
Sfl	Salinity in floodplains derived from saline groundwater in contact with Tertiary clay and sand and weathered schist.
Sfn	Salinity in lower parts of fans derived from groundwater in contact with saline materials.

TABLE 1. DEFINITIONS OF SALINE PATCH GEOMORPHIC UNITS AND THEIR RELATIONSHIPS WITH LANDFORMS OF CENTRAL OTAGO'S BASINS AND VALLEYS (SEE FIGURE 1). ABBREVIATIONS FOR ORIGINS OF SALINITY ARE GIVEN IN THE CAPTION TO FIG. 1.

SALINE PATCH GEOMORPHIC UNIT	DEFINITION	RELATIONSHIP TO CENTRAL OTAGO'S LANDFORMS
Salt pan	Shallow circular to oval depressions distributed over uplands and valley floors and clearly removed from natural drainage channels (following suggestion of Raeside, 1948).	Terraces of older schist alluvium over Tertiary sediments (St)
Salt meander channel	On alluvial plains that are either seasonally or permanently wet.	Terraces of older schist alluvium over Tertiary sediments (St) Terraces of younger schist alluvium (Sfl) over Tertiary sediments
Salt plain	Near-level interfluves on alluvial plains or on extensive fans not affected by high water tables or flooding.	Terraces of older schist alluvium over Tertiary sediments (St) Schist fans (Sfn) Rolling terrain on Tertiary sediments (Sm)
Salt knoll	Patches on convex or planar eroded land surfaces.	Hill slopes of schist rock (Sw)
Salt apron	Patches on concave or planar land surfaces on which erosion sediments have accumulated or are accumulating, generally down-slope from eroding salt knolls	Hill slopes of schist rock (Sw) Schist fans (Sfn)

Raeside (1948) noted that 'pans, or saucer-shaped depressions occur mostly on flat or gently undulating landforms where only a thin veneer of alluvium rests on salt-bearing Tertiary sediments, or where these sediments outcrop on the surface. They develop more rarely on rolling landforms. Pans are roughly circular to oval depressions, flat floored, 1 to 30 yd across, (average 8 yd), and from 1 to 6 ft deep (average 4 ft). On some sloping land surfaces the pans show a conspicuous linear alignment and appear to follow the lines of outcrop of horizontal Tertiary beds. Some pans are congregated on terraces, where the salt-bearing clays lie close to the surface. Pans are abundant where the alluvial cover on the surface of the Tertiary sediments is 3 ft thick or less. The floors of many pans correspond with the surface of the salt-bearing Tertiary sediments, particularly where the sediments are impermeable'. Numerous pans appear in early aerial photographs of the Maniototo (Raeside 1948).

In terms of their geomorphic origin, Park (1906) described pans as sink holes, but did not suggest how they were formed. Ferrar (1929) appeared to agree with Park by suggesting that pans were formed by the removal of material by downward drainage into underlying gravel beds, or into underlying Tertiary sediments by way of joints. Others he regarded as watercourse meanders formed by the migration of streams that formed them, and cited the meanders of the Taieri as examples. Raeside (1948) added to the debate on two fronts. First, he rejected the sink hole origin and suggested instead that pans were formed by wind ablation of surface alluvium following salinisation. The surface accumulations of salts had toxic effects on plants and the resulting bare ground was exposed to erosion. Second, to avoid confusion, he suggested confining the use of the term 'pan' to the shallow basins (depressions) distributed indiscriminately over uplands and valley floors, associated with Tertiary landforms, and clearly removed from natural drainage channels. Subsequent workers have not adopted this latter suggestion, and have applied the term 'pan' variously or inclusively to all sites of salt concentration, including bare-earth pavements developed on deeply weathered schist, heavily vegetated salt-rich depressions in meanders on flood plains, and the circular to oval depressions on Tertiary landforms (sensu Raeside 1948).

To advance this debate, and to emphasise and accord due significance to the geomorphic complexity of salt accumulation in the semi-arid inland landscape, we suggest 'saline ecosystem' as a unifying taxonomic and functional term. The inland saline ecosystem, in which salt is derived from rock sources, is differentiated from coastal saline ecosystems, in which salts are derived from sea water. The inland saline ecosystem is expressed as 'saline patches', which may be either 'saline vegetated patches', or 'saline bare-earth patches' depending on vegetation cover. Saline patches is a generic habitat term that embraces the geomorphic-based units defined in Table 1 that distinguish the geophysical variability.

1.3 CLASSIFICATION OF SALINE ECOSYSTEM SOILS

Saline soils are strongly influenced by sodium ions. These ions occur in two chemical environments in the soil as either, (1) salts of sodium chloride or sodium sulphate, together with calcium salts, in crystallised form in dry soils or as ions in the soil solution, and (2) as sodium cations attached to the negatively charged exchange complex of soil clay minerals and soil organic matter. These two states give rise to three soil types. *Saline soils* are dominated by sodium salts, *sodic soils* are dominated by exchangeable sodium, and *saline-sodic* soils are where sodium is predominant in both salts and in exchangeable forms. These classes may be defined by electrical conductivity (or EC, an estimate of total soluble salt content), and exchangeable sodium percentage (or ESP, as the concentration of sodium ions on the cation exchange complex). Alkalinity is frequently associated with sodicity and accessory pH limits are given but they are not differentiating. These classes correspond closely with those defined by Raeside et al. (1966) except that they used the term 'alkaline' rather than 'sodic'.

Saline soils	EC of 0.18 mS/cm or more, ESP less than 15% , and pH values below 8.5.
Saline-sodic soils	EC of 0.18 mS/cm or more, ESP of 15% or more, and pH values near or above 8.5.
Sodic soils	EC less than 0.18 mS/cm, ESP of 15% or more, and pH above 8.5.

1.4 SITE MODIFICATION AND EROSION

Virtually all saline patches have suffered anthropogenic modification as evidenced by truncated soil profiles and invasion by exotic plants. Farming and mining activity are the main causes. The corollary is that some have even been created by mining activity. For instance, the two *Lepidium kirkii* habitats at Patearoa are on sedimentary silts and clays deposited on the floor of a breached and abandoned dam associated with past mining activity. The habitat is therefore anthropogenic. Deep erosion of cover beds has exposed subterranean salts at some sites, while redistribution of surface detritus has formed salt aprons or fans at others (e.g. Butchers Dam). Lag gravels are common on salt knolls and indicate the loss of surface sediments by wind erosion and storm-water dispersion. Irrigation for pastoral farming and orcharding has mobilised soluble salts, particularly from terraces and fans, with subsequent deposition concentrated along the toes of fans or on outwash alluvial plains.

Saline soil materials are susceptible to erosion. Where salt contents are high, the soil is in a flocculated state, meaning that sand, silt, and clay particles clump together to form aggregates. In this state they are relatively well protected, but if vegetation cover is reduced, wind, or surface water erosion processes will effectively act on even flocculated soil materials. Where soils are highly sodic and salinity relatively low, soils become dispersed, that is, sand, silt, clay, and organic particles in the soil deflocculate and behave as individual particles. In this state soils are extremely erodible. Swallow holes (shallow surface depressions) on the Maniototo plain testify to the dispersibility of sodic soil. They have been observed during the construction of irrigation races (Ministry of Works 1984): when subsoil materials are exposed to drying, they shrink and cracks form. Rain or irrigation water then rapidly disperses soil, which is carried by drainage water through the cracks with deposition either into underlying permeable materials or at a lower elevation exit point at the ground surface. It is possible that many of the salt pans (sensu Raeside 1948) in the Maniototo were initiated as swallow holes.

1.5 SALINE PATCH MORPHOLOGY AND VEGETATION

Otago's inland saline ecosystem occurs in six broad alluvial basins within the semi-arid climate zone: upper Clutha above Cromwell, mid Clutha about Alexandra, Manuherikia, Ida, upper Taieri-Maniototo, and upper Waitaki. Saline bare-earth patches consist of small areas of clay- and silt-rich soils of apparently extreme chemistry, coloured pink, orange, cream, and white. They may have high concentrations of soluble salts. Where sodicity is high the soil materials at the soil surface are disaggregated, meaning that the sand, silt, and clay particles separate out. The surface may show a hexagonal joint pattern on shrinking and thin layers of soil may exfoliate on drying. In this state the soil is prone to wind or surface water erosion (Raeside et al. 1966). In addition, efflorescence of salts on the surface often occurs following rainfall and evaporation. These crusty deposits may be derived from accumulation of salt-rich storm-water from the surrounding catchment or salt-enriched groundwater rising to the surface, with subsequent evaporation. Transition zones of variable width separate these salty-soil areas from non-saline soils of the surrounding hill slopes and alluvial plains, but the vegetation on most of these transition soils of low to intermediate saltiness is now choked with weeds or pasture grasses. High compositional variability of the native plant component between and within saline patches suggests significant variability in soil physics and chemistry (Allen & McIntosh 1997).

McIntosh et al. (1990, 1992) inventoried most inland saline ecosystem areas of Otago, describing landforms and soil morphology, and listing native halophytic plants and associated insects. Virtually all saline patches are grazed by sheep and cattle. Rabbits are also ubiquitous. Allen et al. (1997) recognised four ecological groups of plant species in the Patearoa and Galloway saline sites, determined mainly by soil pH, conductivity, and soil moisture. Two soil-plant groups were classified as saline-alkaline, separated on seasonal moisture differences, and two were non-saline. The four were: common native perennials of acid, non-saline, shallow, dry soils; common exotic pasture species of slightly acid, non-saline, deep, well-drained soils; herbaceous species of seasonally moist alkaline and saline soils; and herbaceous species of permanently wet alkaline and saline soils. They also noted that two taxa formerly considered halophytic, *Lepidium kirkii* and *L. sisymbrioides* ssp. *matau*, were recorded growing only on non-saline soils, although soils supporting *L. kirkii* were slightly alkaline.

Fifteen native halophytic plant taxa characteristic of Otago's inland saline ecosystem (Table 2).

TABLE 2. NATIVE HALOPHYTIC PLANT TAXA CHARACTERISTIC OF OTAGO'S INLAND SALINE ECOSYSTEM.

Apium prostratum
Atriplex buchananii
Carex sp.
Chenopodium detestans
Chenopodium ambiguum
Lepidium kirkii
Myosurus minimus ssp. *novae-zelandiae*
Plantago spathulata var. *spathulata*
Poa lindsayi
Puccinellia stricta
Puccinellia raroflorens
Samolus repens
Sarcocornia quinqueflora
Schoenoplectus pungens
Selliera radicans

The small group of halophytes are those tolerant of moderate to high levels of sodicity and salinity (see Glossary in Appendix 1). A much greater number of native plants occupy soils of low salinity and sodicity surrounding the saline patches or the more widespread zonal soils of intermontane basins and valley slopes. *Lepidium kirkii* is the one true saline ecosystem endemic. Apart from one Stewart Island record, *Puccinellia raroflorens* (salt grass) is also confined to Otago's saline patches. Most of the remaining native species are disjunct between salt marshes and saline patches. It is likely that *Lepidium sisymbrioides* ssp. *matau* is not a saline patch species at all (Allen et al. 1997), but occurs on non-saline soils of terraces of Manuherikia Tertiary sediments, on terraces of greywacke gravels, and on toe-slopes of colluvial schist in the vicinity of saline patches only, all throughout the Galloway district north of Alexandra.

Sutton salt lake in the Strath Taieri is a large, shallow, lake-filled depression, where salts are concentrated in lake-bed sediments through seasonal cycles of flooding and evaporation. Its physiography and, in particular, its lacustrine processes and periodic inundation set it apart as an entirely separate ecosystem to the semi-arid, saline ecosystem. A separate halophytic flora of lake bed and littoral zone muds tolerant of long periods of water-inundation is recorded there and confirms its distinctive ecosystem conditions (note: we argue that this site and the seven species below, unique in Central Otago to Sutton salt lake, be not included in our definition of the semi-arid, inland saline ecosystem):
Crassula peduncularis
*Crassula mataikona** **
Crassula ruamahanga
*Crassula sieberiana**
Lilaeopsis novae-zelandiae
Limosella curdiana
Triglochin striatum

1.6 INFORMATION NEEDS

A draft species recovery plan for the inland *Lepidium* species (Allen 2000) includes priorities for research to determine further their habitat requirements and declining status. This report, and those of Hewitt & Balks (1988) and Allen & McIntosh (1997) all suggest that an increased understanding is required of the physical and chemical properties of saline soils, spatial patterns of soil-plant relationships for both native and exotic species, and the inherent weediness of the ecosystem. Allen & McIntosh (1997) also noted a need for detailed discrimination of soil-plant relationships as a basis for translocation of threatened species. Accordingly, broad questions to be addressed by the present study are:

- How robust are pH and electrical conductivity in typifying pedological variability in saline patches?
- How adequate is the present set of three protected areas in accommodating the bio- and eco-diversity of Otago's saline patches? In other words, can we

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*Validity of these records (from Murray 1972) requires further investigation
**CHR 181160

accommodate most ecosystem variability throughout the c. 30 known sites in a small number of representative reserves?

To achieve the study objectives attention was focussed on the following tasks:

- Determine the chemical and physical properties of the soils that support threatened inland halophytic plants.
- Determine the role of soil chemical regulation in the distribution of a salt-tolerant flora.
- Determine the role of soil chemical regulation in the inherent weediness of salty soils and seek an explanation for the high within- and between-site patchiness of native halophytes.
- Provide management guidelines for the conservation of threatened Central Otago halophytes, and for the re-establishment of these plants at other sites in the region.

1.7 STUDY AREA

Saline patches and closely adjacent, apparently non-saline, control soils were sampled on a range of geomorphic units at nine inland sites in three of Otago's six catchments that contain the saline ecosystem (Table 3). Our sampling effort concentrated on the diverse physiography at Patearoa and Galloway, along with further examples of geomorphic units at several other lower Manuherikia sites. (Table 3). The saline area at Pisa Flat in the upper Clutha was not included (see below), likewise the few saline patches of the Waitaki Valley around Otematata and Otamatapaio because resources were insufficient for coverage of that catchment. Separate pattern analysis research has been undertaken for the arid gravel terraces and their associated saline patches at Pisa Flat (Allen & McIntosh 1994) and Patearoa (Allen & McIntosh 1993).

TABLE 3. GEOMORPHIC UNITS SAMPLED AT THE NINE SITES OF THE PRESENT STUDY.

CATCHMENT	SITE	GEOMORPHIC UNITS
Upper Taieri	Patearoa	plain, meander
Manuherikia	Upper Galloway	pan, knoll, apron
Manuherikia	Galloway	knoll, apron
Manuherikia	Springvale	knoll, plain
Manuherikia	Dunard	apron
Mid-Clutha	Chapman Road	knoll, apron
Mid-Clutha	Patricks	knoll, plain
Mid-Clutha	Earnscleugh	knoll, apron
Mid-Clutha	Butchers Dam	apron

2. Objectives

The Department of Conservation commissioned this study to advance an ecosystem-based conservation strategy for the Central Otago (inland) saline ecosystem by:

- determining the geomorphic and soil factors controlling habitat diversity;
- understanding the landform/soil requirements of conservation target species;
- providing a sound terminology and indicators to identify, record, and archive information relevant to the conservation status of target species and habitats.

3. Methods

3.1 DATA COLLECTION—SOILS

At each sampling site, 10 topsoil cores (2.5 cm diameter, 10 cm deep) were collected randomly over a plot sized 2 m × 1 m, or smaller if the site was of smaller size. These cores were bulked for chemical analysis. Soil horizons and morphology were described following Milne et al. (1995). At 19 of the 36 patches sampled, a subsoil sample was collected at 40 cm depth from a pit.

Soil analysis followed Blakemore et al. (1987). Salinity is expected to vary considerably depending on the amount of rainfall sites have received just prior to sampling and the water table height. To minimise these variables, soils were sampled over a short period in a prolonged dry spell in November 1998.

3.2 DATA COLLECTION—VEGETATION

The point-height intercept method was modified to record only canopy surface intercepts of plants and bare-ground cover where arboreal vegetation was missing in each of the plots. Percentage cover for all species and bare ground was calculated.

A list of iconic taxa of native plants was compiled (Table 4) on the basis of their high profile in previous research and inventories and their likelihood of featuring prominently in a comprehensive strategy for protection of the inland saline flora.

TABLE 4. ICONIC NATIVE TAXA OF OTAGO'S INLAND SALINE ECOSYSTEM AND SURROUNDING SOILS SPECIFICALLY TARGETED IN THE PRESENT SAMPLING STRATEGY.

Atriplex buchananii
Carmichaelia compacta
Ceratocephalus pungens
Lepidium kirkii
Lepidium sisymbrioides ssp. *matau*
Myosurus minimus ssp. *novae-zelandiae*
Plantago spathulata var. *spathulata*
Puccinellia raroflorens
Puccinellia stricta
Schoenoplectus pungens
Selliera radicans

3.3 DATA ANALYSIS

We undertook the following analyses:

- To examine differences in soil chemistry across landforms, we used correlation analysis and ordination using Principal Components Analysis on soil chemical data.
- To investigate plant species associations, we used cluster analysis and ordination.
- To find relationships between plant species associations and soils, we regressed the floristic ordination axes on soil chemical data.
- To examine the role of soil surface and profile morphology as indicators of plant species distributions, we regressed the soil and floristic ordination axes on soil morphology data.
- To examine the inherent weediness of soils, we used multiple regression analysis.
- To determine whether pH and electrical conductivity are good indicators of the primary and secondary soil gradients and vegetation patterns, we regressed the soil and vegetation ordination axes against pH and electrical conductivity data.

4. Results

4.1 LANDFORMS AND SOIL CHEMISTRY

A correlation matrix of the 18 soil chemical attributes analysed showed a high degree of covariance between many of them. Two groups of attributes were notable. One group including pH, exchangeable sodium, carbonate, bicarbonate, and ESP is an expression of sodicity. The other group, electrical conductivity and soluble sodium, calcium and magnesium, chloride, and sulphate, is an expression of salinity. Detailed soil chemical data for each plot are given in Appendix 2 and a soil classification for each in Appendix 3.

An ordination on soil chemical values (not shown) emphasising high soluble and exchangeable magnesium, high soluble calcium and high chloride, isolates a salt plain site on Tertiary sediments at Springvale (Appendix 2) as a distant outlier. This site also has extremely high pH, electrical conductivity, and soluble sodium. Because we sampled few exposures, further testing of the distinctiveness of Tertiary outcrops is required.

After this outlier is excluded from the analysis, sites such as Galloway salt apron, and Earnscleugh salt knoll, and two Patearoa salt plains, all with high sodicity and salinity, occur at the left hand end of axis 1, segregated from other sites low in sodicity and salinity, such as Galloway hill-slope and terrace sites, Patearoa terrace site, and the Patricks plain site (ordination diagram not shown). The second axis separates sites of high sodicity which plot below axis 1, from sites with high salinity which plot above this axis. Axis 2 also contrasts sites high in soluble and exchangeable bivalent cations (magnesium and calcium), such as Moa Creek knoll, Galloway knoll and plain, Chapman

Road meander, and Springvale knoll, with sites high in exchangeable potassium (monovalent cation), with associated anions of carbonate, bicarbonate, and nitrate, such as Dunard salt apron and Patearoa salt plain.

The two soil chemical factors that are not explained by the two-dimensional ordination are cation exchange capacity (CEC) and soluble potassium. Interpretation of the ordination points to variation in soil chemistry reflecting four characteristics: sodicity, salinity, and the concentration of monovalent cations (potassium) and bivalent cations (calcium and magnesium). Overall, the chemical factors do not vary independently. Two ordination axes account for much of the variation.

Landforms differ significantly in several topsoil properties. Flood plain sites are the highest in both salinity and sodicity. They have highest pH, exchangeable sodium, nitrate, bicarbonate, electrical conductivity, exchangeable calcium, soluble sodium (the latter two do not differ significantly from those of salt knolls on deeply weathered schist), and exchangeable potassium (not significantly different from terrace sites). Terrace sites are lowest in salinity and sodicity. They are lowest in electrical conductivity and lowest but not significantly different from weathered schist in pH, exchangeable calcium, exchangeable sodium, bicarbonate, soluble sodium, and ESP. The evolution of these landform units is described in more detail in section 5.1.

4.2 VEGETATION PATTERNS

4.2.1 Vegetation associations

Cluster analysis of plant species identifies eleven ecological groups (Table 5). Group A is isolated in a separate lineage from the remainder, and includes species tolerant of soil moisture deficits on zonal terrace gravels. Group B occurs on periodically moist flood plain interfluves. Group C occupies colluvial hill slopes of low sodicity. Group D occupies a seasonally flooded pond in a salt meander. Group E includes the spring annuals *Myosotis pygmaea* var. *minutiflora* and *Ceratocephalus pungens*, and the minute grasses *Poa maniototo* and *Rytidosperma pumilum* on what is suspected to be a seasonally dry and elevated plain. Group F occurs in damp meanders of flood-plains, the most reliably moist sites of the saline ecosystem. The small Group G comprises the bare-earth salt-tolerant species of salt knolls and aprons. Group H is another group of dry terrace species. Group I is of the seasonally drier flood-plain soils (see also Allen 1997). Group J is indicative of semi-arid hill-slope soils of low salt content. The large Group K is tolerant of slightly acid, semi-arid, hill-slope soils and is dominated by introduced grasses and herbs, but includes *Lepidium sisymbrioides* ssp. *matau*, *Plantago spathulata* var. *spathulata*, and *Elymus apricus*. In summary, the plant groups are strongly indicative of landform-soil relationships and of associated soil chemistry.

An ordination of vegetation by plots (Fig. 2) largely supports the plant groups derived from cluster analysis. The first axis of the vegetation ordination contrasts four poorly-drained salt meander sites with all other sites. Species characteristic of the salt meander sites are *Alopecurus geniculatus*, *Ranunculus* sp., *Juncus articulatus* and, to a lesser extent, *Schoenoplectus*

TABLE 5. GROUPS OF PLANT SPECIES IDENTIFIED BY CLUSTER ANALYSIS.

GROUP A
Acaena agnipila
Dactylis glomerata
Raoulia australis
Scleranthus uniflorus
Stellaria gracilenta

GROUP B
Anagallis arvensis
Holcus lanatus
Juncus sp.
Myosurus minimus var. *novae-zelandiae*
Myosotis discolor
Veronica verna
Rumex acetosella

GROUP C
Bromus diandrus
Hordeum distichon
Carmichaelia compacta

GROUP D
Alopecurus geniculatus
Ranunculus repens

GROUP E
Aphanes arvensis
Ceratocephalus pungens
Myosotis pygmaea var. *minutiflora*
Poa maniototo
Rytidosperma pumilum

GROUP F
Agrostis capillaris
Agrostis stolonifera
Juncus articulatus
Schoenoplectus pungens
Eleocharis gracilis

GROUP G
Atriplex buchananii
Puccinellia raroflorens
Lichenothelia sp.
Hordeum hystrix
Lepidium kirkii

GROUP H
Aira caryophyllea
Chenopodium ambiguum
Gypsophila australis
Cirsium arvense
Lagurus ovatus
Lachnagrostis striatum

GROUP I
Plantago coronopus
Poa lindsayi
Puccinellia stricta
Selliera radicans
Trifolium dubium

GROUP J
Anthoxanthum odoratum
Bromus tectorum
Malva neglecta
Marrubium vulgare
Trifolium fragiferum
Trifolium repens

GROUP K
Bromus mollis
Rytidosperma maculatum
Taraxacum officinale
Hypochoeris radicata
Sonchus oleraceus
Lepidium sisymbrioides var. *matau*
Vittadinia gracilis
Vulpia myuros
Cirsium vulgare
Hordeum murinum
Puccinellia distans
Spergularia rubra
Echium vulgare
Lolium perenne
Vulpia bromoides
Trifolium arvense
Poa pratensis
Plantago spathulata var. *spathulata*
Elymus apricus
Sedum acre

pungens, *Eleocharis gracilis*, *Agrostis stolonifera*, *Agrostis capillaris*, and *Trifolium repens*. The second axis contrasts sites with the spring annuals *Ceratocephalus pungens*, *Myosurus minimus* subsp. *novae-zelandiae*, and *Myosotis pygmaea* var. *minutiflora*, along with *Aphanes arvensis*, *Rytidosperma pumilum*, and *Poa maniototo*, with *Carmichaelia compacta* and a group of semi-arid *Bromus* grasses.

4.2.2 Species patterns

Fifty-seven percent of the 73 plant species encountered in the sample plots are exotic (Appendix 4), and this component had an average canopy cover per plot of 39.6%. The native 43% of the flora (including an aggregate group for moss) had an average canopy cover per plot of 29.3%. Because the sample plots included a wide range of saline and alkaline soils, including transition zone soils, the vegetation cover figures are not representative of the bare-earth patches, often with efflorescence of salts on the surface (Fig. 3). Bare patches seldom have plant cover exceeding 5%. *Puccinellia raroflorens*, *Atriplex buchananii*, and *Lichenothelia* sp. (a cyanobacterium) were the most widespread native halophytes in the 41 plots.

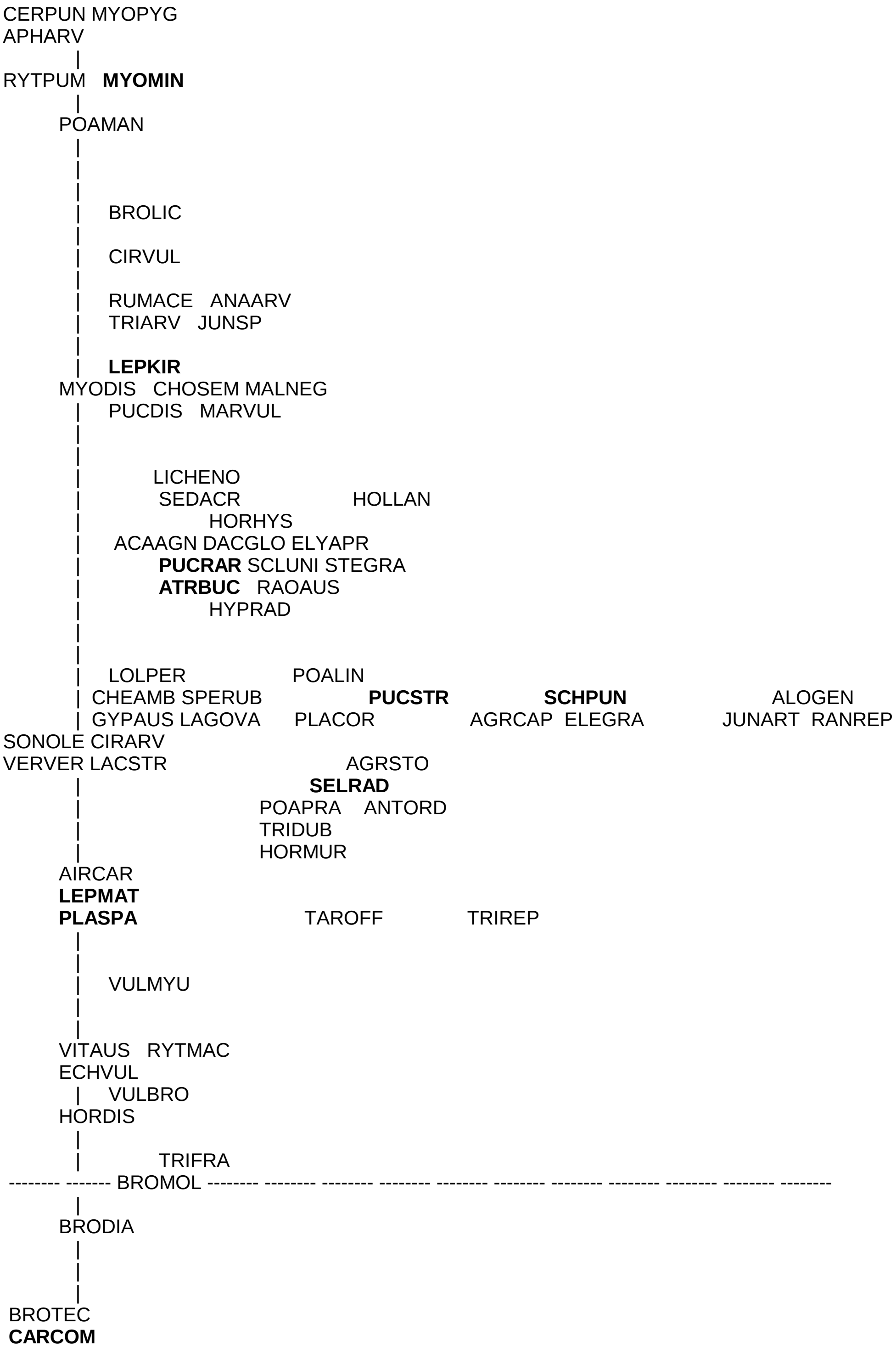


Figure 2. Ordination of plant species from the inland saline ecosystem with component 1 (horizontal) and component 2 (vertical), from detrended correspondence analysis. Highlighted are several native species which, along with their attendant exotic species, occupy a wide range of the ordination. See Appendix 4 for full plant names.

The species ordination (Fig. 2) shows native and exotic species co-occurring throughout virtually all of the ordination space. The first axis on the right hand side separates out salt meander species from salt plain communities. The second axis separates strongly the spring annual site at Patricks at the top from the semi-arid terrace sites with their *Bromus* grasses at the bottom. Salt knoll and salt apron communities occupy intermediate positions of the second axis. Overall, the species ordination demonstrates the strong landform-soil patterning of saline vegetation and species gradients.

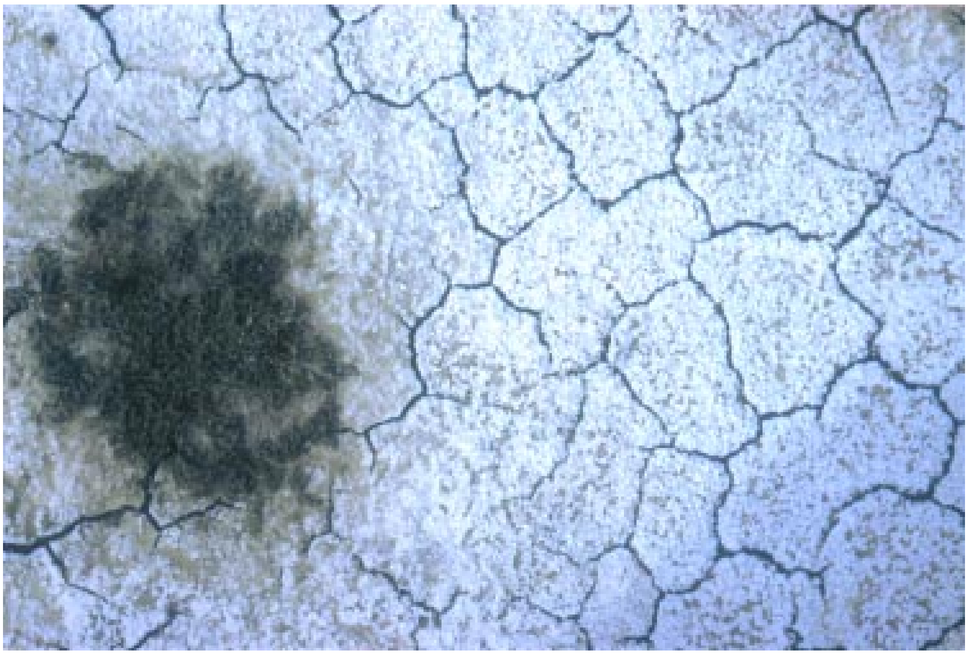


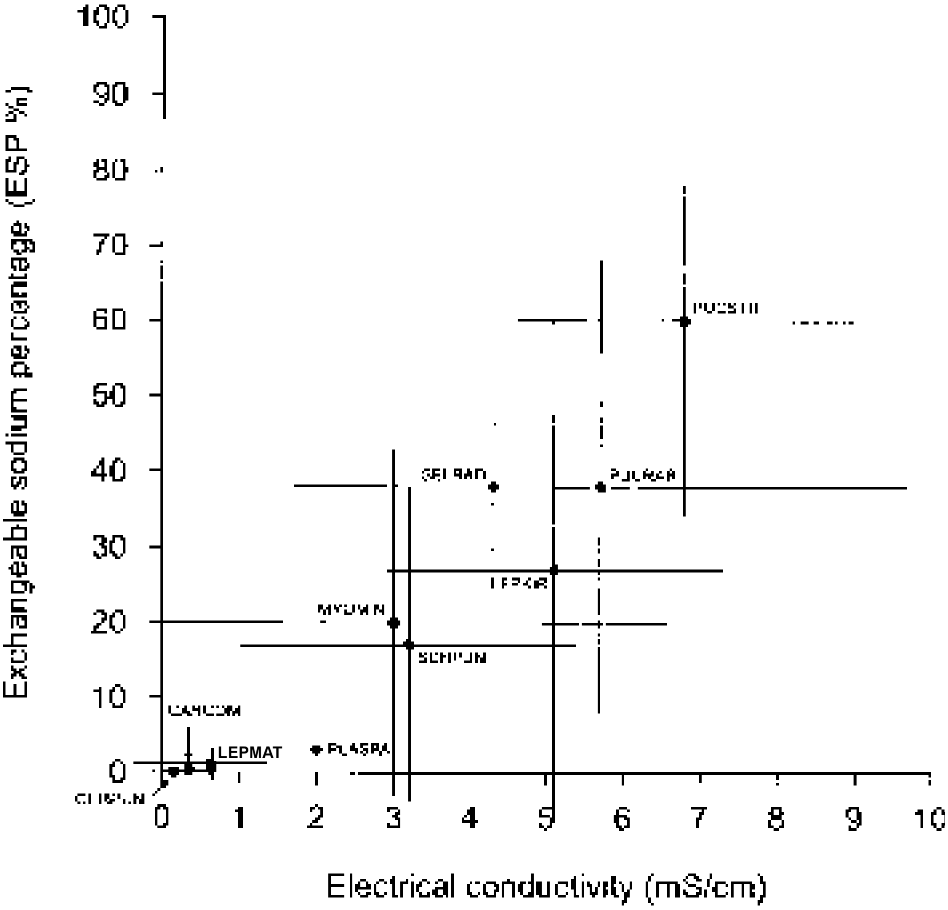
Figure 3. Plan view of the soil surface of a salt apron at Chapman Road, Alexandra, showing a white efflorescence of salt and hexagonal cracking of the soil. A colony of *Atriplex buchananii* is shown at left. The distance from the top to the bottom of the view is approximately 80 cm.

There are both generalists and specialists (Fig. 4) in the native halophytic flora (Section 1.6) as expressed in their distributions within geomorphic units (not all the following taxa were included in field samples): *Plantago spathulata* var. *spathulata* is specialised to mildly saline salt knolls and aprons on Tertiary sediments; *Selliera radicans* occupies saline-sodic soils on salt plains; *Schoenoplectus pungens* occupies a saline meander at Patearoa; *Myosurus minimus* ssp. *novae-zelandiae* occurs on mildly sodic knolls and mildly saline plains and pans; *Puccinellia raroflorens* and *P. stricta* are generalists by occupying saline-sodic soils on knolls, aprons, and plains. They are separated along sodicity and salinity gradients, with the latter exhibiting higher tolerances. *Lepidium kirkii* is also a generalist of saline-sodic soils (Fig. 4) on knolls, aprons, and plains. Outside this data set, but included in the inventories of McIntosh et al. (1990, 1992) are other native halophytes. *Sarcocornia quinqueflora* is confined to two salt-plain sites and is therefore tolerant of saline soils. *Samolus repens* is known from two salt meanders and is also a saline species. *Chenopodium detestans* has been recorded from Tertiary sediments in the upper Waitaki Valley. *Chenopodium ambiguum* and *Apium prostratum* occur on aprons and plains, and despite the previous widespread occurrence of their geomorphic unit, both are now sparse. *Eleocharis gracilis* and *Carex* sp. occur in the Patearoa meander.

4.3 RELATIONSHIPS BETWEEN PLANTS AND SOIL CHEMISTRY

Cluster analysis (not shown) of plots based on the vegetation shows strong soil chemistry, landform and site associations. A range of *Lepidium kirkii* bare-earth sites at Patearoa, Galloway, and Chapman Road forms a cluster, which is separated from a cluster of several flood-plain sites at Patearoa and a mid-slope bare-earth area at Earnscleugh by exchangeable sodium. The transition zone

Figure 4. The distribution of several iconic native species of the inland saline ecosystem across the range of soil chemical conditions, represented by electrical conductivity (salinity) and exchangeable sodium percentage (sodicity) of topsoils. Horizontal and vertical bars are standard deviations of values from soil samples for each chemical property. See Appendix 4 for full plant names.



soils with *Lepidium sisymbrioides* ssp. *matau* and *Carmichaelia compacta* at Galloway form a large cluster. Another group comprises mostly bare-earth soils at several locations in the lower Manuherikia and mid Clutha basins about Alexandra. This includes a *Lepidium kirkii* site at Chapman Road, a flood-plain soil with spring annuals at Conroys Road, a *Myosurus minimus* site at Earnscleugh, a *Lepidium sisymbrioides* ssp. *matau* site on Manuherikia sediments at Springvale, a redistributed fan soil at Butchers Dam and, curiously, a terrace soil at Patearoa. This cluster is separated from three flood-plain soils at Chapman Road and Dunards. The last two clusters are flood-plain soils at Patearoa, Springvale, and Conroys Road.

Regression of the vegetation axis 1 on both topsoil and subsoil chemistry is significant. In the topsoil, exchangeable magnesium, nitrate, and sulphate explained 57.3% of the vegetation variation across all sites. In the subsoil, exchangeable magnesium and nitrate explained 55% of the vegetation variation. Regression of vegetation axis 2 on topsoil, but not subsoil, chemistry is significant. Fifty-seven percent of the variation can be explained by using pH, CEC, exchangeable and soluble potassium, exchangeable sodium, chloride, and soluble calcium.

In summary, both topsoil and subsoil chemistry are significant predictors of the vegetation. Overall, the conspicuous native halophytic flora occupies a wide range of soils with divergent chemical properties. Although vegetation axis 1 prediction is almost as good with subsoil factors as with topsoil, these subsoil factors are probably proxies for the soil water regime.

4.4 RELATIONSHIPS BETWEEN PLANTS AND SOIL SURFACE AND PROFILE MORPHOLOGY

Features of the soil surface and soil profile morphology (topsoil thickness and structure) indicate the stability of the site and hence the ability of plants to cope with erosion and sedimentation. Because of the low number of sites investigated, we make tentative observations only for four of the iconic species.

Lepidium sisymbrioides ssp. *matau* sites on the terrace gravels and weathered schist (four sites) are stable, with topsoils either present or only partially eroded. The soils are mature Semi-arid Soils (Hewitt 1998) occurring on landforms that have been stable for periods of many thousands of years as indicated by the presence of argillic horizons (Leamy 1973). One site on Manuherikia Tertiary sediments at Springvale differs from the other sites, however, because the topsoil is severely eroded. At all five sites the topsoils are neither saline nor sodic, but subsoils are saline at two sites. (*L. sisymbrioides* ssp. *matau* develops deep taproots and therefore tolerates saline subsoils).

Lepidium kirkii sites are all severely eroded with either crusted or gravel pavement soil surfaces. Raw Soils at all sites indicate that the land surfaces are young and the erosion has truncated most of any pre-existing soil profiles. Erosion has probably been a long-term feature of the sites. Within the extensive areas of severe erosion where the *L. kirkii* colonies are located, the patches occupied by the plants are relatively stable, as indicated by association with *Lichenothelia* sp., a cyanobacterium that helps with surface stability. Therefore, *L. kirkii* appears to survive in patches of transitory stability within broader areas of severe erosion.

Carmichaelia compacta was sampled at three sites and observed at another site, where it occupied head scarps at the upper margin of a patch of severe erosion. The species appears to be able to colonise and stabilise active erosion scarps.

Puccinellia raroflorens was observed at 20 sites. The sites were either eroded (15 sites), sedimented (4 sites), or not eroded (1 site), indicating that the plants can withstand instability in the form of inundation by sediment as well as erosion. Soils range from Raw Soils to mature Argillic Semi-arid Soils, indicating that at some sites erosion has been severe enough to truncate soil profiles (Raw Soils) and at other sites land surfaces are either relatively stable or erosion is not severe.

Quite apart from soil chemistry, soil morphology is also a useful predictor of site variability. Region (in our data set a surrogate for landform) and surface stability are the most powerful predictors of variability. In addition, soil morphology is also useful for predicting vegetation composition. The individual factors of region, topsoil morphology, and drainage account for 83% of the variation in vegetation composition.

4.5 WEEDS AND THE NATIVE FLORA

The proportion of native species in the total flora is significantly affected by soil chemistry. Low CEC (which reflects low soil organic matter), low ESP (sodicity) and high sodium and chloride (salinity) in the topsoil are the strongest indicators of higher proportions of native species. Subsoil chemistry had little influence on the proportion of natives in the total flora. Cover of native plants is enhanced at high pH and chloride content. The number (richness) of iconic species (Table 4) and their cover cannot be predicted from the topsoil or subsoil chemistry, confirming the specialisation to individual geomorphic units of many iconic species.

The species ordination (Fig. 2) and species cluster analysis show the strong presence of exotic weeds across almost the entire spectrum of the sample space. Only Group G of the cluster analysis (Table 5), which contains *Lepidium kirkii*, *Atriplex buchananii*, *Puccinellia raroflorens*, and *Lichenothelia* sp. has just one exotic, *Hordeum hystrix*, among species tolerant of the most sodic knolls and aprons. *Plantago coronopus* is a most aggressive weed of salt plains and salt pans (Group I) and is a major threat to the habitat of the native halophytes *Samolus repens*, *Selliera radicans*, and *Myosurus minimus* ssp. *novae-zelandiae* that occupy these seasonally wet soils. The *Bromus* grasses prosper on the seasonally arid terrace and toe-slope soils of low sodicity. *Sedum acre* and *Lagurus ovatus* are tolerant of low to intermediate salinity and sodicity. The latter becomes prominent in midsummer as soil moisture deficits intensify.

4.6 UTILITY OF pH AND ELECTRICAL CONDUCTIVITY

Electrical conductivity and pH are quite good indicators of the primary and secondary soil gradients (as elucidated by ordination), but are poor predictors of vegetation composition. The soil chemistry is highly variable between and within the sites occupied by the native halophytic flora. However, ESP and EC have emerged as reasonable indicators of the range of soil types occupied by the iconic species.

5. Discussion

5.1 GENESIS OF SALINE SOILS AND THE EVOLUTION OF THE SALINE ECOSYSTEM

It is understood that, in Central Otago, sodium salts have been derived by weathering of the schist basement rock during long periods of landscape stability from the late Cretaceous to mid-Tertiary. A proportion of these salts was transported by surface erosion of the weathered schist, and by drainage waters, and concentrated in the inland lacustrine sediments of the Manuherikia (Tertiary) group. Salts were further redistributed in the Pleistocene and Holocene by erosion and by water tables as sedimentary gravels in-filled the basins in cycles of erosion and deposition. Salt-affected soils are now found on remnants of the weathered schist, on some outcrops of the Manuherikia Group sediments, and some terraces, fans, and flood plains (Fig. 1). Salts weathered in the distant past have been preserved in the modern landscape because of the semi-arid climate. Precipitation has not been sufficient to leach soluble salts out of the soils. Irrigation, however, has been effective in leaching salts, particularly on terraces and fans, and the total area of land that was thought to be saline at the time of European settlement is now greatly reduced.

The three soil types (defined in section 1.3) may be arranged into an evolutionary sequence from saline soils to saline-sodic and to sodic soils (Duchaufour 1977). The process starts with soil materials that have a cation exchange complex dominated by calcium and magnesium cations. The incursion of a shallow saline water table will produce a saline soil with high sodium activities in the soil solution. Given time and sufficient activity these sodium ions will displace other cations on the exchange complex and a saline-sodic soil will develop. While soil solution salinity remains high, the soil structure will remain flocculated and the soil profile will remain permeable. If the water table is lowered, rain water (or irrigation water) of low ionic strength will leach out the saline soil solution, but sodium ions that are relatively firmly bonded to cation exchange sites will remain in the exchange complex and a sodic soil is formed. Soil aggregates may then disperse, clay will migrate down the profile to form a clay-enriched (argillic) horizon, and permeability will be reduced.

This soil evolution is consistent with the distribution of the soil types in the Central Otago landscape, where saline and saline-sodic soils occur on young surfaces (either eroded since human occupation or of Holocene age) or are in low parts of the landscape where water tables have remained high. Sodic soils with characteristic clay-enriched horizons (argillic horizons) are on high parts of the landscape: relatively un-eroded hill slopes or terraces where water tables have been lowered by natural down-cutting of streams into the landscape.

This is demonstrated by the distribution of soils in the south-western Maniototo-upper Taieri catchment as mapped by mid 20th century soil survey (Raeside et al. 1966) and is shown in Fig. 5. Areas of sodic soils (brown areas) occur on terraces. This sodicity is a 'ghost' of former salinity. Lower terraces and fans (violet areas) are also sodic but have patches of salinity, where either former salinity has not been completely removed by leaching or salinity has been reintroduced. On the flood plains, saline patches are sporadic (light blue areas) or are extensive (dark blue areas). This map is based on an interpretation of the Maniototo soil map (Raeside et al. 1966). The sodic soils are those that have argillic horizons, which have high exchangeable sodium percentage (ESP). There are few analysed soil profiles, and although ESPs are consistently high, the results must be considered provisional. There is no modern survey of the current distribution of saline soils. Changes are to be expected because irrigation development since the early 1960s will have caused some redistribution of the soluble salts.

In terms of the origin of salt pans on Tertiary sedimentary landforms, we offer tacit support to Park (1906) who ascribed their derivation to sink-hole or swallow-hole processes involving the dispersibility and subterranean transport of capping alluvial sediments. Raeside's (1948) mechanism of aeolian removal of surface alluvium following loss of surface vegetation would not be likely to produce the remarkably regular, oval- to circular-shaped, and steep-walled outline of salt pans. Aerial photographs in Raeside (1948) suggest the floors of pans were variously vegetated, bare-earthed, or water-filled depending on

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