MINERAL NITROGEN REGIMES IN SOILS OF NATURAL AND MODIFIED SNOW TUSSOCK GRASSLANDS OF CANTERBURY AND OTAGO, NEW ZEALAND.

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G.D. McSweeney

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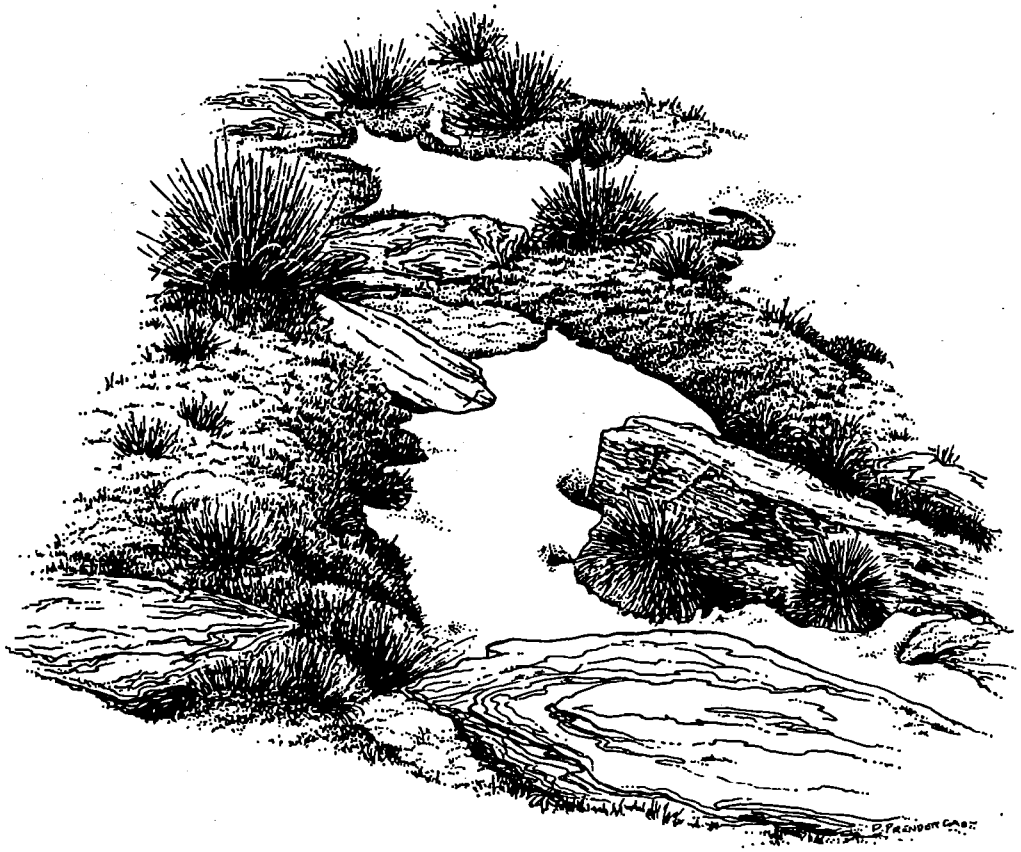

Thin-leaved snow grass(Chionochloa macra) in the spring snow melt.Old Man Range,Central Otago.

ABSTRACT

Mineral nitrogen (N) levels in natural grasslands of the world fluctuate in response to a range of environmental influences but are generally low with ammonium (NH_4-N) levels usually below 10 μg g^{-1} soil and nitrate (NO_3-N) levels even lower. This is considered to reflect active competition for mineral N between grass roots and soil micro organisms although it has been suggested that low nitrate levels may result from nitrification inhibition by plant exudates in grassland soils. Snow tussock *(Chionochloa)* grasslands cover approximately two million hectares of South Island, New Zealand. Such natural grasslands have been extensively modified since European settlement by grazing, burning and cultivation, factors which are postulated to have triggered changes in soil mineral N regimes leading to these becoming N losing ecosystems.

Seasonal mineral N levels were measured at intervals for up to three years in a range of intact tall tussock grasslands in Canterbury and Otago. First a sampling and extraction procedure was devised to avoid the changes in mineral N after sampling which are considered to have marred earlier studies of seasonal soil mineral N. Nitrogen levels in intact grassland soils were compared to levels in similar grasslands subjected to modification ranging from simulated grazing to burning and cultivation.

Intact grasslands showed sometimes high mineral N levels (up to 90 μg g^{-1} soil), particularly in winter months and also after a spring dry-wet alternation. Most of this mineral N was located in the upper 100 mm of soil. Only in autumn did mineral N levels approach the levels considered characteristic of grassland ecosystems. Nitrifying bacteria numbers were generally low although this finding possibly reflected analytical limitations.

It was postulated that the surge in mineral N levels detected in winter resulted from alternate freezing and thawing of surface soil layers resulting in the mineralisation of nitrogen in the soil. A laboratory experiment simulating field freeze-thaw conditions in a range of soils induced a major increase in NH_4-N levels within these soils.

Repeated defoliation caused a general surge in soil NH_4-N levels, resulted in a change in the distribution of mineral N in the soil profile, altered soil moisture regimes and generally increased the number of nitrifying

bacteria in soils particularly at higher altitude *Chionochloa macra* sites.

Urea application to defoliated sites amplified the changes in mineral N levels and nitrifying bacteria numbers caused by defoliation. However, urea application to intact grasslands did not cause a general increase in soil mineral N levels although it caused a marked increase in foliar N levels. It was therefore postulated that snow tussocks are capable of absorbing the quantities of mineral N available from periodic surges in mineralization.

Burning and cultivation of *Chionochloa* grasslands caused substantial increases in soil mineral N levels and nitrifying bacteria numbers.

These studies reveal the magnitude of mineral N fluctuations in intact snow tussock grasslands and show the increased potential for N loss which may result from cultural modification of these natural grasslands by grazing, burning and cultivation.

The importance of maintaining snow tussock grassland to prevent the development of N losing ecosystems and to enable similar comparative studies to be done in the future is emphasised.

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NITROGEN TRANSFORMATIONS IN NATURAL AND MODIFIED GRASSLANDS - A REVIEW OF LITERATURE.

CHAPTER 1

1.1 INTRODUCTION

Nitrogen is an essential element in plant nutrition. Nitrogen within plants can be broadly divided into two forms. Structural components include compounds largely associated with cell walls such as cellulosic and lignified compounds and some extra-cellular polysaccharides. Metabolic components incorporate the compounds in cell sap, membranes and organelles whose principal constituents are proteins, amino acids, RNA and DNA.

Grasslands are ecosystems within which nitrogen is in a constant state of flux through internal transfers between pools within the soil-plant system and by a range of external additions to and losses from this system.

The biogeochemistry of nitrogen (N) in grassland ecosystems is similar to that in other ecosystems in that no unique components or pathways are believed to exist. The relative importance of certain transfer pathways and N pools differ, however, from those that characterise forest or shrubland ecosystems. These differences are most significant in annual grasslands and less marked in perennial grasslands (Woodmansee *et al.*, 1981).

The characteristic feature of annual grasslands is the short life span of above ground matter, the dominance of below ground biomass and its influence on nitrogen pathways and transformations and the important role of larger herbivores (Floate, 1981).

Perennial grasslands, which include New Zealand tall tussock grasslands, differ markedly from annual grasslands. Tall tussock grasslands can have almost half of their biomass in above ground tissue including litter (O'Connor, 1983). This still represents, however, only a small proportion of the total soil - plant nitrogen pool because of the large quantity of nitrogen contained in the soil organic matter pool. Since the extinction of most of the avian herbivores in New Zealand, tall tussock grasslands were characterised by the absence of large herbivores for a period of perhaps 400 years until the comparitively recent introduction by European settlers of grazing mammals. In this respect, these grasslands differ substantially from the perennial grasslands of East Africa's Serengeti (McNaughton, 1979) and prairies of the central United States (Woodmansee *et al.*, 1978).

Internal nitrogen transfers as well as losses and gains of N from the grassland ecosystem occur through biological processes such as plant uptake and animal consumption and excretion as well as through microbial activity. Micro-organisms influence the availability of N to plants in a variety of ways (Woodmansee *et al.*, 1981). Through microbial decomposition of soil organic matter, N can be released in a form more available to plant uptake or it can be immobilised in microbial tissue. Microbes can oxidise or reduce inorganic N and thereby make it more or less available to plants (e.g. oxidation of NH_4^+ to NO_2^- and NO_3^-, reduction of NO_3^- to NO_2^-). Microbes also fix atmospheric N and incorporate it into the grassland ecosystem.

Non-biological processes such as physical and chemical weathering of minerals will also affect the transfer and level of N in the grassland ecosystem.

Because a large proportion of the N in the grassland ecosystem lies within the soil organic matter pool, processes whereby it is released from this pool and the ultimate fate of this plant-available N are of particular interest both for studies of plant nutrition and for identifying opportunities for N loss from the grassland ecosystem.

This study examines the size of the mineral N pool at different seasons in a range of South Island tall tussock grasslands to gain an appreciation of the environmental and cultural factors that influence the transformation of mineral N within these grasslands.

Tall tussock grasslands occupy much of the subalpine zone above the timberline and have also been induced over large areas of the montane and lowland areas of South Island, New Zealand, following the burning of the original forest cover (Molloy *et al.*, 1963). Before pastoral use began in these grasslands over a century ago, tall tussock (*Chionochloa* species) grasslands were more widespread than at present. Their abundance has been greatly reduced by repeated burning and grazing (O'Connor and Powell, 1963; Connor, 1964; Mark, 1969). Large areas of tall tussock grassland remain, especially in the upper montane and subalpine zones and provide an excellent opportunity to examine the pathways and processes of N transformations in natural grasslands in relation to a range of environmental factors.

The extensive cultural modification to which these grasslands are still subject, also presents the chance to compare the influence of extensive and intensive grazing regimes, burning, cultivation and pasture development upon soil mineral N and its transformations.

1.2 TERMINOLOGY OF SOIL NITROGEN TRANSFORMATIONS.

Transformation of soil organic matter to inorganic, plant available N and the incorporation of N in micro-organisms are described by a range of names. To avoid confusion, terms are defined below following the recommendations of the Soil Science Society of America (1975).

1. Denitrification - the biochemical reduction of nitrate or nitrite to gaseous nitrogen either as molecular nitrogen or as an oxide of nitrogen.

2. Immobilisation - the conversion of nitrogen from the inorganic to the organic form in microbial tissue so that the nitrogen is not readily available to other organisms or plants.

3. Mineralisation - the conversion of nitrogen from an organic form to an inorganic state as a result of microbial decomposition.

4. Net Mineralisation - the amount of mineralisation over and above that when immobilisation is taken into account.

5. Nitrification - the biological oxidation of ammonia to nitrite (NO_2-N) and nitrate (NO_3-N) or a biologically-induced increase in the oxidation state of nitrogen.

6. Ammonification - the biochemical process whereby ammoniacal nitrogen is released from nitrogen-containing organic compounds.

1.3 NITROGEN TRANSFER PATHWAYS AND POOLS IN NATURAL AND CULTURALLY MODIFIED GRASSLANDS.

1.3.1 Models of grassland ecosystem N transformations.

The processes of N addition to the grassland ecosystem, its transfer between different N pools within that system and the pathways of N loss from the

system can be generally represented by a diagramatic compartmental model such as that of Jackson and Raw (1973) shown in Figure 1.1. below:-

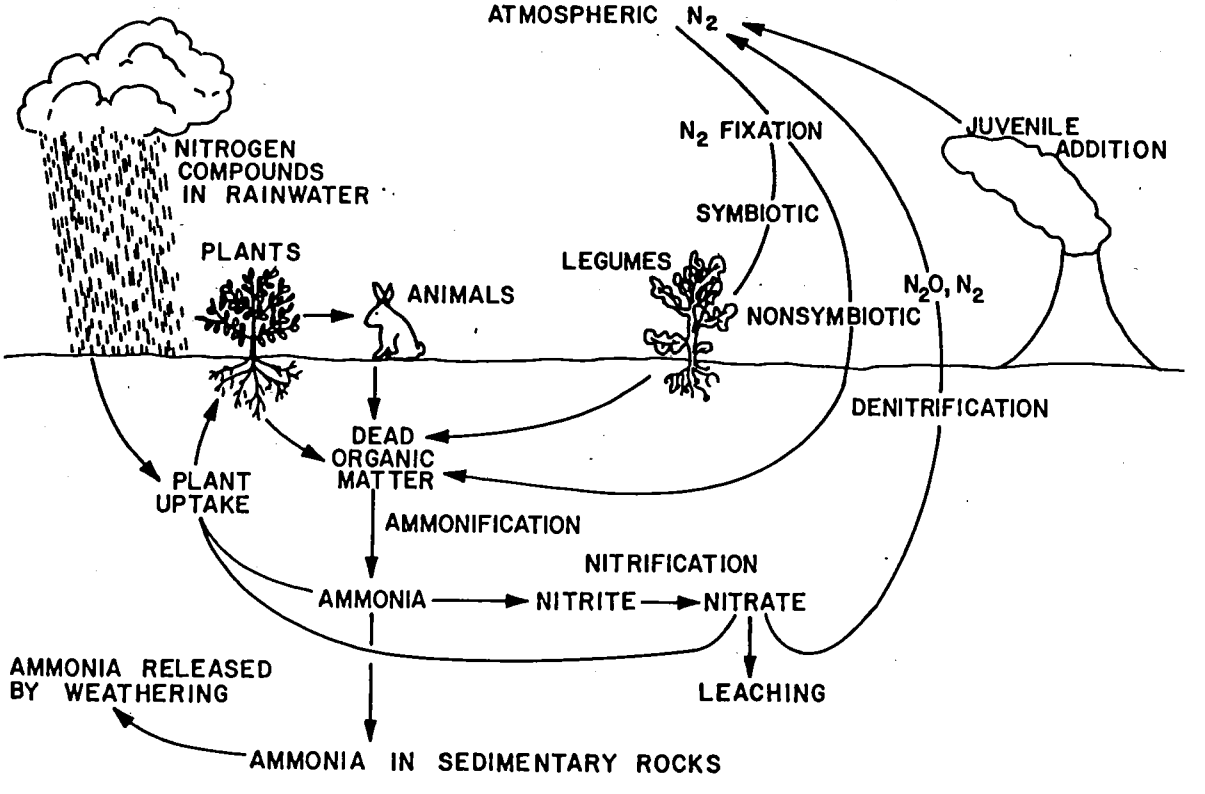

Figure 1.1: A compartmental nitrogen cycle (Jackson and Raw, 1973).

A more detailed compartmental model of the N pools and transfer pathways within a grazed grass-legume system has been presented by O'Connor (1974) and is shown in Figure 1.2.

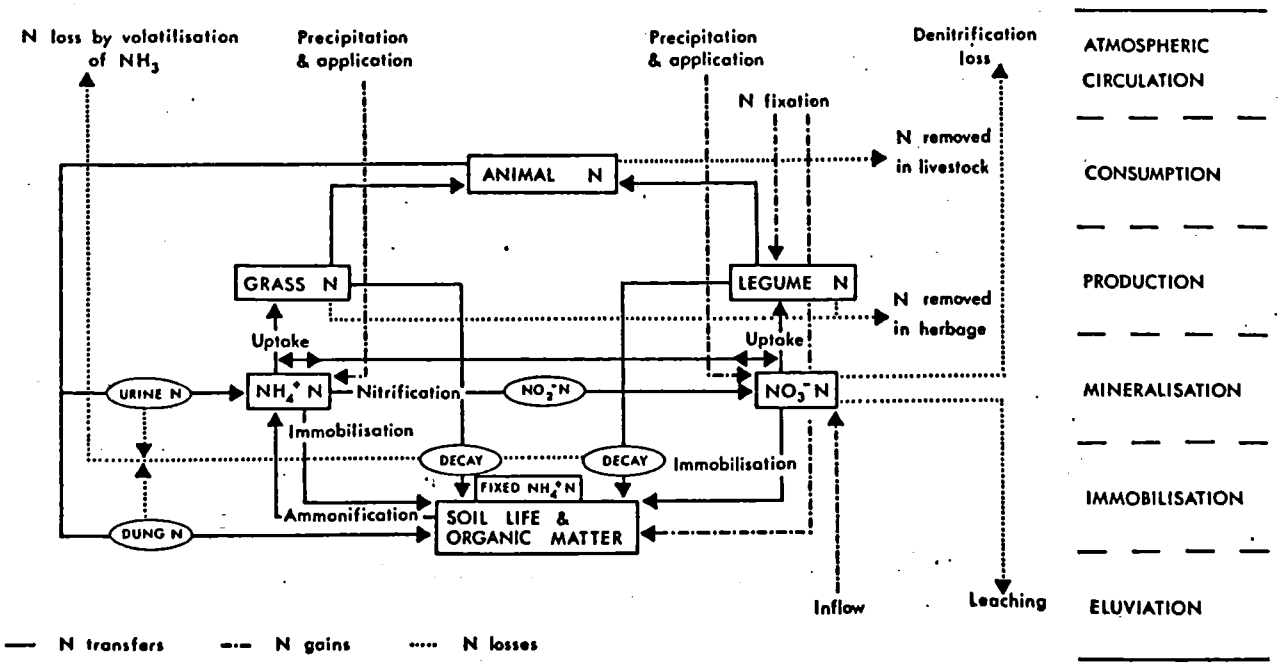

Figure 1.2: Losses, major pools, intermediate states and pathways of gain, loss and transfer for nitrogen circulation in a grazed grasslegume system (O'Connor, 1974).

Provided sufficient information is available on most of the processes involved, a quantitative N cycle can be developed. This can include the amounts of nitrogen within each pool and the magnitude of annual N transfers between pools as well as N additions and losses (source and sink). Such detailed studies have been made on a Colorado short grass prairie resulting in the budgeted nitrogen cycle presented below in Figure 1.3 (Woodmansee *et al.*, 1978). Some of the transfer pathways in this diagram have not yet been quantified.

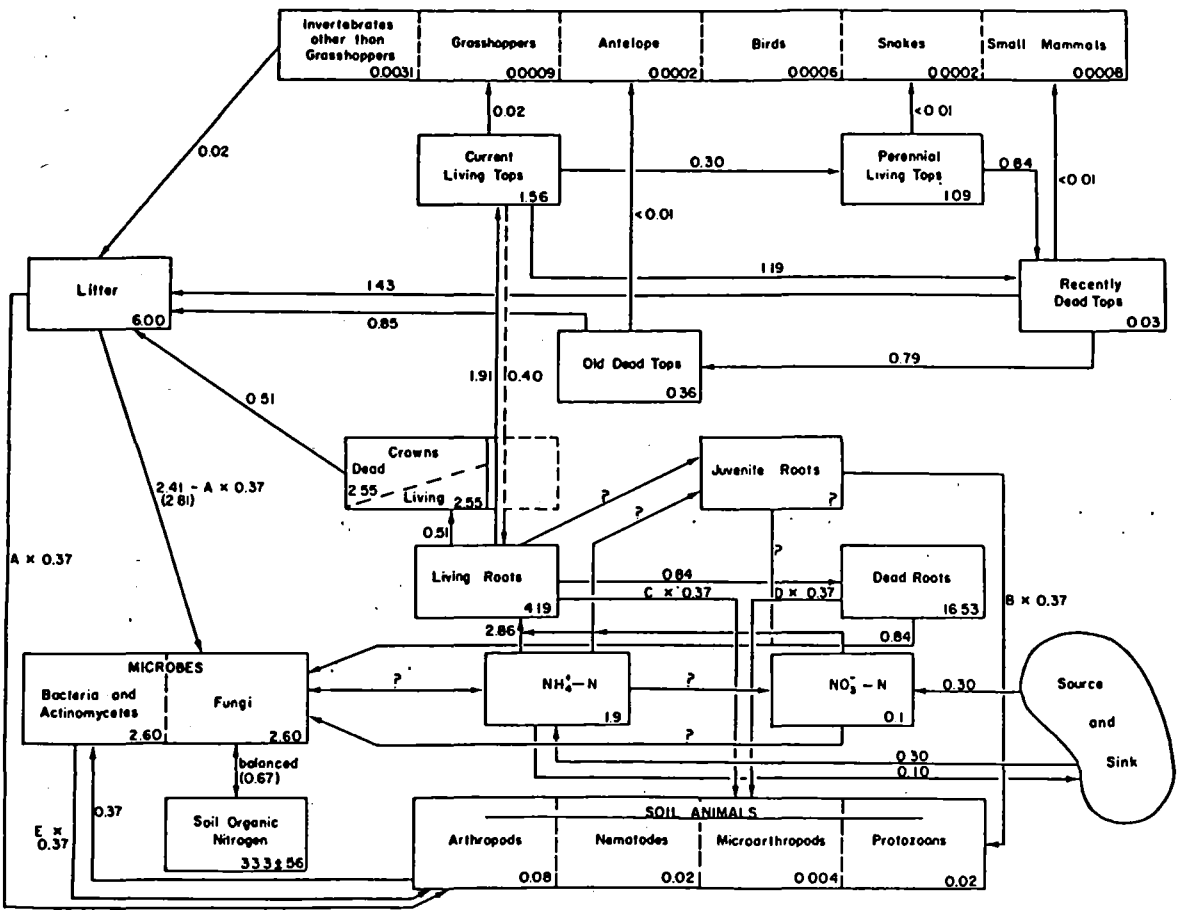

Figure 1.3: A budgeted nitrogen cycle for a Colorado short grass prairie (Woodmansee *et al.*, 1978).

Many other compartmentalised N cycles and N flow diagrams have been developed for grasslands and other ecosystems. These are discussed by Clark (1981) and O'Connor (1983).

Using results from budgeted nitrogen cycles it has been possible to develop simulation models for terrestrial nitrogen cycles in different grassland systems such as the blue grama grassland at Pawnee, Colorado (McGill *et al.*, 1981). Models can then be used as tools for acquiring a better understanding of the functioning of and interrelations within a grassland ecosystem N cycle. They also can be valuable for prediction. In order to reach to such a complex stage, a great deal of quantitative soil information is required.

1.3.2 N cycling in tall tussock grasslands.

No attempt has yet been made to develop a budgeted N cycle for New Zealand

tall tussock grasslands. The comparative unimportance of these ecosystems for agriculture appears to have brought such a task a lower priority compared to that accorded to grazed grass/legume systems of the lowlands where quantitative N flow diagrams have only recently begun to be developed (Ball, 1982; Carran, 1982; Quin, 1982).

There has been a steady accumulation of information on the quantities of N in tall tussock biomass, soil organic N pools and on the transfer of N between plant components and the soil system (Williams *et al.*, 1977; Meurk, 1978; Evans and Kelland, 1982). The magnitude of gains and losses of N within these systems by processes such as dinitrogen fixation, denitrification, NH_3 volatilisation and leaching losses are poorly known and the significance of some of these processes within tall tussock grasslands is unknown.

It is possible, however, to postulate a generalized summary outlined below of N gains, losses and internal transfers within tall tussock grasslands, both in natural state and under cultural modification.

1.3.3 N additions to natural and modified grasslands.

(a) Symbiotic N fixation:-

In the early stages of soil development and ecosystem succession, legumes make a major contribution to the accumulation of soil nitrogen (Reiners, 1981). In mature perennial grasslands, the legume contribution of N declines markedly (Woodmansee *et al.*, 1981). In these systems, legumes will frequently account for less than 5% and at times for no more than 1% of primary production. Annual fixation rates are generally less than 0.1 g N m^{-2} (Woodmansee *et al.*, 1978).

Unmodified tall tussock grasslands support a range of native legumes despite some assertions to the contrary (e.g. Ross *et al.*, 1978), although evidence for their abundance is stronger in the montane and lower subalpine zones than at higher altitudes. The physiognomic importance of these legumes in the grasslands is likely to have been under-rated because of their widespread destruction through selective grazing by mammals. The effectiveness of species of the genera *Carmichaelia, Corallospartium, Sophora* and *Swainsona* to fix N has not been quantified in the field, although their prolific growth on youthful soils where grazing is excluded (i.e.

Carmichaelia in the Bankside Scientific Reserve, Canterbury Plains) suggests that they have a vital N fixing role in the early stages of ecosystem development.

Quantitative studies of the N.Z. non-leguminous N fixing symbionts of the genera *Coriaria, Gunnera* and *Discaria* by Silvester (1977), Silvester and Smith (1969) and Daly (1969) revealed N fixation levels ranging from 6.7 to 19g N $m^{-2}yr^{-1}$.

O'Connor (1983) and Reiners (1981) discuss in detail the pattern of grassland N fixation in relation to ecosystem succession . They emphasise that since symbiotic N fixation is of greatest significance in seral communities, any factor that reverses the progression of soil development (i.e. erosion, phosphate fertiliser, ash and loess deposition, burning) is likely to stimulate symbiotic N fixation.

Heavy grazing of tall tussock grasslands has resulted in range reduction and often in the elimination of many of the palatable N fixing symbionts (O'Connor, 1983). Less palatable symbionts such as *Discaria* have also been burnt to encourage the growth of palatable grasses and facilitate stock movement.

Woodmansee and Wallach (1981) suggest that low intensity burning may encourage the fixation of atmospheric N by symbionts that invade the newly burnt surface. General observations after fires in tall tussock grasslands, suggest that stimulation of N fixing symbionts occurs only in wetter areas, where rhizomatous *Coriaria* is present, where a light burn does not kill *Discaria,* or where adventive *Trifolium* is already well established.

Adventive legumes are found through many modified tall tussock grasslands but are generally physiognomically unimportant (Connor, 1964; Connor and Macrae, 1969). *Trifolium* species (*T. repens, T. pratense, T. dubium, T. arvense*) and in wet sites species of the *Lotus* genus are spread through the grasslands and may partially compensate for the loss of native legumes provided they can cope with soil nutrient deficiencies in many areas particularly deficiencies of phosphorus and sulphur (White, 1959). *T. campestre* and *T. glomeratum* are also adventive especially in some North Canterbury grasslands. Where fertilisation with sulphur and phosphatic fertilisers has occurred and in nutrient accumulation zones such as dung and

urine patches and flush sites, adventive legumes demonstrate vigorous growth.

(b) Non-symbiotic N fixation:-

Woodmansee *et al.* (1981) cite studies estimating that N fixation by free-living bacteria ranges from 0.1 to 0.2 g N m^{-2} annually. Non-symbiotic fixation of nitrogen by algae can be significant (Paul, 1976) but algal blooms are considered uncommon in dense perennial grasslands. Rhizospheres of tropical grasses have been shown to harbour N fixing bacteria (Dobereiner, 1977).

The presence of non-symbiotic N fixing bacteria of the genera *Azotobacter, Klebsiella* and *Clostridium* in a range of Canterbury and Otago tussock grassland soils was shown by Line and Loutit (1971, 1973). An unpublished study in tall tussock grasslands at Paddle Hill Creek, South Canterbury by D.A. Lynch in 1978 of Lincoln College (pers. comm.) also revealed moderate levels of *Azotobacter* and *Biejerinckia.*

The quantitative input of N from free-living bacteria is difficult to assess. Line and Loutit found that numbers of these bacteria were low even though the estimated rates of dinitrogen fixation were comparitively high. No information is available on the effects of grassland modification on these bacteria.

(c) Wet and dry deposition.

Annual nitrogen depositions from the atmosphere on coastal areas in different parts of the world are generally 0.1 - 0.3 g N $m^{-2}yr^{-1}$. Variations are related principally to the amounts and the frequency of precipitation at different locations (Woodmansee, 1979). The major N cycle contributions from the atmosphere are NO_3-N and NO_2-N ions, the products of electrical discharges. Other sources of atmospheric nitrogen additions include fertiliser drift, decomposing nitrogenous wastes in water bodies, litter and the burning of fossil fuels. There is some controversy over the level of direct absorption of NH_3 from the air by plants and soils and whether these systems are sources or sinks for NH_3 (Woodmansee *et al.*, 1981).

In New Zealand, Wilson (1959a; 1959b) surveyed atmospheric N additions in snow and rainfall at a range of sites including coastal areas, North Island volcanic mountains, and the Southern Alps of the South Island. He found low to negligible NO_2^- and NO_3^- additions but substantial quantities of

NH_4-N and organic (albuminoid) nitrogen. NH_4-N levels in snow reached 0.2 ppm on Mt Ruapehu and on the Tasman Glacier, Mt Cook. Organic N inputs also reached these levels. Wilson attributed the origin of these high N levels to a surface concentration of nutrients on the white caps of the ocean. Since annual rainfall in the western South Island tall tussock grasslands can exceed 10 metres annually (Chinn, 1979; Westland National Park unpublished rainfall survey), atmospheric additions may represent an important source of N for these tall tussock grasslands.

1.3.4 N pools and transfer pathways.

In most non-desert soils more than 90 percent and often more than 95 percent of soil N is in soil organic matter. Mineral nitrogen (NH_4-N and NO_3-N) is less than 0.5 percent of the total nitrogen in the system, except for some unknown amount that may be fixed as NH_4^+ in clay minerals and can be presumed to be in equilibrium with exchangeable NH_4^+ (Woodmansee *et al.*, 1981).

Distribution of nitrogen between living tissues of plants, dead litter, soil biota and above ground herbivores can vary markedly in relation to environmental factors and between annual and perennial grasslands.

In a study of a Colorado semiarid short grass prairie ecosystem it was found that nitrogen was located in the components detailed below:-

TABLE 1.1: Location of nitrogen in a Colorado short-grass prairie ecosystem on 29 July 1973. All aerial parts and below ground components to 36cm below the soil surface (Woodmansee *et al.*, 1981).

N location	g N m^{-2}	Per cent of total
Total N	375.2	100.0
Organic N	373.2	99.5
Mineral N	2.0	0.5
Soil organic N	333 ± 56	88.8
Dead roots	16.53	4.4
Litter	6.00	1.6
Dead crowns	2.55	0.7
Old dead tops	0.36	0.1
Recently dead tops	0.03	<0.05
Total "dead"	358.47	95.6
Current living tops	1.56	0.4
Perennial living tops	1.09	0.3
Living crowns	2.55	0.7
Living roots	4.19	1.1
Above-ground animals	0.01	<0.05
Below-ground animals	0.12	<0.05
Bacteria	2.60	0.7
Fungi	2.60	0.7
Total living	14.72	3.9

The importance of some of these nitrogen pools in the tall tussock grassland ecosystem is now considered.

(a) Nitrogen in soil organic matter:-

The size of the soil organic matter N pool depends on the degree of maturity of the tall tussock grassland ecosystem. Patterns of change in organic nitrogen storage during primary and secondary succession of terrestrial ecosystems have been described by O'Connor (1974) and Reiners (1981) who draw heavily from research by Walker (1964) and Vitousek and Reiners (1974).

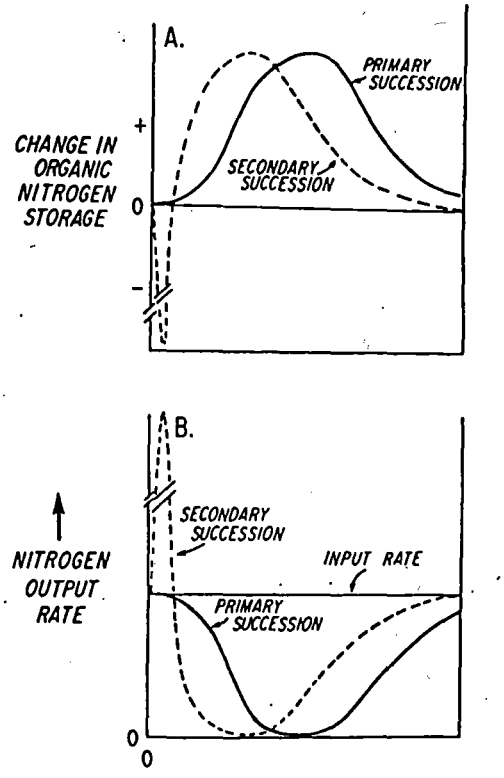

Figure 1.4: *A. Patterns of change in organic nitrogen storage during primary and secondary succession of terrestrial ecosystems. The starting time for primary succession is immediately following exposure of a new site; for secondary succession it is immediately following a destructive disturbance. Note the scale break for the pulse of negative storage following disturbance. This negative pulse depends on the degree of nitrogen loss to the disturbance (burning, harvesting, erosion, leaching).*

B. Patterns of nitrogen output rates, on the assumption storage is principally in organic form and the input rates are constant as shown. Note the break in scale for the pulse of high output rates following disturbance in secondary succession.

(from Reiners, 1981).

Total organic nitrogen is generally higher in more mesic or colder environments. Harvey (1974) has presented data on organic nitrogen in tall tussock grassland soils at Paddle Hill Creek, South Canterbury. Molloy and Blakemore (1974) discussed the major pool of soil organic nitrogen present in Otago tall tussock grasslands and found that these pools were markedly higher in the yellow-brown earths beneath tall tussock grassland than in the yellow-grey earths beneath short tussock (*Festuca*) grassland. Yellow-brown earths characteristically receive greater precipitation than yellow-grey or brown-grey earths. The pool of soil organic nitrogen in the surface 10cm of soil of a *Chionochloa rigida* grassland at the Paddle Hill Creek Lower site (see Chapter 3) was 307.8 g m^{-2} and 225.5 g m^{-2} in *C. macra* at the PHC Upper site (Williams *et al.*, 1977).

The effects of grassland modification through grazing on the soil organic nitrogen pool are not clear. If, as O'Connor (1974) suggests, grazing leading to range depletion stimulates nitrification, then long term leakage of N through the mineralisation pathway from the organic matter pool will occur and this may lead to a reduction in the size of this pool. Grazed grasslands, where grazing does not lead to range depletion, have been shown to accumulate organic matter during rotations (Floate, 1981).

Jackman (1964) studied the accumulation of organic matter in New Zealand soils under grazed pasture. Unfortunately this study did not provide any comparison with the accumulation of organic matter in such pasture systems in the absence of grazing, so the influence of herbivores on this accumulation is not clearly defined.

The effects of burning upon soil organic N have been reviewed by Woodmansee and Wallach (1981). Intense burns, in particular, can destroy the upper layers of soil organic matter and soil biota with large quantities of nitrogen being lost by volatilisation.

Cultivation generally causes a reduction in soil organic nitrogen in the long term (Power 1981). Allison (1973), found that the soil organic matter and organic nitrogen content decreased for the first 25-50 years after a range of natural grasslands were put under cultivation. This was attributed to increased biological activity and turnover of organic matter within the soil system.

Losses of N from organic nitrogen pools may occur through the production of ammonia and nitrate. The magnitude of these losses depends upon the stage of ecosystem succession and the type of disturbance that affects the ecosystem. In Figure 1.5 below a scenario is presented for these changes in a terrestrial ecosystem (Reiners, 1981). Clearly a blowdown is likely only to occur in a forest ecosystem. It is postulated later in this chapter, however, that intensive grazing of a grassland ecosystem may cause a similar response in soil-N levels to that initiated by the blowdown shown here.

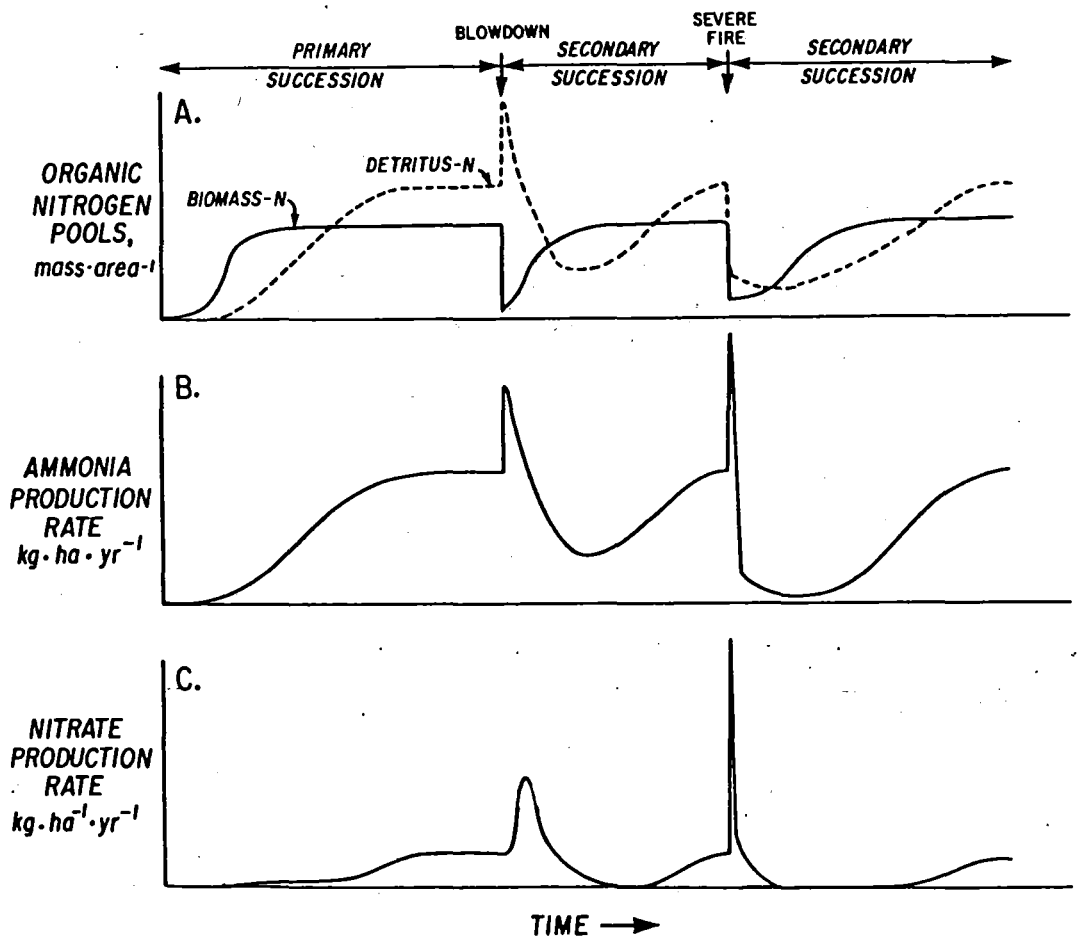

Figure 1.5: A scenario for changes with time in organic nitrogen pools and mineral nitrogen production in biomass and detritus pools of a terrestrial ecosystem.
(from Reiners, 1981).

(b) Plant and litter N pool:-

Distribution of plant and litter nitrogen in a sward of blue grama grass in Colorado is presented in Table 1.1. The proportion of total nitrogen within this pool varies between different grassland systems. In most perennial grasses and forbs, all tops grow and die each year (Woodmansee *et al.*, 1981) although Williams *et al.* (1977) showed that in Paddle Hill Creek (PHC) tussock grasslands, plant tops persist for a much longer period. In many grasslands, short lived perennials and annuals make up much of the biomass. When their tops die, the whole plant may die.

When death of plant components occurs, plants may mobilize nitrogen from their dying tissues and translocate it to perennial or actively growing tissues (Staaf and Berg, 1981). Between one-third and two-thirds of the total living tissue nitrogen may thus be conserved and become available for the next flush of growth. The remainder falls to the ground in litter.

Roots and crowns in perennial grasslands are the dominant living plant fractions and at peak standing crop the mass of living perennial roots can be two to four times as large as that of tops (Woodmansee *et al.*, 1981).

O'Connor (1983) has contrasted the PHC tall tussock grassland plant and litter nitrogen pool with that of the Colorado short grass prairie (Table 1.1) by using the results of Williams *et al.* (1977). *C. macra* grassland contained 15.7g N m^{-2} in plant tissue of which 64 percent was in live and dead root tissue. *C. rigida* grassland contained 29.1g N m^{-2} in plant tissue with 53 percent of this in root tissue. Clearly the pool of nitrogen in plant and litter tissue is small in comparison to the pool of total soil nitrogen, being only 9.5 percent as large as the total soil nitrogen pool in *C. rigida* grassland and 7.5 percent as large as that in *C. macra* grassland.

Marked seasonal variation also occurs in plant nitrogen levels in tall tussock grassland (Williams *et al.*, 1977). Some evidence is presented in Williams' work that indicates that tissue N concentrations, especially in leaf sheaths, may be highest early in the spring.

Total defoliation of all live shoots by grazing would remove approximately 1.5 percent of the total organic nitrogen from a PHC *C. rigida* grassland and 0.8 percent from a PHC *C. macra* grassland (O'Connor, 1983). However, total defoliation by grazing rarely occurs at a single time in extensively

grazed grasslands, except for a highly favoured plant or site. N is also returned to the grassland as dung and urine. While a single defoliation is likely to remove only a small quantity of N from organic N pool, repeated defoliation is likely to be more serious as the small losses by animal production, volatilisation, and leaching from excreta are multiplied.

Burning is likely to result in an even greater loss of N from the plant and litter N pool, since more than half of the above ground portion of this pool is present as dead shoots (sheath and leaf blade tissue and litter in the PHC tall tussock grasslands. Most of the N within the tissue will be lost by volatilisation especially where burning is intense (Woodmansee and Wallach, 1981). Evans and Kelland (1982) report even higher proportions of plant and litter N in the form of litter than were found in the Paddle Hill Creek grasslands, but it is not clear how much of this litter pool N is subject to burning loss. After burning, fresh regrowth contains increased concentrations of nutrients compared to unburnt foliage (Williams and Meurk, 1977). Grazing of the foliage would further deplete the plant/litter N pool. Mark (1969) showed that repeated burning of Otago tall tussock grasslands repeated at intervals of less than five years had a severely debilitating effect on these grasslands.

Cultivation obviously destroys the plant/litter N pool, but because the plant and litter tissue is incorporated into the soil, much of the N they contain will enter the soil organic or soil biota N pools.

(c) Soil biota N-pool:-

Reference to Table 1.1 shows that N in soil biota makes up 18.5 percent of the N in the total living components of the ecysystem and is primarily present as bacteria. It was considered in the simulation model of McGill *et al.* (1981) that nitrogen in bacteria and fungi turned over several times in a year. Causes of microbial death in grassland include drought, freezing and thawing, substrate starvation and predation. Once micro-organisms die, N in their cell membranes and metabolic tissues enters a pool of organic matter which can be rapidly mineralised.

(d) Nitrogen in large animal tissue:-

The study by Woodmansee *et al.* (1981) presented in Table 1.1 shows the very small proportion (<0.05 percent) of total nitrogen represented in above-ground grazing herbivores. Under extensive grazing conditions, animals consume only a small proportion of the standing crop of plant matter

and assimilate only a small fraction of the nitrogen they consume. If the animals are harvested or die in the system without their tissue elements becoming available to the system, Woodmansee *et al.* (1981) calculate that between 0.1 - 0.4 g N m^{-2} yr^{-1} would be removed from grasslands ranging from low to high productivity. The general effect of grazing on grasslands, as well as the limited role of the grazing herbivore in natural N.Z. tall tussock grasslands is discussed in more detail in Chapter 4.

Modification of these grasslands through the introduction of browsing mammals such as sheep, cattle, deer, rabbits and hares has increased the importance of the animal N pool in tall tussock grasslands.

Under extensive grazing conditions (<2.5 sheep ha^{-1}) no more than 10 percent of the above ground plant matter (5 percent of the tussock plant/litter N pool) is likely to be consumed (O'Connor, 1982). Only a very small proportion (5-15 percent, Woodmansee *et al.*, 1981) of this N is retained in animal tissue, representing from 0.02 - 0.08 percent of total organic nitrogen. Obviously, under more intensive grazing regimes these proportions will increase.

The major effect of grazing on tall tussock grassland N cycling will be the increase in the proportion of N that enters the rapid cycling pool and therefore becomes available for loss by leaching and volatilization. A much larger quantity of N will be involved in such a rapid cycling pool than the quantity of N incorporated into animal tissue.

(e) Mineral N pools and immobilisation of N in micro-organisms.

The process of mineralisation releases N from the organic N pool into the mineral N pool. Inputs of mineral N may also occur through precipitation. The main substrates for mineralisation include newly added dead plant tops and roots, root debris, recently dead soil fauna and micro-organisms, partly decomposed plant and microbial debris, and secondary organic compounds in soils. In the Colorado short grass prairie, the largest source of mineral N appeared to be a combination of recently dead plant and microbial debris (Woodmansee *et al.*, 1981). Plants and micro-organisms take up mineral N simultaneously during periods of rapid plant growth. In natural grasslands, the uptake capabilities of micro-organisms and plants together are considered generally to exceed the mineralisation potential of these systems and therefore all mineral N produced in the soil is likely to be quickly immobilised in living organisms. Because of the

intense competition for mineral N and its immobilisation in living tissue very low concentrations of soil mineral N (NH_4- N<10µg g^{-1}, NO_3-N<1µg g^{-1}) are considered characteristic of natural grasslands (Woodmansee *et al.*, 1981). This is a feature of the short grass prairie ecosystem shown in Table 1.1 where mineral N represents only 0.5percent of total N.

O'Connor (1983) points out, however, that substantial pools of perhaps temporarily fixed NH_4-N and of NO_3-N often occur in natural grasslands where they can be associated with strong seasonal or climatic pulses.

The influences of grazing, burning and cultivation upon mineral N pools are reviewed in more detail in Chapters 4 and 5.

1.3.5 Losses of N from grassland ecosystems

(a) Leaching

Leaching will be important only if N is in a mobile chemical form. NO_3-N is highly mobile, NH_4-N is much less mobile. Water must also be present in sufficient amount to carry mobile ions through the profile and out of the rooting zone for leaching to occur.

Woodmansee *et al.* (1981) suggest that leaching losses of N from natural grasslands are generally very small because soil NO_3-N levels are usually <1µg g^{-1} and inadequate water is present in these systems for leaching to occur. Even when adequate water is present, ions must frequently migrate through well developed B horizons with high ion-exchange capacities as well as through a complex matrix of plant roots and micro-organisms which are capable of extracting ions from solution.

Studies of undisturbed grassland and forest catchments have shown that there may be periodic substantial outflows of NO_3-N from these systems. Lewis and Grant (1980) found a close inverse relationship between snowpack and stream NO_3-N levels in an undisturbed catchment with forest (80percent) and grassland (20 percent) at 2900 metres altitude in Colorado. They attributed the presence of NO_3-N to the effect of freeze-thaw activity in surface soil when snow cover was absent. Todd *et al.* (1975) compared an undisturbed fescue grass catchment, a white pine plantation and an undisturbed hardwood forest catchment in the U.S. Southern Appalachian mountains and found a close

correlation between the number of nitrifying bacteria in the soil of gauged watersheds and NO_3-N content of the streams. This relationship is also discussed by Vitousek *et al.* (1979).

Nitrification may not always lead to leaching losses. In dry grassland situations in Northern Australia (Wetselaar and Norman, 1960) and in North America (Power, 1970), it has been shown that nitrification does not always result in leaching losses of NO_3-N from the total soil system. NO_3-N ions may move downwards with temporary moisture impulses but can remain within deep soils without being leached out or denitrified. In conditions of seasonal drying, such nitrate may again move up the soil profile and be absorbed by plants.

Grassland disturbance by grazing, burning and cultivation have all been shown or suggested to cause increased nitrification and NO_3-N loss through leaching (O'Connor, 1983; Woodmansee and Wallach, 1981; Floate, 1981; Power, 1981). The mechanisms of this stimulation of nitrification and of NO_3-N loss are discussed in more detail in Chapters 4 and 5.

Studies of stream catchments draining New Zealand tall tussock grasslands provide fragmentary evidence for N loss by leaching. Burrows (1968) presents chemical analyses of stream samples from tall tussock grassland/ forest at Arthurs Pass, Canterbury, in which no NO_3-N was detected and NH_4-N levels range up to 0.05 gm^{-3}. Studies by D.A. Holdsworth of Otago University, Dunedin (pers. comm.) of dissolved ions in streams draining from tall tussock grassland in the Deep Creek catchment revealed levels of NH_4-N and NO_3-N up to 1 gm^{-3}.

There is clearly need for a study which relates range condition of tussock grassland both in natural and culturally modified state to nutrients in water and streams draining from these systems. This will show whether the nitrate pollution of waterways from agricultural development, which O'Connor (1974) warned about from developed pasture systems, is also a feature of tussock grassland development.

(b) Nitrogen volatilisation:

Woodmansee *et al.* (1981) consider that the major pathway of loss of N from natural grasslands is by volatilisation of NH_3 from decomposing litter and excreta. This is particularly significant where conditions do not favour

denitrification (i.e. in aerobic conditions) or leaching (i.e. with lack of surplus soil water).

Floate and Torrance (1970) showed that small quantities of NH_3 evolved from decomposing litter. Even though only a small amount of the total N in litter may be lost by this process, if this quantity is extrapolated over all decomposing litter in a pasture, the quantity lost becomes significant compared to the amounts of N added to the system.

The major pathway of N loss in a grazed grassland is likely to be through the volatilisation of NH_3 from faeces and in particular from urine (Floate, 1981). Urine usually contains 50-80 percent of excreted N (protein-rich forage producing the higher amount). Watson and Lapins (1969) suggested that more than 80 percent of the N in urine may be lost in this way in dry intensively grazed grasslands.

O'Connor (1981) suggests that the risk of volatilisation loss from New Zealand tussock grasslands may be much lower than the figure proposed by Watson and Lapins because the acid soils, wide C:N ratios and cool, moist soil environment of the tussock grasslands do not favour such a pathway. While considerable work has now been done on measuring the quantities of NH_3 volatilised from N.Z. grass-legume pastures (Ball *et al.*, 1979; Quin, 1977), the significance of this process in tall tussock grasslands has yet to be studied.

In the original natural tall tussock grasslands, it is possible that uric acid produced by the herbivorous birds and insects that inhabited these systems may have been less subject to volatilisation than urea produced by grazing mammals (Woodmansee, 1979).

Allied with N loss by volatilisation of NH_3 is gaseous loss from fire. The occurrence of periodic natural fires in the tussock grasslands is described in Chapter 5. Fire would have resulted in significant losses of N from the ecosystem in smoke. These losses may have been compensated for by surges in symbiotic N fixation after burning had taken place.

The increases in the frequency of fires with human settlement of New Zealand and the major volatilisation losses of N associated with this have already been described and are covered more fully in Chapter 5.

(c) Erosion:-

The extent of N losses through wind or water erosion is very dependent on the natural grassland involved and the incidence of wind and rainstorms, avalanches, earthquakes and other erosive events.

O'Connor (1980, 1982) traces the geological instability that characterises the mountains of New Zealand, and outlines some biological and pedogenic adjustments to this instability that he considers have taken place.

Tall tussock grasslands are shown to have clearly evolved in an environment in which natural erosion is likely to represent an important mechanism of N loss. Where such erosion exposes fresh parent material however, it leads to a further cycle of symbiotic N fixation and organic matter development.

(d) Denitrification:-

Denitrification is the enzymatic or chemical conversion of biologically active nitrogen to N_2O, NO_2, NO or N_2. Soil conditions that favour enzymatic denitrification are poor aeration, a supply of suitable substrate for microbial growth and the presence of NO_3-N and denitrifying bacteria. Fluctuating aerobic and anaerobic conditions favour denitrification. During aerobic phases, NO_3-N will accumulate by nitrification. This can then be denitrified when anaerobic conditions prevail. Woodmansee *et al.* (1981) considered that enzymatic denitrification is likely to be low in grasslands because of their low NO_3-N content and the rare occurrence of waterlogging within these systems. They suggest that more study is needed to determine whether denitrification may occur from urine patches after these are saturated by rain.

Chemo-denitrification is the volatile loss of N_2 and N_2O by reactions of nitrite with organic substances. Woodmansee *et al.* (1981) consider that although chemo-denitrification may cause substantial loss of N in some fertilised soils, its role in grassland is limited largely to urine patches and even there the major pathway of loss is probably NH_3 volatilisation.

There have been no detailed studies of denitrification processes in tall tussock grasslands. Bacteria capable of denitrification were isolated from tall tussock grassland soils on the Old Man Range, Otago (Hollings *et al.*, 1969), although active denitrification was not demonstrated under field conditions. In 1975, in a small unpublished study of Paddle Hill Creek

soils at the Microbiology Department, Lincoln College, M.J. Noonan and G.D. McSweeney used a dilution-incubation technique, (Alexander, 1961) to reveal the presence of low to moderate denitrifying bacteria numbers beneath both *Chionochloa macra* and *C. rigida* grassland.

Laboratory activity of these bacteria under ideal conditions does not confirm their field activity since dry, aerobic conditions will inhibit denitrification (Knowles, 1981). However, certain tall tussock grasslands, particularly those supporting *Chionochloa rubra*, are characterised by seasonally wet, anaerobic conditions where, provided NO_3-N was present and pH remained comparatively high (optimum between 7.0 and 8.0 according to Knowles, 1981), denitrification might be favoured. In New Zealand tall tussock grasslands the first three conditions might sometimes be encountered. However, because of high rainfall and zonal soil weathering regimes, it is unlikely that soil pH would be in the optimum range. Since it has been suggested that nitrifying bacteria in tussock grassland (Robinson, 1962) and elsewhere (Weber and Gainey, 1961) may be acid-tolerant, the possibility of a similar adaptation amongst denitrifying bacteria should not be discounted.

The significance of denitrification processes in tall tussock grassland clearly needs further study.

1.4 VARIATION IN SOIL NITROGEN TRANSFORMATIONS.

Mineral N is released from soil organic N in a biological reaction. The rate at which this release occurs is therefore dependent on environmental and physical factors which include temperature, soil moisture and aeration, acidity, carbon/nitrogen ratio, salt concentrations and trace elements, partial soil sterilisation, soil structure and composition and above ground vegetation. The general effects of some of these influences on nitrogen mineralisation and nitrification together with the studies that have examined their specific effects upon mineralisation processes in tall tussock grasslands are described below.

1.4.1. Temperature

Most early concepts about mineralisation - temperature relations were derived from laboratory incubation studies of fallow soils at constant temperatures (e.g. Stanford *et al.*, 1973). However, under field conditions

marked diurnal and seasonal temperature fluctuations can occur (Campbell and Biederbeck, 1972). Biederbeck and Campbell (1971) found that when an unamended soil was incubated at fluctuating low temperatures, the viable count of micro-organisms, particularly non-spore forming bacteria, declined sharply. Microbial growth was much greater at constant mean temperature than at corresponding diurnally fluctuating temperatures.

Freezing and thawing of soils introduces not only a temperature effect but also induces physical changes in soil structure and substrate availability for mineralisation. This is discussed in greater detail in Chapters 4 and 7.

Many studies have shown that microbial activities in soil are stimulated by temperature increases (Alexander, 1965), The temperature-mineralisation relationship is not linear, at least for temperate soils, since Stanford *et al.* (1973) found that in the temperature range of 5°C to 35°C, the activity doubled with every 10°C rise in temperature in a range of eleven different soils. Under tropical conditions, soil N mineralisation increased with temperature to a maximum at approximately 50°C, with a decline being apparent at 60°C (Myers, 1975). In incubation studies, Kowalenko and Cameron (1976) found that ammonification activity increased up to 35°C.

The temperature in a soil before N mineralisation is measured has an important effect on the rate of N mineralisation. For example, significantly less nitrification was found in a loam soil when the incubation temperature was shifted from suboptimal to optimal temperature than vice versa (Chandra, 1962).

Generally, rates of nitrification decrease relative to rates of mineralisation at low incubation temperatures (Tyler *et al.*, 1959, Ross and Bridger, 1977). A detailed laboratory incubation study was undertaken by Ross and Bridger (1978b) to test the influence of temperature on N mineralisation in six soils from a climosequence of tussock grasslands in Otago. The soils were incubated at 5, 10, 15, 20 and 24°C. In only four of the soils was it possible to calculate temperature coefficient (Q_{10} values). The average values ranged from 1.7 to 3.0. When calculated over various temperature intervals, Q_{10} values tended to be higher at the lower temperatures and were considered therefore to indicate that N mineralisation would slow down appreciably with decreasing temperatures in the field. In most of the soils

(Tawhiti, Obelisk, Tima) NO_3-N contents relative to NH_4-N contents tended to be greater at the higher incubation temperatures. This was considered to confirm the greater inhibitory effect low temperatures have on nitrification than on mineralisation.

Low temperature adaptations of both ammonifying and nitrifying bacteria have been shown in studies by Anderson *et al.* (1971) and Mahendrappa *et al.* (1966). Such adaptations might be expected for high altitude sites in tall tussock grassland.

1.4.2. Soil Moisture.

Gray and Williams (1971) describe three ways in which soil moisture influences N mineralisation:

a) As moisture increases, particularly in dry climates, water is more easily absorbed by microbial cells promoting their growth and activity.

b) If moisture continues to increase and waterlogs the soil, aeration decreases, inhibiting the activity of aerobic microbes that effect N mineralisation.

c) Cycles of wetting and drying tend to increase the amount of readily available microbial substrate.

Campbell and Biederbeck (1976) found that in grasslands, factors (a) and (c) above had the major influence on microbial activity because waterlogging was rare. The effect of moisture change was related to microbial response but was rarely independent of initial moisture content and/or temperature.

A variety of optimum moisture contents for N mineralisation have been found depending on the soil involved (e.g. Miller and Johnson, 1964; Stanford and Epstein, 1974). Both Reichman *et al.* (1966) and Stanford and Epstein showed that soil N mineralisation was proportional to soil water content as the latter fell to permanent wilting point (15 bars matrix suction). Miller and Johnston (1964) found, however, that N mineralisation tended to decline exponentially as soil moisture content declined to permanent wilting point.

Since it was first demonstrated by Birch (1964), wetting and drying of soils has been widely demonstrated to have a major influence on soil N mineralisation (Campbell *et al.*, 1973, 1974; Shields *et al.*, 1974). Birch hypothesised

that drying killed the soil microbes and that increasing mineral N was due to the mineralised N from dead microbial bodies. However, because the mineralised soil N did not decrease rapidly with successive drying cycles it is more widely accepted now that wetting and drying cycles weaken bonds between humus and/or plant particles and clay surfaces and thereby facilitate mineralisation.

In New Zealand tall tussock grassland, Mark (1965b) noted from a study of Central Otago grasslands that the snow tussock zone is characterized by abundant, readily available soil moisture. He considered, however, that sufficient tendency existed towards summer water shortage, near the lower altitudinal limits of snow tussock vegetation, for soil moisture deficits to be a possible limiting factor to plant growth at these sites. Molloy and Blakemore (1974) considered moisture to be limiting to the organic regime in the brown-grey earths and yellow-grey earths of their Otago climosequence but not limiting in the yellow-brown earths which supported *Chionochloa* vegetation. Ross and McNeilly (1975) considered that because of these conditions, the wetting and drying stimulation of mineralisation was unlikely to be important in tall tussock grasslands.

In his studies at Paddle Hill Creek, South Canterbury, Williams (1977) concluded that soils beneath tall tussock grassland probably contained adequate moisture for plant growth throughout the growing season. He found that the soils he studied never dried beyond wilting point over several years of measurement, a conclusion also reached by Harvey (1974) at the same locality.

In these studies the upper 100mm of soil was bulked in moisture investigations which may have therefore obscured moisture deficits very close to the surface of the soil where organic N and mineral N are likely to be concentrated (Molloy and Blakemore, 1974).

Archer and Collett (1971) noted that in the alpine *Chionochloa* grasslands they studied in the north-east Ben Ohau range, Canterbury, there were several months in which calculated evapo-transpiration rates exceeded net precipitation. Desiccation of the surface soil from exposure to the prevailing north-west winds was shown to occur throughout the year when the ground surface was free from snow. Seasonal moisture deficits and shorter term desiccation by north-west winds were much more severe on windward

slopes which supported degraded *Chionochloa* vegetation.

North west winds are a dominant climatic feature of much of New Zealand tall tussock grasslands (Mark,1965a). It is concluded therefore, that in tall tussock grasslands soil moisture deficits occur periodically in the surface soil layers. These deficits may not be manifested by any drought induced reduction in plant growth because they do not penetrate down to the main rooting zone. They may, however, result in alternate drying and wetting of surface soil layers thereby stimulating N mineralisation.

1.4.3 Aeration

High soil moisture levels can result in anaerobic conditions in the soil. Oxygen diffusion rates in undisturbed soils have been shown to be greater in larger aggregates with greater porosity and declined with increasing depth below the surface (Lemon and Erickson, 1952).

In reviewing this subject, Bartholomew (1965) found general agreement that reduced aeration such as that found in waterlogged soils, curbed or entirely suppressed nitrification whereas mineralisation was less affected.

McPherson (1966) conducted some field research into soil aeration in *Chionochloa* grasslands. He traced the progressive development of anaerobic conditions in a transition from *C. flavescens* grasslands to waterlogged soils supporting *C. rubra* grasslands on Mt Kaipororo, North Island. Likewise Williams (1975) demonstrated the local significance of waterlogging in the mosaic of *C. pallens* and *C. flavescens* grasslands on the Tararua mountains.

1.4.4. Carbon/nitrogen ratio

The carbon/nitrogen (C/N) ratios of organic residues added to the soil can strongly influence the mineralisation and immobilisation rates of soil N. The heterotrophic organisms involved in these processes require carbon-containing compounds as a source of energy and nitrogen for cell synthesis. Maximum immobilisation of soil N is likely to occur when large quantities of plant material with a wide C/N ratio are added to the soil.

Alexander (1961) reports that a C/N ratio below 30 is needed before net mineralisation can take place. Harmsen and Van Schreven (1955) consider this ratio should be below 20-25 before mineralisation can occur.

In tall tussock grasslands, C/N ratios were presented by Molloy and Blakemore (1974) for a range of Otago soils. These were generally below 20, particularly in the lower soil horizons.

1.4.5. Soil acidity

Soil acidity is known to affect nitrification more than it affects mineralisation of nitrogen. Harmsen and Kolenbrander (1965) consider that the optimum pH level for N mineralisation is slightly above 7.0, but mineralisation is still slightly active at pH levels around 4.0 (Harmsen and Van Schreven, 1955; Dommergues and Magenot, 1970). Waksman (1927) considered pH 3.9 to be the extreme lower limit of nitrification with a rapid decrease in the rate of nitrification as this point is approached.

The presence of acid-tolerant nitrifying bacteria was reported from a study of several U.S. soils by Weber and Gainey (1961). They found that nitrification (as measured by NO_3-N accumulation) occurred during incubation of the most highly acidic, naturally-occurring soils studied with a pH of 4.0 - 4.7.

Robinson (1962) suggested that acidophilic nitrifiers might be present in a N.Z. tussock grassland soil. Sarathchandra (1978) found a significant nitrification rate in a Horotui sandy loam at its natural pH of 5.5 and also found that nitrification occurred in this soil down to a pH of 4.3.

Studies of highly acid tea soils in Sri Lanka and Bangladesh have enabled suggestions to be advanced for the mechanisms of nitrification in acidic conditions. Isahaque and Cornfield (1972) incubated soils of pH 4.1 - 4.2 and noted significant NO_3-N accumulation. In one of these soils, nitrification decreased with increasing pH above 5.0. It was concluded that either this indicated the presence of acid-tolerant autotrophic nitrifiers, or that a heterotrophic process might be responsible for nitrification under acid conditions.

Culture studies of heterotrophic nitrification have implicated fungi in

the process (Doxtader and Alexander, 1966) and it is well known that fungi can function at relatively low pH (Alexander 1961). Isahaque and Cornfield (1976) consider that it is heterotrophic nitrifiers that cause NO_3-N production under acid conditions because under such conditions, dilution plate counts of autotrophic nitrifiers revealed only very low numbers of these bacteria (most probable numbers (mpns) of nitrifiers below 40 g^{-1} D.W. soil). However subsequent studies of acid tea soils by Walker and Wickramasinghe (1979) isolated autotrophic nitrifiers of the genera *Nitrosolobus, Nitrosospira* and *Nitrosovibrio* which were found actively to nitrify in the acidic (pH 4.0 - 4.5) conditions of these soils. Low plate counts of autotrophic nitrifiers do not necessarily reveal what the nitrifier population may have been at the time nitrate was produced, since as Belser (1979) points out, nitrate may persist in the soil well after nitrification has taken place. Williams and Mayfield (1971) advanced an alternative explanation for nitrification under acidic conditions. They suggested that occasional periods of activity by neutrophilic streptomycetes occurred at microsites where ammonia adsorption onto organic fragments takes place. Provided these microsites can be initially formed through the activities of acid-tolerant ammonifiers, nitrifiers could subsequently operate at these sites. The existence of such sites may also explain the presence of small numbers of nitrifying bacteria in forest soils with acidity as low as pH 3.7 - 3.9 which are capable of rapidly increasing in numbers with small increases in pH (Chase, Corke and Robinson, 1968).

Nitrification in acid soils would be of particular significance in acidic N.Z. tall tussock grassland soils. A mean pH of 4.5 was found in the A horizons of seven Otago tall tussock soils studied by Molloy and Blakemore (1974). Williams *et al.* (1978) in summarising the soil features of a much wider range of tall tussock grasslands found pH values ranged from pH 4 - pH 5.5.

1.4.6. Other factors

(a) Salt concentrations and trace elements:-

Salts not directly toxic to micro-organisms may reduce N mineralisation in soil due to an osmotic suction effect. Sindhu and Cornfield (1967) found that additions of chlorides and sulphates to soil at levels above 1-2 percent reduced mineral N production. Liang and Tabatabai (1977) found that the addition of a range of trace elements normally found in sludge samples

inhibited N mineralisation. Bhuiya and Cornfield (1972) considered that the inhibitory effects of certain elements arises from the ability of toxic elements to compete with essential elements (e.g. Mn, Fe, Mg) for the active sites of enzymes. No clear evidence of such effects is apparent from New Zealand tussock grassland studies which have generally not extended to include micronutrient issues.

(b) Phosphorus:-

Verstraete (1981) described the vunerability of nitrifying bacteria to phosphorus deficiency and considered that nitrite-oxiders were more sensitive to P deficiency than were ammonia-oxidising bacteria. Robinson (1963), with Craigieburn soils under fescue tussock grassland, and Purchase (1974b) stimulated mineralisation and nitrification by the addition of phosphate to soils deficient in this element.

(c) Priming effect:-

Fresh organic matter or inorganic N added to either fallow or cropped soils may stimulate or retard decomposition of organic matter already present in the soil. However, the effects may be short-lived and small in comparison to the amounts of native organic matter present. Jenkinson (1971) has reviewed this subject, while Paul and Juma (1981) have documented the concept of an active N phase and passive N phase.

(d) The effect of plants on substrate levels for N mineralisation:-

Plants contribute to the supply of organic matter in the soil through the deposition of stem, sheath and leaf and root material. They can also secrete small amounts of organic substances, the quantities of these exudates varying with the species and age of plants (Rovira, 1969). Rovira also described how the amounts of N immobilised through this deposition and the extent to which N mineralisation was stimulated by it also depend on factors such as plant species and the stage of growth of plants .

Marked stimulation of ammonifying and denitrifying bacteria has been demonstrated in the rhizosphere zone (Rouatt *et al.*, 1963). Root exudation into the rhizosphere zone varies with the health of the plant and is therefore responsive to variation in light intensity, soil moisture, temperature and plant nutrition status (Rovira 1969).

As well as rhizosphere exudates which stimulate N mineralisation, there has been some support for the hypothesis that root and plant exudates may inhibit nitrification. The possible presence of these inhibitors and the role of competition between plant roots, heterotrophic micro-organisms and nitrifying bacteria for soil mineral N are reviewed in the next section.

1.5 NITRIFICATION INHIBITION IN NATURAL GRASSLANDS.

The capacity of agricultural soils to nitrify readily is usually related to overall nutrient availability and soil fertility (Verstraete, 1981).

In natural ecosystems only limited nitrification appears to occur. Such a condition would ensure N conservation within the grassland soil because the NH_4-N ion is much less mobile than the readily leached NO_3-N ion (Vitousek *et al.*, 1979).

Two hypotheses have been advanced to explain the low levels of nitrification that characterize many natural grassland and forest ecosystems:

(a) The restriction of nitrification is caused by inhibitory plant exudates (Allelopathic inhibition).

(b) Nitrification is limited by a lack of NH_4-N substrate caused by plant and microbial uptake (Substrate competition).

1.5.1. Allelopathic inhibition.

The proposal that plants in climax vegetation exude toxic substances was first advanced by Theron (1951) to explain low rates of nitrification in South African grasslands. Secretions from grass roots were considered the most likely source of the inhibitor (Moore and Waid, 1971; Rice and Pancholy, 1972; 1973). A range of root washing and macerating techniques were used both in these studies and in those by Munroe (1966a; 1966b) to isolate the inhibitory root exudates which were considered to include tannins, phenolics and phenolic glycosides. Odu and Akerele (1973) found that macerated root extracts, prepared in the same way as the extracts of Munroe (1966a) which inhibited nitrifying bacteria, also inhibited heterotrophic micro-organisms. However, when these extracts were added to soil, nitrification activity was unaffected or possibly even increased.

The major problem with these studies is, however, that the extraction of toxic substances from plant tissues does not imply that they are exuded into soil under natural conditions. Purchase (1974a) has criticized the grassland inhibitor hypothesis. He showed that the depression of NO_3-N production, attributed to an inhibitor released by washing roots by Rice and Pancholy (1972), was reversed by the addition of lime to the soil. This suggested that nitrification inhibition resulted from increased acidity caused by water leaching. There have been several other reviews disputing the inhibitor hypothesis (e.g. Dommergues *et al.*, 1978, Verstraete, 1981).

In recent laboratory studies of N.Z. tussock grassland soils, the hypothesis of a nitrification inhibitor secreted by plants has re-surfaced. Ross and McNeilly (1975) suggested that exudates might be responsible for a lag in NO_3-N production in a Hari Hari gley-recent soil. Ross and Bridger (1978a) considered inhibitory compounds present in Cluden and Tima yellow-grey earths might account for the restricted N mineralisation found in these soils in laboratory incubation studies. To test this they looked at the influence of standing dead material, roots and aqueous extracts of three *Chionochloa* species (*C. macra, C. rigida, C. flavescens*) and two short tussock species (*Festuca novae-zelandiae, Poa colensoi*) on net soil N mineralisation (Ross and Cairns, 1980).

Mineralisation of soil organic N was markedly inhibited by the addition of either standing dead material or roots of the five tussock species. This was attributed to their high C/N ratios resulting in a high level of immobilisation of N. They found that net nitrification appeared to be little influenced by the added tussock material. Aqueous extracts of root material had little effect on net soil N mineralisation, while extracts from standing dead material had a slight stimulatory influence.

These studies, like those from overseas research, do not therefore provide conclusive evidence for the exudation of nitrification inhibitors by plants in natural grasslands.

1.5.2 Substrate competition - the nutrient sink hypothesis.

The alternative hypothesis to explain low nitrification activity in natural grassland soils centres around the ability of grass roots and heterotrophic micro-organisms to rapidly absorb most mineral N from the

soil, resulting in a deficiency of substrate for autotrophic nitrifying bacteria. This hypothesis was founded on the concept of centrality of the ammonium ion rather than the nitrate ion to microbial growth and decomposition reactions, as established by Jansson (1958). It was first advanced by Robinson (1963) and has subsequently gained widespread support (Huntjens, 1972); Purchase, 1974a). Cornish and Raison (1977) suggested that soil nitrogen mineralised near roots may be absorbed before competing microorganisms can re-immobilise it. They found that for ryegrass seedlings (*Lolium perenne*) grown in pots under controlled environmental conditions, the nitrogen mineralisation response was proportional to plant growth response to phosphorus. Huntjens (1972) has pointed out that grassland ecosystems produce large quantities of carbonaceous material (dead root hairs, root cells, root excretions) and that large quantities of N can often be immobilised within these components.

The ability of many slow-growing wild plants and shortgrass prairie species to absorb large quantities of NH_4-N from the soil has been demonstrated by Houston *et al.* (1973) and discussed by Chapin (1980).

Verstraete (1981) provides further support for the nutrient sink hypothesis in studies that have shown that the phenomena of soil bacteriostasis and fungistasis can be explained by the theory of nutrient deprivation. This is particularly significant because of the potential interaction between mycorrhizae and soil nitrifiers.

Mycorrhizae have a preference for N as NH_4-N and can scavenge phosphorus from the soil. They may, therefore, have an additional regulatory function in natural ecosystems in the biological control of nitrification as well as in assisting phosphorus uptake.

Crush (1973) showed endomycorrhizae to be widespread in tussock grassland soils. He also found that steaming a range of tussock grassland soils to destroy indigenous endophytes often enhanced the calcium, potassium and phosphorus status of the soils.

Unfortunately the mineral N status of steamed and unsteamed soils were not compared to determine if mycorrhizae were accumulating NH_4-N in the manner described above.

1.6 CULTURAL MODIFICATION OF N.Z. TALL TUSSOCK GRASSLANDS.

1.6.1 Tall tussock grassland grazing history.

Prior to human settlement of New Zealand, forests were more extensive than at present. Tall tussock grasslands were likely to have occurred only above bushline in the sub-alpine and alpine zones, at wet sites *(Chionochloa rubra)*, in forest clearings, along rivers and possibly on some sand dunes (Connor and Macrae, 1969).

Large grazing birds of the suborder *Ratites*, the moas, are believed to have evolved mainly in a forest environment although it may not have been exclusively forested (Simmons, 1968). These birds lacked teeth and their presumed lack of a prehensile tonue is likely to have made clamping, pulling and breaking actions important, while chewing in the manner of an ungulate would have been impossible (Greenwood and Atkinson, 1977).

No empirical evidence is available on the extent to which moa grazed *Chionochloa* grasslands. Burrows (1980) found tree and shrub particles were common in gizzard contents and grass or sedge particles (unidentified species) rare. This finding may apply, however, only to sites where gizzard contents were preserved and may not indicate the feeding habits of the birds over their full range. The grazing habits of moa may have been similar to those of the present day takahe. Takahe pull out *Chionochloa* tillers and generally eat only the basal meristematic portion (Mills, 1977). This contrasts with browsing of leaf blades by red deer at the same locality (Mills and Mark, 1977).

There is some experimental evidence from studies by W.R. Lee, of Botany Division. D.S.I.R. (pers. comm.) and from unpublished growth trials the author has conducted at Lincoln, that removal of whole tillers by plucking may stimulate tiller production in the remaining *Chionochloa* plant. Leaf defoliation caused little increase in tiller production and in some situations killed the tiller or the whole tussock. Extensive tiller plucking by browsing birds may well have invigorated *Chionochloa* grasslands rather than degrading them in the manner of much of the present day grazing by mammals.

Reconstruction of the browsing patterns of moas and the effects of this upon tall tussock grasslands can only be largely speculative. It is clear,

however, that when burning accompanied Polynesian settlement, the *Chionochloa* grasslands had sufficient vigour to expand their range enormously into former forest areas in the subalpine, montane and parts of the lowland zones. Periodic Polynesian burnings served to maintain the tall tussock cover against forest reinvasion.

O'Connor (1980) has detailed the development of European settlement and grazing of the tall tussock grasslands. With European settlement grazing mammals were introduced to these grasslands which were opened up through regular burning. In many areas, the first stocking of runs was with cattle but sheep were dominant on most runs by the early 1880s.

The growth in the sheep population which accompanied pastoral settlement is likely to have been explosive. Sheep numbers recorded in the earliest high country statistics of the 1880s were extremely high and soon declined as range condition deteriorated. Only in recent years, since high country pasture development programmes began, have sheep numbers increased to the levels of the 1880s (O'Connor, 1980; 1982).

The impact of these high sheep numbers, rabbit plagues and regular burning were disastrous for tall tussock grasslands. In much of Canterbury and Marlborough, at altitudes below about 1000 m, *Chionochloa* grasslands gave way to *Festuca* short tussock grassland and, in places, to bare ground. (Connor and Macrae, 1969). Much of the *Chionochloa* grassland in the dry valleys of Otago and Southland disappeared. Higher up in these regions, on the block mountains, *Chionochloa* grassland survived but it was severely depleted, particularly the more palatable high altitude *Chionochloa macra* (O'Connor, 1976).

Tall tussock grasslands are still grazed by stock and continue to suffer reduction in range condition. O'Connor, (1971) reviewed the value of tall tussock for grazing animals and identified different seasonal grazing importance. In winter, the tussocks serve primarily as an emergency food supply. Regular annual winter browsing will destroy the plants. Tussocks shelter a sward component and act as a grazing supplement themselves. In late winter, by forming melt tubes, tussocks break snow cover and provide much needed food supplies.

In summer, O'Connor viewed tall tussock grasslands as a convenient haystack

for summer periodic lax grazing rather than as being suitable for periodic hard grazing, especially with topdressing, a combination which is known to elmininate most tall tussocks. Summer tall tussock grazing is of particular importance when drought limits growth in improved grasslands at lower altitudes.

The introduction of increasing numbers of cattle into the high country over the last 10-20 years has had a marked effect on grazing of tall tussock grasslands. The reluctance of sheep to consume unmodified tall tussocks contrasts with the willing consumption of cattle of most species of *Chionochloa*, particularly *C. flavescens* and *C. macra*. (Connor *et al.*, 1970; Hughes *et al.*, 1971). In response to the introduction of cattle, reduction of tall tussocks has continued even at high altitude sites such as on the block mountain ranges of Otago and Southland.

Following tall tussock grazing at many lower altitude sites, oversowing and topdressing have allowed the introduced pastures of legumes and grasses to take the place of the depleted *Chionochloa* cover. At many higher altitude and dry sites, such grassland improvement has either not been attempted or has been unsuccessful and the elimination of tall tussock cover has led to range degradation.

1.6.2. Range degradation and soil nitrogen.

O'Connor (1966, 1974, 1981, 1982) has described how many of the present and former tall tussock grasslands have become N-losing, modified systems. Close defoliation, either with or without burning, has severely reduced above ground biomass and has led to rapid changes in species composition. This has resulted in permanently lowered total biomass and has been postulated to result in reduced N-uptake. O'Connor proposed that this situation has led to, at least, a temporarily increased seasonal soil ammonium pool and an increase in nitrification and nitrate loss in leachate. Eventually, he considered, the loss of nitrogen, or the disappearance of a relatively fast N cycle with grassland degradation, will lead to a new steady-state system. In such a new system, mineralisation and nitrification are likely to be of a small magnitude such as in the degraded grasslands discussed by Robinson (1963) and Ross and McNeilly (1975).

These N losing grazed systems are considered to occur not only in New Zealand, but also in the grasslands of southern Chile (O'Connor *et al.*, 1966), in south east Australia and in *Andropogon* prairie in Kansas (O'Connor, 1974) and in some prairie soils of western Canada subjected to different management techniques (O'Connor, 1983).

1.6.3. The 1975 range degradation study

A pilot study, prior to the major tall tussock soil mineral N study described in the following chapters, was undertaken in 1975 to test the validity of O'Connor's hypothesis that range degradation leads to an N losing modified system (McSweeney, 1975).

At a range of Otago sites, depletion sequences were identified from tall tussock grassland through to short tussock grassland and bare ground. Field sampling of soils for mineral N and nitrifying bacteria levels was completed on return to the Lincoln laboratory. Here, perfusion studies were conducted on each soil.

Unfortunately, a soil suspension technique was used for field mineral N sampling. Experiments in Chapter 2 will show that this significantly over-estimated NH_4-N levels and resulted in variation in NO_3-N levels, so any conclusions based on these values must be disregarded.

Nitrifier counts were not subject to any such misleading techniques. Four out of the five localities where depletion sequences were identified, showed a marked increase in nitrifying bacteria accompanying the progressive depletion of vegetation. The fifth locality showed high nitrifier numbers of both its intact and depleted sites. This was considered to reflect the intense grazing pressure on all vegetation types at this locality.

Such results, conform to those described earlier in Chile, Kansas and Canada and appear to support the O'Connor hypothesis.

The experiments described in the following chapters begin with the development of a satisfactory field technique to accurately measure mineral N levels and nitrifying bacteria populations in tall tussock grassland soils. These techniques are then used in a study of seasonal variation in soil mineral N

and nitrifying bacteria across a range of healthy tall tussock grasslands. Cultural modification of these grasslands, involving defoliation and urea addition (simulated grazing), burning and cultivation, is then described to test the effects of these treatments upon the transformation of mineral N within the soil.

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CHAPTER 2

FIELD SAMPLING, STORAGE AND ANALYTICAL TECHNIQUES FOR THE DETERMINATION OF SOIL MINERAL NITROGEN LEVELS

CHAPTER 2

2.1 INTRODUCTION

2.1.1 Mineral nitrogen and soil sampling

Levels of mineral nitrogen (N) in soil result from the interplay of many chemical and biological processes. The discussion in Chapter 1 highlights mechanisms by which mineral N is gained and lost by the soil. Inputs include N in rain and snowfall, underground flow, wind-blown and eroding material, litter, animal faeces and urine and through the mineralisation of soil organic matter. Levels are reduced by plant microbial and animal uptake, leaching, volatilization and denitrification.

Soil sampling interrupts some of these processes (e.g. plant uptake), while others (e.g. mineralisation of organic matter, nitrification) may continue at the same or an even greater rate in a soil after sampling. Sampling may also destroy the structural characteristics of a soil, particularly if sampled cores are subsequently crumbled or sieved. Spatial relationships within the soil are altered. Soil particles from surface layers are thown alongside particles from deeper down the soil profile. Particles adjacent to plant roots, perhaps depleted in mineral N but with high microbial activities, collide with particles distant from this zone, which may have quite different properties. Conditions of aeration, temperature and moisture regimes may be altered. Coupled with these are new influences such as vehicle vibration and sunlight. These all combine to influence the rates of transformation of mineral N in soil samples.

Soil mineral N analysis should therefore be carried out as soon as possible after sampling if an accurate record of soil mineral N levels at the time of sampling is required. When samples are collected at long distances from analytical facilities this is often not possible and reliable storage techniques are needed to fix the levels of mineral N at the time of sampling.

2.1.2 Characteristics of the proposed study.

In a study of seasonal mineral N levels in South Island tall tussock grasslands, development of reliable analytical techniques were of paramount importance for three reasons:-

(a) A range of sites:
To gain a broad picture of seasonal variation in mineral N levels in tall tussock grasslands in Canterbury and Otago, a wide range of sites had to be visited. Development of a "field laboratory" at any one site would have prevented the study looking at other sites where conditions might have been markedly different.

(b) Distance from analytical procedures:
Although all sites could be reached individually within a long day from Lincoln, economic and physical constraints meant it was often easier to visit several sites during each journey. Soil storage periods of up to one week were therefore likely between sampling and analysis.

(c) Simple field techniques:
Severe field conditions, especially at high altitude sites, and primitive field facilities meant any field extraction procedures needed to be simple and that the provision of cold storage facilities would be difficult.

Working within these constraints, a review of suitable mineral N sampling and storage techniques was undertaken and these techniques were experimentally tested.

2.1.3 Soil storage investigations.

It has long been recognised that changes can occur in soil mineral N after soil sampling. As early as 1938 Richardson, in his Rothamsted Park experiment, warned that if soils were allowed to air dry before the ammonium nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) contents were determined, then marked changes could take place, especially an increase in NH_4-N levels. He took care to store his samples in a cool place and to complete extraction procedure on the same day as sampling. Bremner (1965) asserted that little heed had been taken of Richardson's warning. Bremner considered that results from many mineral N analyses might be invalid because of microbial activity during the preparation and storage of soil extracts.

However, even in 1965, the labile characteristics of mineral N in soil were widely recognised and a range of storage and pre-treatment methods had been adopted. These have been reviewed by Storrier (1966).

In most of the 70 experiments reviewed by Storrier, some of the following methods had been used either separately or in combination:-

1. Pretreatment
   (a) Drying < Air / Heat assisted
   (b) Sieving
   (c) Grinding

2. Use of biological inhibitors or retardants, e.g. toluene, chloroform, mercuric chloride.

3. Storage
   (a) Permeable or impermeable container.
   (b) Varying lengths of time.
   (c) Temperature variation.

Air drying was considered to cause substantial increases in soil mineral N levels, particularly NH_4-N. These increases were even greater where additional heat was used to speed up drying. Sieving and grinding of soil samples also influenced mineral N levels. However, evidence of their effect on subsequent biological activity was conflicting.

Biological inhibitors had proved effective in short term control of nitrification but in small quantities were unable to prevent mineralisation. Because of this, inhibitors were regarded as generally unsuccessful. Storage of soil in plastic bags was found to be preferable to storage in paper bags which permitted both the absorption of ammonia from the atmosphere and allowed soil samples to dry out.

Because storage of soils, even for short periods, was acknowledged to result in substantial changes in mineral N levels, cool temperatures were often used to slow down biological activity. However, even at $+2^{o}C$, Storrier reports Gasser (1958) finding an increase of 100 percent in soil mineral N over a 30 day period. On the basis of favourable findings from three studies, Storrier considered the technique that showed most promise was storage of moist soil samples at sub-zero temperatures. He made his conclusion despite results from three other studies that had found changes in either mineral N levels or biological activity after freezing. In subsequent studies, the effectiveness of soil freezing in preventing mineral N changes has been

investigated and challenged (Robinson, 1967; Selmer-Olsen *et al.*, 1971).

An important approach not considered by Storrier was investigated by Robinson (1967). If interaction between mineral N and the soil still took place after sampling, the logical approach was to separate the two. This could be achieved by a field extraction procedure followed by filtration and storage of the extract in controlled conditions until analysis. After an intensive investigation of storage techniques using East African soils and soil extracts, Robinson concluded that sub-zero storage of neutral Potassium chloride (KCl) soil extracts was the most reliable method for the preservation of mineral N in tropical soils. This conclusion had also been reached by Bremner (1965), although Bremner gave no experimental details to support his conclusion.

More recently, studies in Norway (Selmer-Olsen *et al.*, 1971) and in Iowa (Nelson and Bremner, 1972) indicated that storage of 2M KCl extracts at sub-zero temperatures was unnecessary since equally reliable results were shown to be obtained with refrigerated ($4^{o}C$) storage of soil extracts. Such a technique might easily be applicable to a study of tall tussock grassland soils. There were, however, some features of all the investigations to suggest that a further study of soil and soil extract storage techniques was warranted.

Many of the reported studies had found that changes in mineral N with each treatment were not uniform for all soil types. Robinson (1967) found that soils with high initial microbial activity and high organic matter contents showed the greatest change in mineral N during storage. Harding and Ross (1964) considered variation between soils, in mineral N increases with soil freezing, might be related to the variety of moisture and carbon contents of the different soils studied.

It seemed important to find out, before launching into a major field survey, whether soil storage techniques developed for mineral N analysis in African, Iowan and Norwegian soils were applicable to New Zealand tussock grassland soils. These experiments could also determine whether refrigeration of soil extracts recommended in the overseas studies could be dispensed with, thereby simplifying field procedures.

2.2 EXPERIMENTAL WORK.

There were two major stages in the investigation of soil storage techniques for mineral N analysis.

In the first stage, results are compared from a survey of 19 Otago grassland soils in which three different soil storage techniques were used. One of these techniques was not used by the author, but by personnel from Soil Bureau, Department of Scientific and Industrial Research (DSIR) in a study of the same soils simultaneous with this study. The findings of this study have been made available for comparison (D.J. Ross, pers. comm.).

The second stage was in investigation of a high country soil where seven different storage treatments were used. These included variations of the 2M KCl extract storage technique (Selmer-Olsen *et al.*, 1971; Nelson and Bremner, 1972).

A comparison was also made between two mineral N analytical procedures: steam distillation with magnesium oxide and Devarda's alloy (Bremner, 1965) and automated analysis (Grasshoff, 1969). This comparison aimed to determine whether automated analysis, which was well suited to handling large numbers of samples rapidly, yielded consistently reliable results.

2.2.1 Otago grassland survey.

(a) Methods:-

In March 1975, 19 natural and modified grassland soils across Otago were sampled for mineral N. Physical and chemical properties of the soils at each site have been described by Molloy and Blakemore (1974) and McSweeney (1975).

Twenty 25mm diameter soil cores were sampled from the top 100mm of the soil profile at each site. Cores were bulked into double plastic bags and mixed to form a composite sample. For each soil, duplicate samples of 4g were taken from the composite sample. These were added to screw-top jars containing 40ml of 2m KCl in the manner described by Noonan (1969). These samples were cooled to $4^{o}C$ and held at this temperature for up to five days before analysis for NH_4-N and NO_3N by steam distillation. These samples are referred to as SOIL SUSPENSION.

The remainder of the composite sample from each soil was stored at 7°C in insulated containers containing ice packs. These samples were analysed for NH_4-N and NO_3-N by steam distillation up to five days later on return to the laboratory. This treatment is referred to as LAB EXTRACT 1.

Soil Bureau staff collected the third set of samples, LAB EXTRACT 2. They used identical equipment and took soil samples from the same sites at identical times to those described above. Their procedure also involved bulking of large numbers of soil cores to form a composite sample from each site. Composite samples were stored in plastic bags and stored at ambient temperature (mainly 15° - 22°C) during transport to the laboratory. Analysis for NH_4-H and NO_3-N by steam distillation was carried out up to thirteen days after soil sampling.

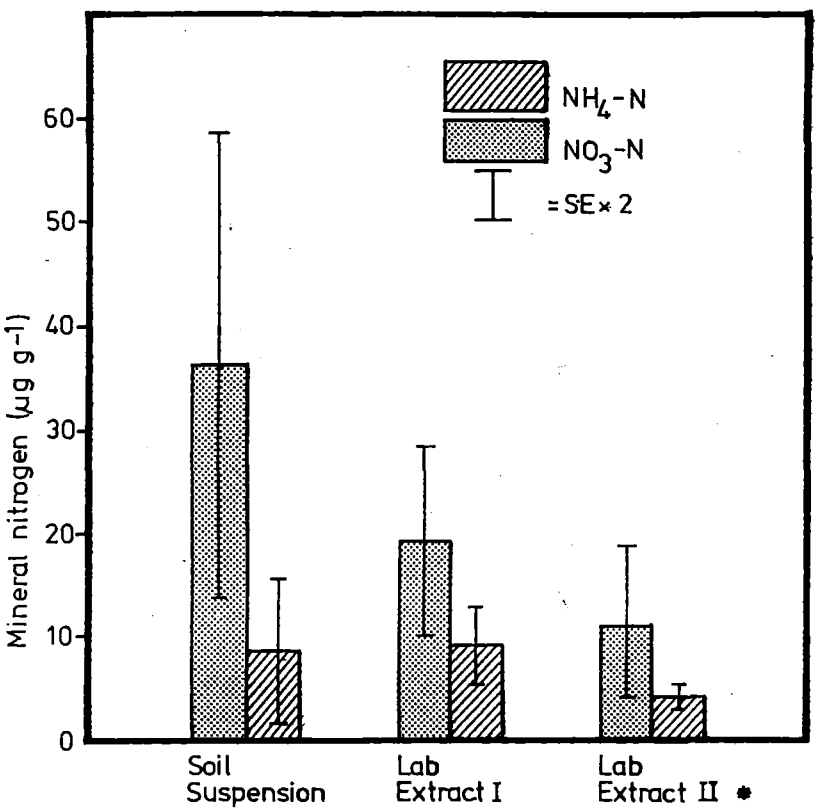
All results are reported on an oven dry (105°C) soil weight basis.

(b) Results and discussion:-

NH_4-N and NO_3-N levels for the three treatments are graphed in Figure 2.1. Detailed mineral N values are presented in Appendix 2.1. There is wide variation in mineral N levels between soils. Marked differences are also apparent between the three treatments. Many NH_4-N and some NO_3-N levels in the soil suspension samples are particularly high compared with levels reported from other New Zealand tussock grassland soils (Robinson, 1962; Tan, 1967). In contrast, levels in the stored soil of LAB EXTRACT 2 were generally low and those of LAB EXTRACT 1 intermediate between the other two. Correlation coefficients calculated for mineral N levels in soils subjected to the three treatments in Table 2.1. below, show no significant correlation between these treatments. Variation due to analytical techniques is therefore greater than variation between mineral N levels in the different soils.

TABLE 2.1: Correlation coefficients (r) for mineral nitrogen levels recorded in the three sampling procedures used in the Otago survey.

	Form of Mineral Nitrogen		
Treatment	NH_4-N	NO_3-N	Degrees of Freedom
Soil suspension x Lab Extract 1	.05ns	-.06ns	18
Soil suspension x Lab Extract 11	.12ns	.18ns	8
Lab Extract 1 x Lab Extract 11	.29ns	.09ns	8



* Information on Lab Extract II supplied by Dr. D.J.Ross Soil Bureau, D.S.I.R.

Figure 2.1 Mineral nitrogen levels from a range of Otago soils subjected to different extraction techniques

Nitrification might have been responsible for the observed decrease in NH_4-N during storage. If this was the case, NO_3-N levels might have been expected to increase in those soils which showed a decrease in NH_4-H. However in only eight out of the 14 soils which showed a decrease in NH_4-N during storage was an increase in NO_3-N also recorded. Furthermore, there was little correlation between the magnitude of the NH_4-N decrease and the magnitude of the corresponding increase in NO_3-N.

Mineralisation of organic matter to NH_4-N might have accounted for the increase in NH_4-N between the SOIL SUSPENSION and LAB EXTRACT 1 treatments observed in five of the soils (McKerrow intact, two Carrick soils, Obelisk semi-depleted and Tima pasture). Robinson (1967) found that soils with a high organic matter content showed the greatest increases in NH_4-N during storage. However, organic matter content of these five Otago soils was no higher than that of comparable soils from the group that showed a decrease in NH_4-N with storage.

Similar sampling and analytical procedures were used to determine mineral N levels in both LAB EXTRACTS 1 and 2. Despite this, there were major differences in the results obtained by the two treatments. This difference might reflect the changes that took place during the longer storage time of the soil used for LAB EXTRACT 2.

(c) Conclusions:-

There seemed little advantage in investigating more fully the widely different results obtained for each soil by the three storage techniques. These storage techniques have been widely used in studies of mineral N where a time lapse between sampling has occurred, both in natural grasslands (Ross and McNeilly, 1975) and exotic forests (Noonan, 1969). The large variability in mineral N levels found in this experiment suggests chemical and biological changes in forms and levels of mineral N do occur with these storage procedures. Clearly there was a need to develop a more reliable field technique and therefore further investigations were undertaken. These culminated in the work outlined below and in independent research findings published recently (Ross *et al.*, 1979).

2.2.2 Craigieburn soil mineral nitrogen study.

This was an intensive investigation of the effect of storage techniques on

mineral N levels in a New Zealand high country soil. Mineral N levels from soil and soil extracts stored at a range of temperatures for a week are compared with those from fresh samples.

(a) Methods:-

Soils and Sites:

Craigieburn soil, a high country yellow brown earth (Soil Bureau, 1968) supporting a low cover of slim snow tussock (*Chionochloa macra*) was chosen for the study. This soil was readily accessible by vehicle from Lincoln and could be sampled and transported to Lincoln within an hour for laboratory study.

On November 10 1976, a large sod, complete with vegetation, measuring 1m x 1m x .5m depth, was lifted from a terrace above the Porter River (NZMS 1.S74:148 881) and transported rapidly to Lincoln on an open trailer.

Sampling and Analysis:

Cores of 25mm diameter (0 - 100mm deep) were sampled randomly from the upper surface of the sod. Each core was used as one of six replicates for each of the treatments listed in Table 2.2. below.

TABLE 2.2 Craigieburn soil mineral nitrogen study.
Summary of experiments carried out on soils and soil extracts.

Sample Number	Sample Handling	Treatment Conditions	No. of Replicates
1	"Field" Extract	Standard extraction and filtration. and addition of toluene preservative	6 (4 drops)
	Soil Extract	Extraction and treatment as for (1) above.	
2	" "	Extract storage 1 week 7°C	6
3	" "	Extract storage 1 week 25°C	6
	Soil Suspension	Soil cores suspended in 2M KCl without filtration then extracted as in (1) above.	
4	" "	Storage for 1 week 7°C	6
	Soil Storage	Moist soil cores stored in sealed polythene bags then extracted as in (1) above.	
5	" "	Storage for 1 week 20°C deep freeze	6
6	" "	Storage for 1 week 7° C refrigerator	6
7	" "	Storage for 1 week 25°C incubating room	6

Standard extraction procedure involved the crumbling and mixing of each core. 20g of this soil was added to 200ml of neutral 2M KCl analytical reagent. The equilibrium extraction technique described by Bremner (1965) was used. The solution was shaken for one hour, filtered, and the extract analysed for NO_3-N and NH_4-N. Duplicate analyses were carried out on this filtered sample to determine experimental error.

All results are reported on an oven dry (105°C) soil weight basis.

Soil sieving was not attempted in this experiment. Sieving is impractical with wet, greasy high country soils. It has been shown by Ross *et al.* (1979) to cause a slight but significant increase in mineral N levels.

(b) Results and Discussion:-

Mineral N levels for the soil storage, suspension and field extract and stored extract samples are presented in Figure 2.2 and in Appendix 2.2.

"Field" Extract: Moderate NH_4-N levels were recorded with this treatment. Variability between replicate cores was relatively low (S.E. = 6%). NO_3-N levels were low with higher variability between cores (S.E. = 15%) than in NH_4-N extracts. Levels of mineral N recorded for this soil were similar to mineral N levels reported in the same soil type from another location (Robinson, 1962; O'Connor *et al.*, 1972).

Soil Extract: Mineral N levels from the 7°C and 25°C storage treatments were not significantly different to those found for the field extract. However, the mean NH_4-N level in samples stored at 25°C was 24 percent higher than that of either the 7°C extract or the field extract. This 25°C sample also showed high variability in NH_4-N levels between replicates.

Soil Suspension: Mineral N levels are particularly high in soils subjected to this treatment. NH_4-N levels showed nearly a seven-fold increase during storage, while NO_3-N levels showed almost a two-fold increase. There was enormous variability between replicates in both NH_4-N (S.E. = 43%) and NO_3-N (S.E. = 50%). A range of possible reasons can be offered to explain the increases. Mineralisation and nitrification may occur within the soil suspension despite the high concentration of KCl. Fixed ammonium ions adsorped by soil and clay minerals may be released by prolonged storage in KCl.

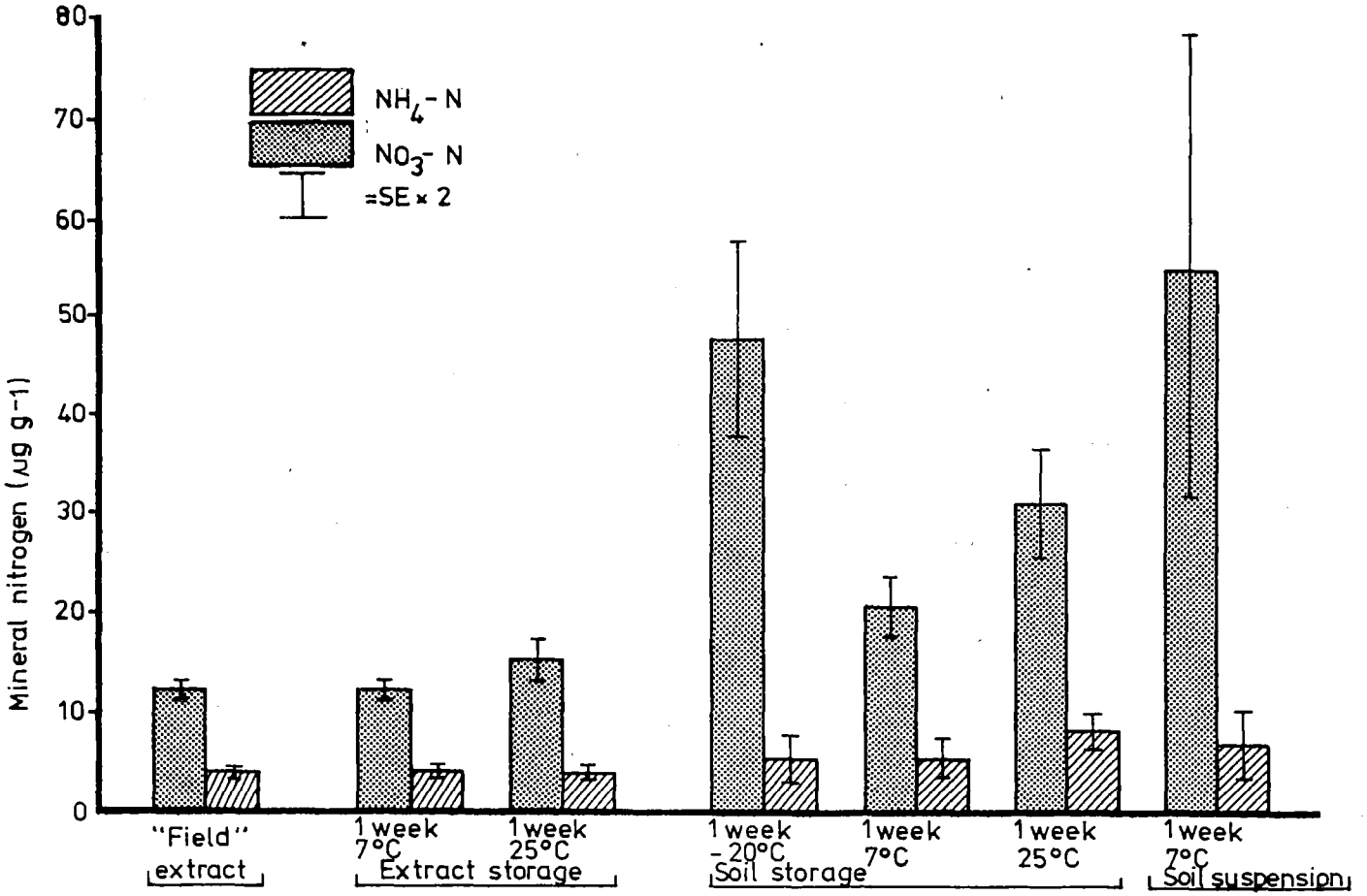


Figure 2.2 Mineral nitrogen levels in Craigieburn soil subjected to a range of extraction and soil storage conditions.

Scott *et al.* (1960) showed that the amount of fixed ammonium released by the addition of potassium (K^+) ions to soils depends on the conditions of treatment including the temperature, concentration of added K^+ and the length of time the K^+ was shaken with the soil.

Results from the soil suspension treatment suggest that the high mineral N levels recorded in Section 2.2.1 using this treatment were an experimental artifact.

Soil Storage: There are marked differences in NH_4-N levels between the soil storage treatments. All three show higher levels of NH_4-N and NO_3-N than the field extract.

Freezing of soils clearly caused a dramatic increase in NH_4-N and a small increase in NO_3-N. Allen and Grimshaw (1962), Harding and Ross (1964) and Hinman (1970) also found this. Hinman attributed increases in NH_4-N with freezing to the release of previously non-exchangeable NH_4-N from organic or inorganic soil colloids through disruption of these by freezing and thawing. Ivarson and Sowden (1970) showed that freezing markedly increased the total amount of free amino acids in the soil.

Increases in NH_4-N with freezing and subsequent thawing may therefore result from both a direct increase in extractable NH_4-N and from an increase in substrate availability for ammonifying bacteria resulting in rapid mineralisation once the soil thaws.

Although Nelson and Bremner (1972) concluded that soil storage at minus 50°C was a satisfactory method of preserving moist soil samples for mineral nitrogen determinations, the results presented here suggest that freezing is an unsatisfactory way of preserving soil samples for mineral N analysis. Ross *et al.* (1979) reached a similar conclusion in their studies.

Soil storage at 7°C and 25°C caused similar though smaller increases in NH_4-N to those experienced with freezing. Mineralisation appears to have continued during storage. The absence of plant uptake of NH_4-N may have resulted in the observed increase in NH_4-N levels which thereby increase substrate levels for nitrification, a process which was shown to be of minor significance in unamended Craigieburn soils (Robinson, 1963). Although no counts of nitrifiers were made, the higher soil storage temperature (25°C)

would favour more rapid nitrification (Alexander, 1961). NO_3-N levels would be expected to be higher in the 25°C samples if this were the case. In the experiment, the mean NO_3-N level in soil stored at 25°C (8.1 $\mu g\ g^{-1}$) was 50 percent higher than mean NO_3-N levels in soil stored at 7°C.

These results suggest that soil storage is unreliable and inaccurate for the determination of mineral N. Not only were NH_4-N and NO_3-N levels much higher in stored soils than in the field or stored extracts, but variability between replicates was also very high for each soil storage treatment.

The most reliable ways of determing mineral N in soils appear to be by obtaining field extracts or by the storage of soil extracts at 7°C.

2.2.3 Ammonium (NH_4-N) and nitrate (NO_3 - N) ion analytical methods.

This experiment compared steam distillation with automated colorimetric techniques for NH_4-N and NO_3-N analysis. The studies described earlier in this chapter used the steam distillation technique. This has been used in many other studies of soil mineral nitrogen (Robinson, 1967; Ross and McNeilly, 1975; Hart, 1978). However, many recent studies of soil mineral N have adopted automated procedures which can cope with large numbers of samples (Selmer-Olsen *et al.*, 1971; Sarathchandra, 1978; Ross *et al.*, 1979). Critics of auto-analytical techniques for mineral N studies (A.H. Nordmeyer, Forest Research Institute, pers. comm.) suggest the technique is unreliable, yielding "apparently precise" results markedly different from those obtained through steam distillation. However, no studies to support these assertions have been published.

(a) Methods:

Two soils were used in the study - the Craigieburn soil described in Section 2.2.2 and a Snowgrass silt loam (Harvey, 1974) from Paddle Creek, South Canterbury, where subsequent studies of soil mineral N were planned.

Six cores were taken from the surface 100mm of each soil. Soil extracts were prepared for immediate analysis as described in Section 2.2.2.

Steam distillation apparatus used the MgO/Devarda's alloy technique (Bremner, 1965). A Technicon auto-analyser used the cadmium reduction technique (Grasshoff, 1969) for NO_3-N analysis and the phenol-hypochlorite

reaction (Weatherburn, 1967) adapted to the auto-analyser (A.H. Horn, Soil Science Department, Lincoln College, pers. comm.) for NH_4-N analysis.

Duplicate analyses were carried out on each extract with both steam distillation and auto-analysis. Results are expressed on an oven dry soil weight basis and differences between the two analytical treatments were determined by the Students t test.

(b) Results and Discussion:

NH_4-N and NO_3-N levels for each extract, presented in Table 2.3, show few differences between the two techniques with both soil types. With auto-analysis variability between duplicates (2 percent maximum) was lower than with steam distillation (9 percent maximum). One possible cause of this is experimental error in the titration step of steam distillation. Repeated titrations with a standard sample gave an experimental error of up to 10 percent. The end point in the titration is difficult to define with precision.

In contrast, the Technicon auto-analyser gave consistent results. It has therefore been chosen for all subsequent analyses of mineral N described in this thesis.

2.3 GENERAL DISCUSSION

Evidence presented in this chapter highlights the major changes in soil mineral N that can occur with prolonged storage of soils or soil suspensions. Widely varying NH_4-N and NO_3-N levels from a survey of Otago grassland soils (Section 2.2.1) gave the first insight that traditional techniques used to prevent changes in soil mineral N with storage (suspension, soil cooling) were unsatisfactory. These results inspired both the experiments described in Section 2.2.2 and independent studies undertaken by Ross *et al.* (1979) of DSIR.

Ross *et al.* (1979) examined mineral N levels in nine soils over three seasons with different storage procedures. Soil storage at 4^oC and -20^oC caused marked changes in NH_4-N and NO_3-N levels within 24 hours of sampling. Soil suspensions stored for 14 - 18 days at ambient temperatures (15 - 22^oC) showed highly significant increases in mineral N. Results from these experiments which used soils from Otago grasslands closely parallel the results obtained with the Craigieburn soil described in Section 2.2.2.

It was concluded in both the DSIR studies and the studies described here that field extraction, filtration and extract storage is the only reliable way to sample soil mineral N long distances from analytical facilities. Whereas Ross *et al.* (1979) consider extract storage at ambient temperature satisfactory for preserving mineral N, the experiments with the Craigieburn soil showed a slight increase in NH_4-N in extracts at 25°C (Figure 2.2). It is therefore considered that extract storage at 4° - 7°C is preferable to storage at 25°C. Nelson and Bremner (1972) also recommended this procedure. The use of toluene (1 percent) in extracts is optional (Davies *et al.*, 1940; Jackson, 1960), but may prevent any microbial activity during extract storage. Ross *et al.* (1979) used phenyl mercury acetate.

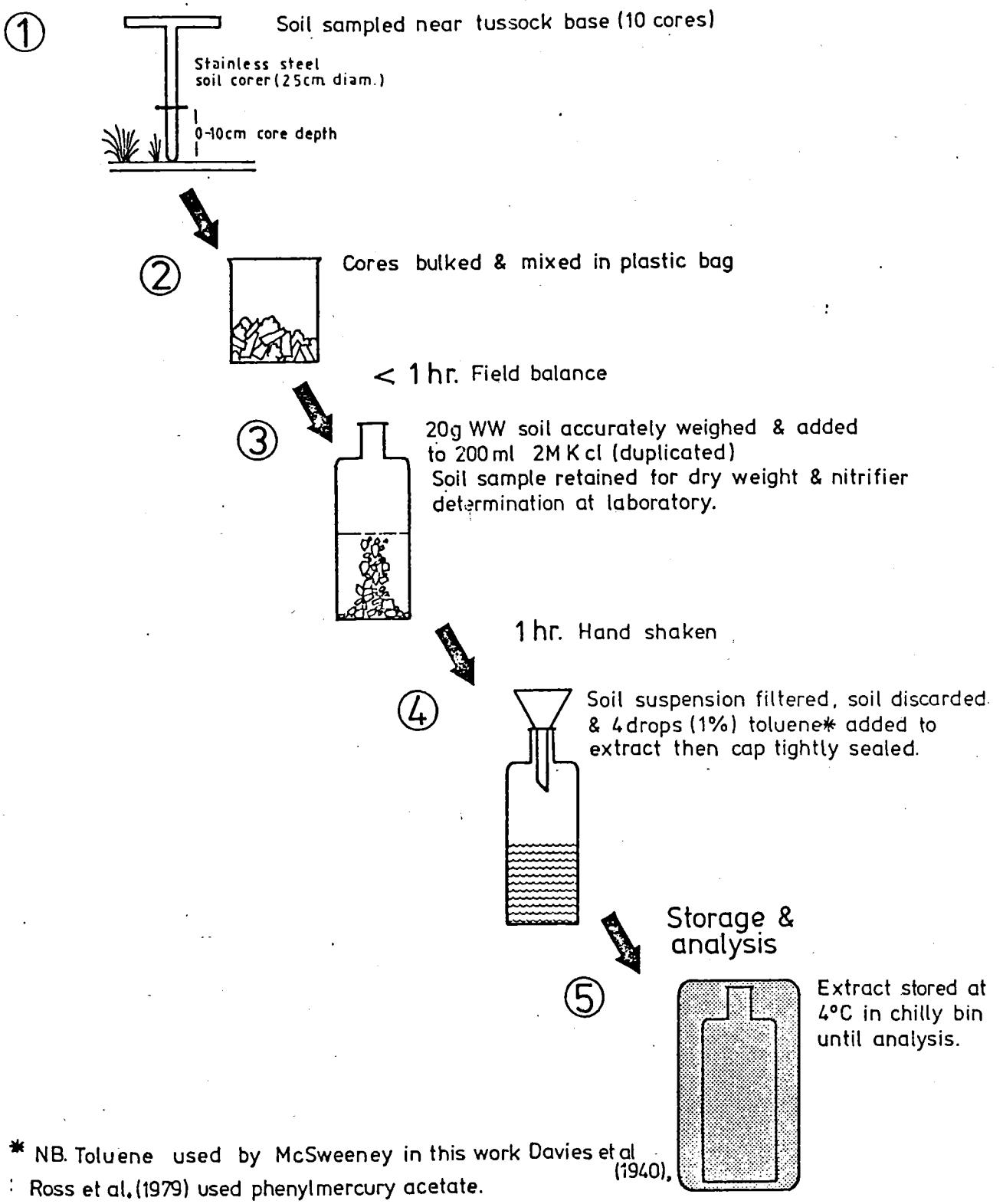
Standard extraction procedure to be followed in studies of grasslands described in the following chapters is described diagrammatically in Figure 2.3.

2.4 CONCLUSIONS

Results from experiments described in this chapter and the review of other investigations of storage procedures cast serious doubts on the validity of results from many studies of soil mineral N levels where considerable time elapsed between soil sampling and N analysis.

Many techniques have been used in such studies. Sieving of moist soils followed by immediate analysis was used in studies of South African grasslands (Theron, 1963), New South Wales pasture (Simpson, 1962), British grassland soils (Williams, 1969) and in numerous other studies. Yet Ross *et al.* (1979) showed immediate increases in soil NH_4-N following sieving and found that these increases became even greater with soil storage.

Storage of moist soil has been a procedure followed in many investigations of grassland soils. Skyring (1962) stored moist soil at ambient temperatures (22°C - 25°C) for up to 10 days before analysis. O'Connor *et al.* (1966) stored sealed soil samples for 11 days at 2°C during their transport from the grasslands of Southern Chile to Canada for mineral N analysis. Ross and McNeilly (1975) stored sieved moist soils, from Otago tussock grasslands, at both 4°C and -20°C for up to 14 days while the soils were transported to Wellington for analysis.



* NB. Toluene used by McSweeney in this work Davies et al (1940), Ross et al. (1979) used phenylmercury acetate.

Figure 2.3 Recommended extraction procedure for mineral nitrogen in soils distant from analytical facilities.

The most serious changes in soil mineral N levels are likely to be those where soil is both air dried and stored before analysis. Charley and West (1977) studied mineral N levels in soils from semi-desert shrublands of Utah, USA. They air dried, sieved and stored these soils for an unspecified time period before mineral N analysis. The longest storage period encountered by the author was in the study of mineral N in soils of Otago by Tan (1967). He stored air dried, sieved soil for 47 weeks before using it for studies of mineralisation and nitrification.

The research in this chapter and the examples of the diversity of storage techniques in common usage show how important is the need for adoption of a standard extraction and storage procedure for studies of soil mineral N. This is particularly important for studies of natural ecosystems which are often located at considerable distances from analytical facilities.

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TABLE 2.3 Mineral nitrogen levels (Ug g^{-1} soil) in six replicate samples of two soil types determined by steam distillation and auto-analysis

Soil Type	Mineral N Form	Analytical Procedure (1)	Duplicate Analysis No.	Replicate No. 1	2	3	4	5	6	$\bar{x}$	SE(mean)
Craigieburn											
	NH_4-N	AA	1	11.6	13.1	12.7	13.5	11.4	11.2	12.3±	1.0
			2	11.6	13.1	12.7	13.6	11.4	1112		
		SD	1	11.8	13.2	12.6	13.5	11.6	11.3	12.3±	.9
			2	11.7	13.0	12.7	13.5	11.4	11.4		
	NO_3-N	AA	1	3.1	3.6	3.1	4.3	4.3	3.6	3.7±	.5
			2	3.1	3.6	3.1	4.3	4.3	3.7		
		SD	1	3.0	3.8	3.1	4.5	4.7	3.6	3.7±	.6
			2	3.2	3.6	3.1	4.2	3.6			
Snowgrass											
	NH_4-N	AA	1	18.1	17.7	18.3	16.9	17.8	19.1	18.0±	.7
			2	18.1	17.7	18.2	16.9	17.7	19.1		
		SD	1	18.0	17.5	18.5	16.9	17.9	19.2	17.9±	.8
			2	18.3	17.4	17.9	16.8	17.5	19.0		
	NO_3-N	AA	1	6.6	6.2	6.7	6.3	6.4	7.1	6.6±	.3
			2	6.6	6.2	6.7	6.3	6.3	7.1		
		SD	1	6.4	6.3	6.8	6.3	6.5	7.0	6.6±	.3
			2	6.4	6.5	6.7	6.3	6.2	7.2		

N.B. (1) AA = Auto-analyser
SD = Steam distillation

(2) Differences between analytical procedures not significant

(3) Maximum difference between duplicate analyses (This is the laboratory error).
AA = 2%
SD = 8.9%

APPENDIX 2.1 Effects of three storage methods on the mineral N contents (μg g^{-1} soil) of soil and soil suspensions from a range of Otago tall tussock and modified grassland soils

SITE (iii)	Soil Suspension		Lab Extract 1		Lab Extract 11(i)	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Maungatua intact	42.0	4.0	10.2	13.7	-	-
Maungatua depleted	87.2	6.0	27.7	15.4	-	-
Tawhiti intact	53.4	28.0	16.5	4.1	6.9	4.3
Tawhiti semi-depleted	41.4	15.9	14.7	11.6	-	-
Tawhiti depleted	42.3	8.5	12.7	4.5	-	-
Tima intact	58.4	19.8	8.1	11.1	16.8	3.9
Tima pasture	15.9	14.1	18.5	9.3	12.5	5.0
Obelisk intact	83.5	5.8	13.7	4.6	8.0	5.8
Obelisk semi-depleted	23.9	10.1	27.3	5.0	-	-
Obelisk depleted	7.6	2.2	3.3	5.6	-	-
Carrick intact	44.4	2.1	35.0	15.0	17.9	4.0
Carrick semi-depleted	20.2	3.2	30.3	7.0	-	-
Carrick depleted	8.9	4.3	14.1	8.1	-	-
Conroy depleted	22.2	5.9	14.7	8.8	1.8	5.8
Cluden semi-depleted	24.8	1.8	18.2	7.9	3.5	2.0
Cluden pasture	20.8	1.3	12.4	6.2	6.4	3.6
Hari Hari intact	31.1	7.1	17.6	5.9	24.0	3.4
McKerrow intact	17.7	13.5	32.9	13.2	-	-
McKerrow depleted	38.5	7.1	33.9	9.2	-	-
$\bar{x}$	36.0	8.5	19.0	8.8	10.9	4.2
SE	±22.5	±7.0	±9.3	±3.7	±7.4	±1.2
F (ii)	-	-	10.82**	.8ns	15.3**	1.5ns.

(i) Results from Soil Bureau, DSIR (D.J. Ross pers. comm.)

(ii) ** = P < 0.01 Lab Extracts 1 and 2 compared with Soil Suspension

(iii) For site details see McSweeney (1975).

APPENDIX 2.2 NH_4-N and NO_3-N levels in Craigieburn soil with different 2M KCl extract and soil storage conditions.

Treatment		Mineral N form	Replicate No.						$\bar{x}$ S.E.	F(1)
Preparation	Storage Temp.		1	2	3	4	5	6		
Field Extract		NH_4-N	12.6	13.2	12.2	11.3	11.6	12.2	12.2 ± .7	
		NO_3-N	3.2	3.7	4.6	3.3	3.8	4.1	3.8 ± .5	
Soil Storage 1 week	(a)-20°C	NH_4-N	50.1	40.9	32.6	62.5	55.4	43.2	47.5 ±10.8	**
		NO_3-N	5.3	6.2	6.5	8.6	2.1	2.6	5.2 ± 2.5	ns
	(b) 7°C	NH_4-N	18.9	26.0	19.2	21.4	17.4	20.7	20.6 ± 3.0	**
		NO_3-N	3.9	5.5	6.2	6.7	2.3	7.7	5.4 ± 2.0	ns
	(c) 25°C	NH_4-N	22.9	29.3	29.2	35.2	38.5	29.9	30.8 ± 5.4	**
		NO_3-N	6.8	8.4	9.3	10.7	5.3	8.2	8.1 ± 1.9	**
Soil Suspension 1 week	7°C	NH_4-N	86.5	54.7	50.8	40.8	19.9	73.3	54.3 ±23.6	**
		NO_3-N	12.3	6.5	8.2	5.1	2.1	6.5	6.8 ± .4	**
Soil Extract 1 week	(a) 7°C	NH_4-N	11.8	13.2	12.7	13.1	11.4	11.2	12.2 ± .9	ns
		NO_3-N	3.0	3.8	3.1	4.6	4.4	3.8	3.9 ± .6	ns
	(b) 25°C	NH_4-N	16.1	18.3	13.0	16.1	14.2	12.9	15.1 ± 2.1	ns
		NO_3-N	3.7	3.6	4.2	4.1	3.2	4.4	3.8 ± .5	ns

(1) *, ** = $P < 0.05, 0.01$ for treatment means compared with field extract.

CHAPTER 3

SEASONAL VARIATION IN SOIL MINERAL NITROGEN IN TALL TUSSOCK GRASSLANDS - CHARACTERISTICS OF THE STUDY AREAS.

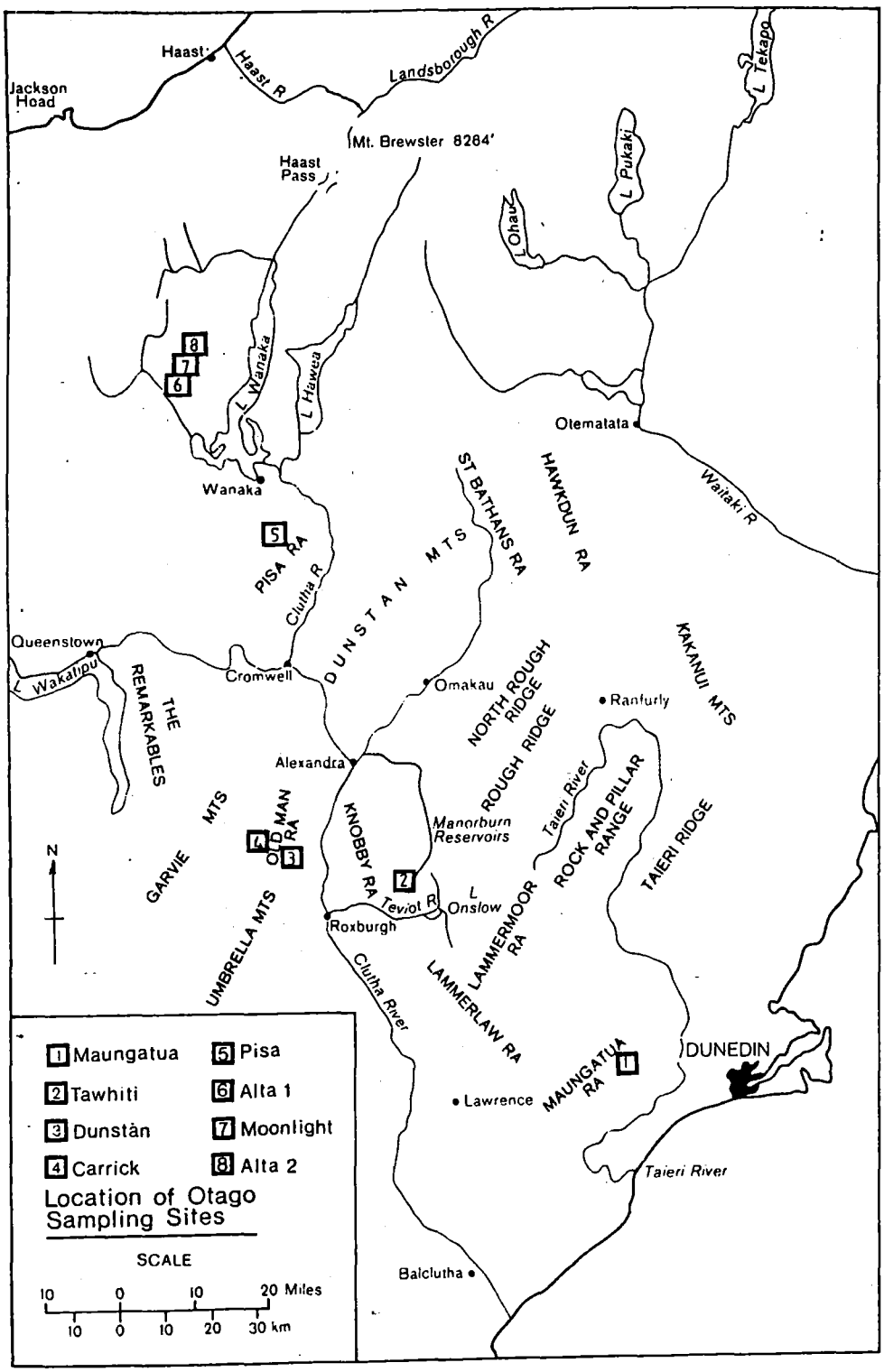

Figure 3.1: Location of tall tussock grassland study sites in Central Otago. (Base map after Molloy and Blakemore (1974)).

CHAPTER 3

3.1 INTRODUCTION.

To gain a broad picture of seasonal trends in grassland soil nitrogen (N) transformations and the effects of cultural modifications upon these, several tall tussock grassland sites in Canterbury and Otago were chosen for study. These sites incorporated *Chionochloa* grasslands at a range of altitudes with a variety of soil types, climatic regimes and vegetation associations.

Eight sites on a transect across Otago and three sites at Paddle Hill Creek South Canterbury, were studied in the general survey. A more detailed study of mineral N transformations was conducted at the more accessible South Canterbury sites to clarify features identified in the general survey.

3.2 OTAGO SITES.

3.2.1 General description.

The Otago sites were chosen along a SE-NW transect from Maungatua, behind the Taieri Plain, to Mt Alta behind Lake Wanaka (Figure 3-1). Three of the eight sites formed part of a climosequence of soils across Otago under study by Soil Bureau of the Department of Scientific and Industrial Research (DSIR). Further site details for these, the Maungatua, Carrick and Tawhiti sites, are given in Molloy and Blakemore (1974). Selection of areas also under study by Soil Bureau allowed comparisons to be made between results from two independent investigations. A site on the Pisa Range with Obelisk soil type was chosen in preference to the Obelisk soil site on the Old Man range studied by Soil Bureau because their Old Man Range site was considered to be an example of *Chionochloa macra* grassland which had been severely degraded by grazing. Climate and soil characteristics for the sites are presented in Table 3-1.

In the Pisa, Carrick, Tawhiti, Dunstan, Alta 1, Alta 2 and Moonlight sites, two altitudinal sequences can be recognised in *Chionochloa rigida* and *C. macra* grassland on upland, high country or alpine yellow brown earth soils.

One, a "dry zone" sequence is in Central Otago:-

Site	Tawhiti	Dunstan	Carrick	Pisa
Altitude	850m	1000m	1300m	1640m
Precipitation[1]	850mm	1100mm	1300mm	1700mm

TABLE 3.1. Site, soil and climate data for Otago and Canterbury study areas

Site	Soil Classification	Altitude (m)	Mean annual precipitation (mm)	Estimated monthly mean air temperature (°C)		Extreme annual temperature range (°C)	Months when soil moisture content at 45cm depth is below wilting point	Soil moisture regime
				Warmest month (Jan/Feb)	Coldest month (July)			
Maungatua[a]	Maungatua podzolized, yellow brown earth	870	1400	8,8	-0.1	35	0	hygrous to hydrous
Tawhiti[a]	Tawhiti upland yellow brown earth	850	c850	11.0	-2.0	c50	<1	hygrous
Carrick[a]	Carrick (Rolling) High Country yellow brown earth (HCYBE)	1300	1300	8.6	-0.8	36	0	hygrous
Dunstan[a]	Dunstan (Steepland) HCYBE	1000	1100	na	na	na	0	hygrous
Pisa[a]	Obelisk Alpine yellow brown earth	1640	1700[e]	4.8[e]	-7.7[e]	40[e]	0	hygrous
Alta 1[b]	Dunstan HCYBE (Terrace variant)	1200	1500	na	na	na	0	hygrous
Alta 2[b]	Moonlight HCYBE (Terrace variant)	1530	2000	na	na	na	0	hygrous
Moonlight[b]	Moonlight (Steepland) HCYBE	1410	1900	na	na	na	0	hygrous
Paddle Creek lower[c]	Snowgrass[d] HCYBE	884	1000	12.0	2	45	0	hygrous
Paddle Creek mid[c]	Cass Hill[d] HCYBE	900	1000	12.0	2	40	1?	hygrous
Paddle Creek upper[c]	Puketeraki[d] (Rolling) HCYBE	1257	1200	12.0	1.5	35	0	hygrous

na Information not available
a Site information from Molloy and Blakemore (1974)
b Climate data estimated from Minaret climate station N.Z. Meteorological Service (1973)
c Climate data from Williams (1977)
d Soil description from Harvey (1974)
e Estimates from Old Man Range Obelisk site (Molloy and Blakemore, 1974)

The other, a "wet" zone sequence is in West Otago:-

Site	Alta 1	Moonlight	Alta 2
Altitude	1200m	1410m	1530m
Precipitation[1]	1500mm	1900mm	2000mm

[1]Precipitation estimates from N.Z. Met. Service (1973).

The Maungatua site in eastern Otago at 870m altitude with an annual precipitation of 1400mm, podzolised yellow brown earth and an exposed position above the eastern seaboard is markedly different from the other sites and is not easily related to the other sequences.

No low altitude sites were included in the study since *Chionochloa* grassland has generally been eliminated from these lower altitudes by fire and grazing. Other studies of nitrogen transformations have included such lower, drier sites. (Tan, 1967; Ross and McNeilly, 1975).

3.2.2 Vegetation and history of cultural modification.

All Otago sites supported dense tall tussock vegetation as outlined in Table 3-2. *Chionochloa* tussock bases covered up to 40% of the total area of each site. *Chionochloa* foliage covered an even greater area at many of the sites. Beneath this foliage there was generally a deep accumulation of tussock litter.

Chionochloa rigida, narrow-leaved snow tussock, was present at the lower altitude Maungatua, Tawhiti, Dunstan, Alta 1 and Moonlight sites. At the 1300m Carrick site, *Chionochloa rigida* was mixed with the shorter-statured *Chionochloa macra*, slim snow tussock. *C. macra* occupied the high altitude Pisa and Alta 2 sites.

The Otago sites all have a history of both burning and grazing. These cultural modifications have been particularly severe since European colonisation. Prior to this, Polynesian burning and natural wildfires are likely to have also been instrumental in creating many of the tall tussock grasslands of Otago, at least below 1000m altitude where forest and shrubland communities have been shown to have been formerly widespread (Molloy *et al.*, 1963).

TABLE 3.2. Site characteristics - Otago and Canterbury study areas (2)

	Slope	Aspect	Site Cover (% Basal cover by major plant species of total area (3))
OTAGO SITES			
Maungatua Grid Ref. (GR). S163:820-697 (1)	5°	SE	Vegetation 70% litter 25% bareground 5% *Chionochloa rigida* 35%, *Dracophyllum longifolium* 10% *Celmisia coriacea* var. *stricta* 10%, *Poa colensoi* 5%
Tawhiti GR.S153:324-149	5°	NE	Vegetation 60% litter 30% bareground 10% *Chionochloa rigida* 25%, *Festuca novae-zelandia* 10%, *Poa colensoi* 10%
Carrick GR.S143:051-211	5°	N	Vegetation 70% litter 20% bareground 10% *Chionochloa rigida* 20%, *C. macra* 20%, *Poa colensoi* 10%, *Gaultheria depressa* 5%
Dunstan GR.S143:065-202	9°	E	Vegetation 70% litter 30% bareground - *Chionochloa rigida* 40%, *Poa colensoi* 5%, *Lycopodium fastigiatum* 5%
Pisa GR.S124:028-940	4°	NW	Vegetation 55% litter 30% bareground 10% rock 5% *Chionochloa macra* 30%, *Celmisia haastii* 20%, *Raoulia hectori* 5%, *Poa colensoi* 5%
Alta 1 GR.S115:776-325	5°	W	Vegetation 70% litter 20% bareground 10% *Chionochloa rigida* 40%, *Poa colensoi* 5% , *Festuca mathewsii* 5%, *Celmisia spectabilis* 5%
Alta 2 GR.S115:781-325	10°	SW	Vegetation 80% litter 20% bareground - *Chionochloa macra* 40%, *Choinochloa crassiuscula* 5%, *Chionochloa oreophila* 5%, *Astelia petriei* 5%, *Celmisia haastii* 5%
Moonlight GR.S115:782-328	25°	W	Vegetation 60% litter 20% bareground 10% rock 10% *Chionochloa rigida* 35%, *Celmisia lyallii* 10%, *Poa colensoi* 5%
CANTERBURY SITES			
Paddle Creek Lower GR.S81:632-529	3°	S	Vegetation 60% litter 40% bareground - *Chionochloa rigida* 40%, *Festuca novae-zelandiae* 10%, *Poa colensoi* 5%
Paddle Creek Mid GR.S81:630-548	5°	SW	Vegetation 50% litter 25% bareground 25% *Chionochloa rigida* 15%, *Chionochloa macra* 10%, *Gaultheria depressa* 5%, *Celmisia spectabilis* 5%, *Poa colensoi* 5%
Paddle Creek Upper GR.S81:611-553	5°	E	Vegetation 60% litter 35% bareground 5% *Chionochloa macra* 40%, *Poa colensoi* 10%

NOTE: (1) Grid reference refers to New Zealand Map Series 1.

(2) Each study area measured 20m x 20m square.

(3) Vegetation cover estimates based on Point Analysis Sampling (n=200).

Wood charcoal in the soil, charred tree stumps and scattered trees of silver beech, *Nothofagus menziesii*, close to the Alta 1 site suggest that *Chionochloa* grassland here has been induced from forest since European settlement (cf. Buchanan, 1875).

Although none of the sites has been burnt for at least ten years (local run-holders pers. comm.), all are still grazed in varying degrees by both domestic stock and by introduced wild animals. Land retirement schemes and helicopter hunting of deer have reduced grazing pressure at some sites (Alta 1, Alta 2, Moonlight, Carrick, Pisa) but even these sites are still periodically grazed by domestic stock, hares, deer and chamois.

These grasslands can be considered to approximate an ecologically stable situation at least in the short term. Provided grazing pressure is not increased, particularly by the introduction of cattle, further burning or a combination of these influences, *Chionochloa* species are likely to persist. Alternately, if fire and grazing were eliminated over a long time span it is likely that forest or shrubland would develop at the Alta 1, Maungatua, Dunstan and Moonlight sites and, possibly in an extremely long time span, at all the sites except the high altitude Pisa and Alta 2 sites. For the purpose of this study, it is considered appropriate to regard all the sites as examples of natural grassland.

A feature of these grasslands that is of importance when assessing the fate of mineral N in the soil if the predominant tall tussock cover is removed or damaged, is the colonisation of such exposed sites by subordinate plant species. These occur beneath and between the tall tussocks (see Table 3.2). Subordinate plant species often have the ability to spread rapidly into bare sites, by vegetative growth. This expansion of distribution is much more rapid at low altitude sites (below 1200m) than at higher sites. Native plants such as *Festuca novae-zelandiae*, *Poa colensoi*, *Celmisia* and *Raoulia* species and introduced plants such as *Rumex acetosella*, *Anthoxanthum odoratum*, *Agrostis tenuis* and *Cerastium glomeratum* all vigorously colonise depleted tall tussock grasslands at lower altitudes at the Otago sites studied in this survey.

3.2.3. Climate

Fairly precise climatic data is available for the Maungatua, Tawhiti, Carrick and Dunstan sites based on earlier studies done in these areas. Summary features are presented in Table 3.1. Information for the Pisa site has been extrapolated from results obtained for the Obelisk site mentioned earlier in this chapter. Records are unavailable for the Alta 1 and Alta 2 and Moonlight sites. However, estimates based on records for the nearby Minaret and Mount Aspiring climate stations (N.Z. Met. Service, 1973) are presented in Table 3.1. Some indication of temperature regimes and rainfall distribution may assist in identifying the importance of freeze-thaw and wetting and drying influences upon nitrogen mineralisation at these sites.

(a) Temperature

Harsh temperatures occur at all sites, particularly those in the middle of the transect where any moderating coastal or westerly wind influences are reduced and the climate tends more towards a continental one than the maritime climate that prevails over much of New Zealand (Mark, 1965a).

In the coldest month of winter, July, mean monthly air temperature at all the sites is close to or below zero. Temperatures at the Pisa site are likely to be particularly severe. Here, periglacial features including polygons, stone stripes and solifluction terraces are widespread across the summit of the Pisa Range near the study site.

An important feature of all the sites during winter is the fluctuation of air temperatures. Diurnal fluctuations of air and surface soil temperature above $0^{o}C$ after overnight frosts generally occurs when the sun shines on these areas. This is particularly pronounced on north and west facing sites when snow cover is absent such as in early winter (Archer, 1969). These diurnal freeze-thaw regimes are a characteristic feature of winter in the New Zealand high country. In addition, periodic warm westerly winds that sweep across the country on occasions during winter, can melt snow cover, thaw surface soil layers and raise air temperature to well above zero for periods of several days (Mark, 1965b; Archer and Collett, 1971).

(b) Precipitation

Precipitation is well distributed throughout the year although there is a pronounced winter/early spring maximum at the Dunstan, Carrisk and Pisa sites (Mark, 1965a). This reflects the higher frequency of southerly and south-westerly storms during this period.

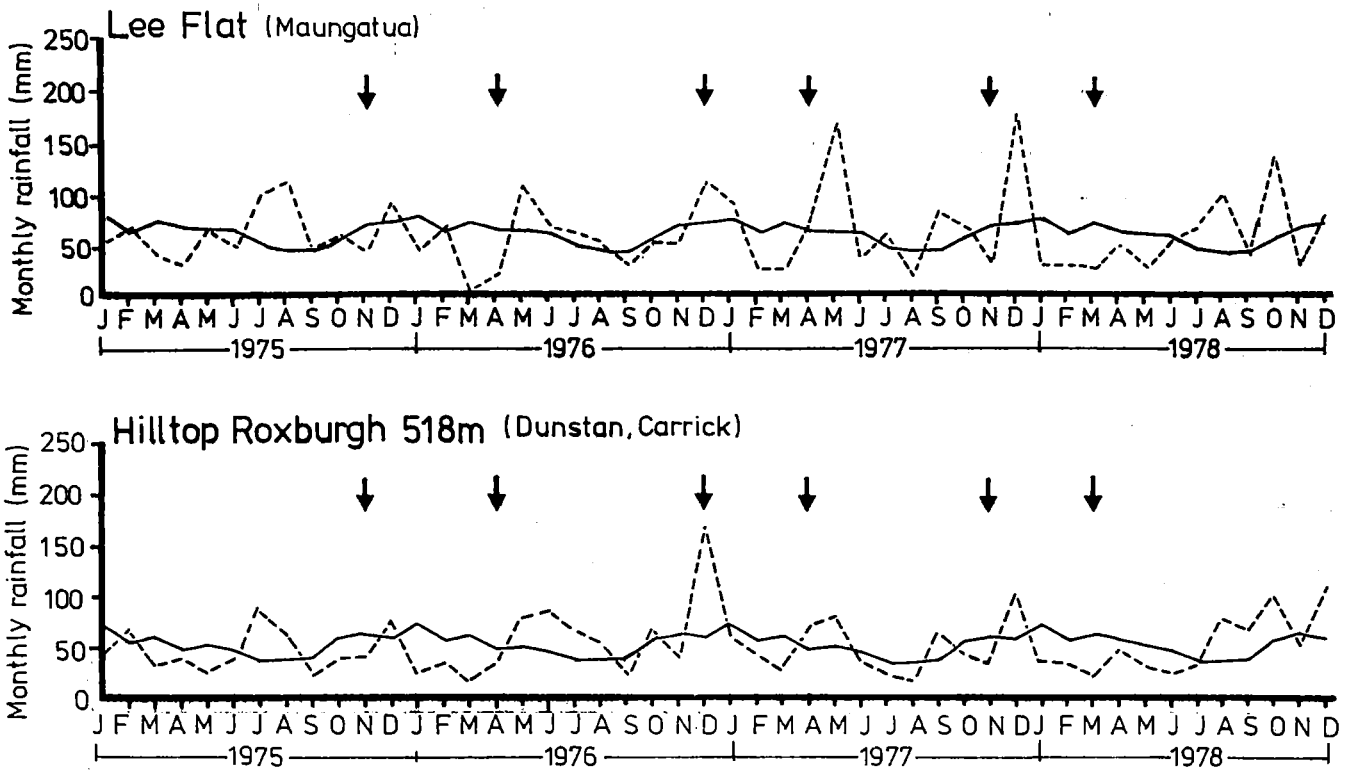

Figure 3-2: Soil sampling dates (⬇) in relation to monthly rainfall (mm) 1975-78 [---] and 30 year (1941-70) rainfall normals [————] Lee Flat and Hilltop Roxburgh Stations, Otago /NZ Met. Service 1973,76,77,78,79/.

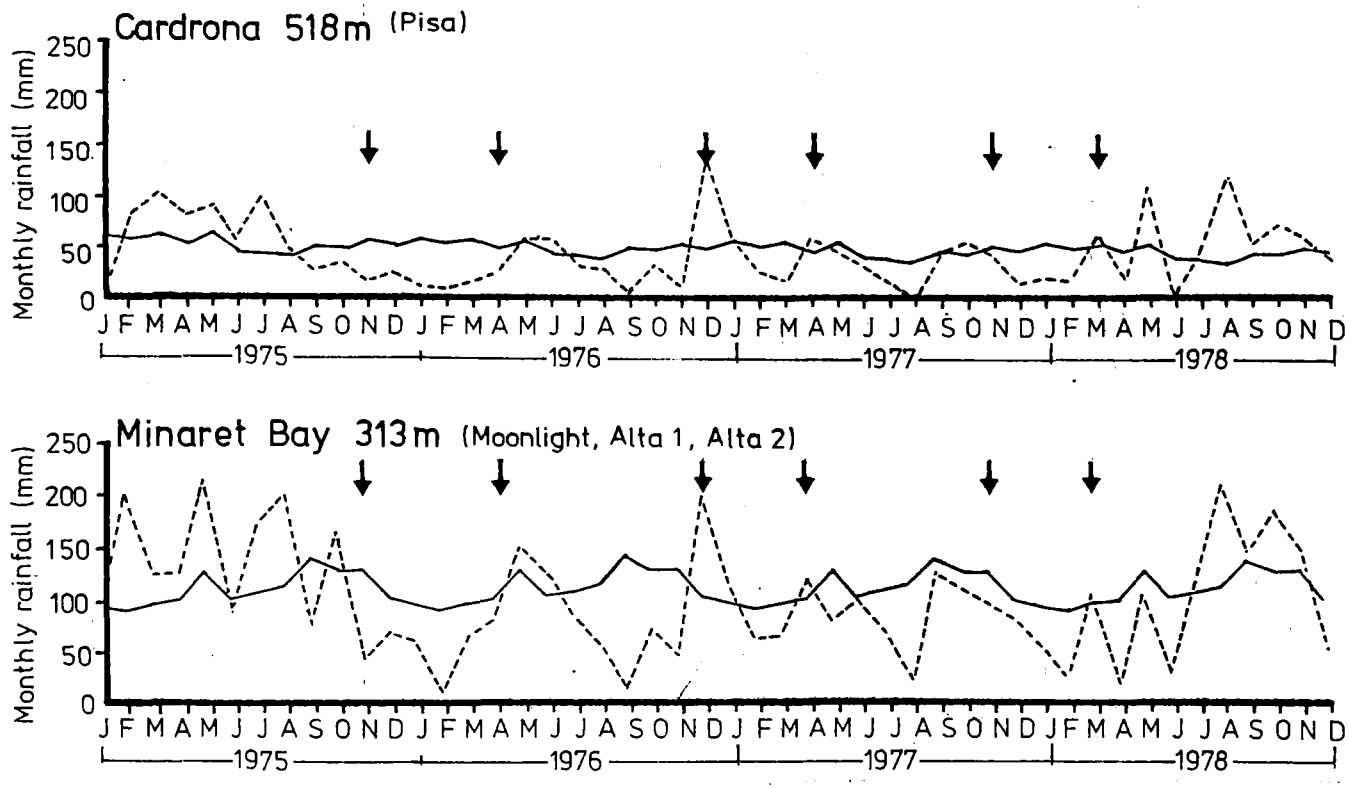

Figure 3-3: Soil sampling dates (⬇) in relation to monthly rainfall (mm) 1975-78 [----] and 30 year (1941-70) rainfall normals [————] Cardrona and Minaret Bay Stations, Otago /NZ Met. Service 1973,76,77,78,79/

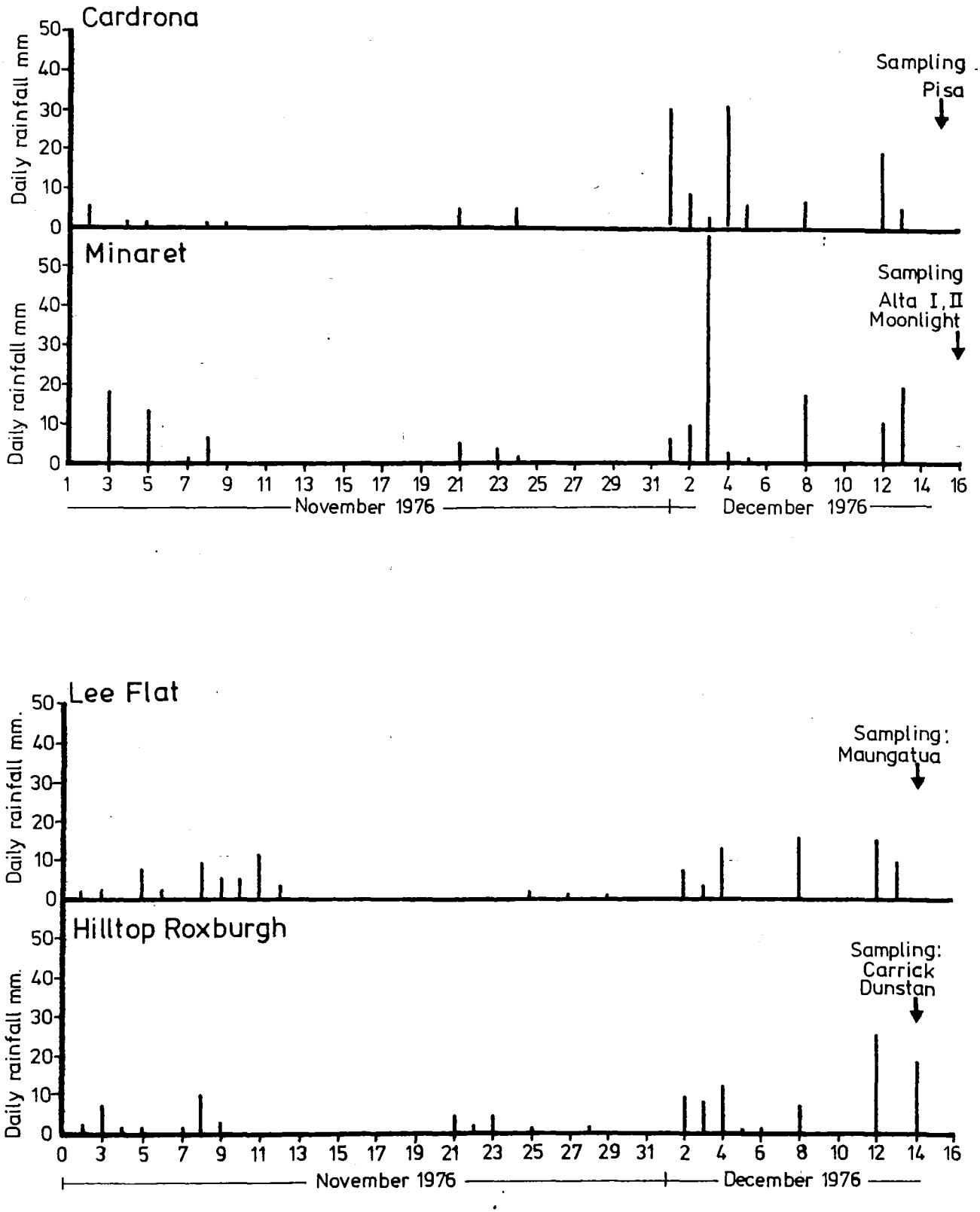

Figure 3.4: Daily rainfall (|) preceeding the December 1976 soil sampling recorded at the nearby rainfall station of Lee Flat (Maungatua), Hilltop Roxburgh (Tawhiti, Carrick, Dunstan), Cardrona (Pisa) and Minaret (Moonlight, Alta 1, Alta II) (NZ Met. Service pers.comm.)

The autumn and late spring precipitation maxima at the Alta and Moonlight sites are caused by prevailing north-westerly conditions over these periods (N.Z. Met. Service, 1973).

Thirty year rainfall normals and 1975 to 1978 rainfall for four stations:- Cardrona 518m, Minaret Bay 313m, Lee Flat 381m and Hilltop, Roxburgh 518m - are presented in Figures 3.2 and 3.3 (N.Z. Met. Service, 1973; 76; 77; 78; 79). These can be related to nearby study sites to give some indication of rainfall patterns for these sites. Since all the study sites are at considerably higher altitudes than the Meteorological Service stations it is likely that they all receive higher precipitation than the levels recorded for these stations.

In the tall tussock grasslands, Mark (1965b) suggests that precipitation is likely to exceed potential evapo-transpiration for most of the year and that therefore soil moisture deficits are unlikely to occur at these sites for sustained periods.

It is apparent, however, from a study of rainfall patterns and soil moisture regimes for some of the different localities that there are dry periods when upper soil layers are subject to soil moisture deficits. Identification of such moisture deficit periods is important since it is the interruption of these with rainfall, a drying-wetting cycle, which occasion the surge of mineralisation and nitrification described by Birch (1958).

Unexpectedly high mineral N levels from all sites sampled in December 1976 inspired a careful study of rainfall patterns prior to this sampling date. It was thought that the high levels of mineral N might result from a flush of mineralisation caused by rainfall after a sustained dry period. All sampling sites in Canterbury and Otago appeared to have undergone such a dry period over October and November 1976. This was broken by sustained heavy rain over the fourteen days of December prior to sampling. Rainfall patterns for this period are presented for the Otago stations in Figure 3.4.

The December 1976 sampling anomaly is discussed in more detail in Chapter 4.

3.3 CANTERBURY SITES - PADDLE HILL CREEK.

3.3.1 General description.

Paddle Hill Creek is located 125km south-west of Christchurch in the Lake Heron intermontane basin amidst the eastern foothills of the Southern Alps (Figure 3.5). The basin of the mid and upper catchment of the creek contains pure and mixed *Chionochloa rigida* and *C. macra* grasslands on soils of various ages and degrees of development over an altitudinal range from 800m above sea level (a.s.l.) to 1400m a.s.l.

In recent years the area has been subjected to several intensive scientific studies. Harvey (1974) described the soils and landforms of the mid and upper catchment of the creek. Noonan (quoted in O'Connor, 1974) made preliminary surveys of nitrifying bacteria present in the grassland soils here. Williams (1977) studied growth, biomass and net productivity of two *Chionochloa* grasslands in the valley at altitudes of 884m and 1257m. In the course of this work he obtained climate data over three seasons for both sites. He also investigated macro-element pools and fluxes in *Chionochloa* sampled from the two sites (Williams *et al.*, 1977).

Four main reasons influenced the choice of Paddle Hill Creek for a semi-intensive investigation of soil nitrogen transformations. These are enumerated.

I. Natural variety.

Glacial and periglacial forces and more recent erosion have moulded the Paddle Hill Creek basin so that it now possesses landforms with a diversity of slopes and aspects at a range of altitudes. The many different soil types found within the basin reflect this natural diversity. Harvey (1974) defined twenty different soil variants in his study of the valley.

Because of this physical diversity, the *Chionochloa* grasslands that cover most of the valley show a biological diversity that ranges from a few scattered, stunted tussocks on rolling fans, moraines and plateau crests to tall, dense tussock communities on the fertile alluvium of the valley floor. The Paddle Creek basin contains some of the best remaining examples of *Chionochloa* grassland in near natural state at comparatively low altitudes in Canterbury.

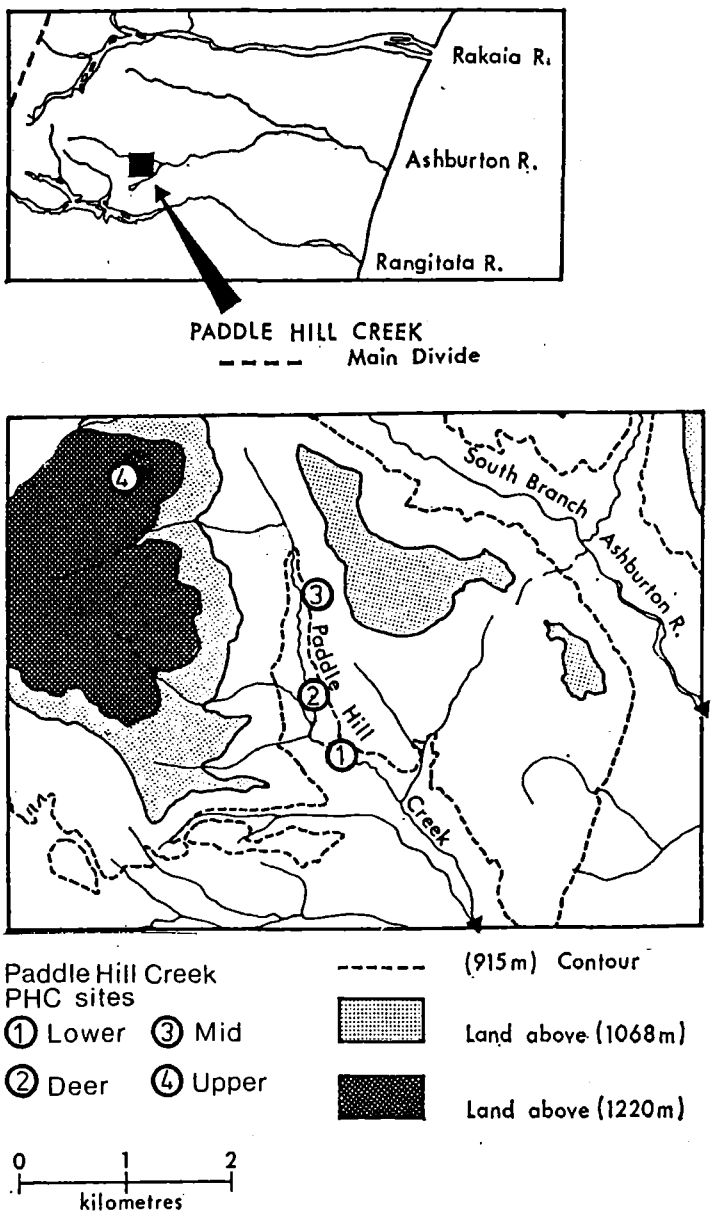

Figure 3.5: Location of tall tussock grassland study sties at Paddle Hill Creek, South Canterbury. (Base map after Williams (1977)).

II. Accessibility.
The importance of processing soil samples on the same day as sampling has been described in Chapter 2. Paddle Hill Creek was close enough to the Lincoln College laboratory for this to be done.

III. Available scientific information.
The pool of information available on the area has been outlined. This proved invaluable during the study both as background information to aid in site selection and in assisting with the interpretation of results.

IV. Paddle Hill Creek - a representative tall tussock grassland.
The Paddle Hill Creek site was considered broadly representative of tall tussock grasslands throughout much of the South Island where agricultural development work is in progress.

While the primary aim of this work was to gain an understanding of soil mineral N transformations in natural grassland communities, studies of grazing, burning, cultivation and urea application were also undertaken. One important application of these is to indicate some of the possible effects of major tall tussock grassland development programmes on soil N transformations.

3.3.2 Site selection, vegetation and cultural history.
Three major study sites were chosen at Paddle Hill Creek (Figure 3.5). Site characteristics of these are presented in Table 3.1. The Paddle Creek lower site (PHC Lower) was adjacent to Williams' site 4 at 994m a.s.l. (Williams, 1977). It was situated in dense, tall *Chionochloa rigida* on the organic silt loam of the valley floor.

The Paddle Creek upper site (PHC Upper) was adjacent to Williams' site 3 at 1257m a.s.l. in dense *Chionochloa macra* grassland growing in a deep organic silt loam near the top of a high plateau. This plateau is composed of an ancient moraine capping a tilted sub-schist and greywacke block (Harvey 1974).

These two sites are excellent examples of vigorous *Chionochloa rigida* and *C. macra* grassland and possibly resemble the type of tall tussock encountered at the outset of European colonisation of Canterbury and subsequently

eliminated over much of the province. Both these sites have certainly been burnt since European settlement and they have also been grazed for most of this period. However, both sites have not been burnt for at least thirty years (Mrs W. Dobbs, Hakatere Station, pers. comm.). Although these sites are grazed by both sheep and cattle, a dense tall tussock cover has persisted here probably because of the high natural fertility of both sites. Tussocks at the PHC Lower site were up to 1.5m in stature while those at the PHC Upper site were up to 1m in height.

The third site chosen at Paddle Hill Creek differed markedly from the other two. It was located at an altitude of 900m on an old fan just down from Williams' site 1. Tussocks at this Paddle Hill Creek site (PHC Mid) were small in stature (less than 50 centimetres in height) and formed only a sparse cover over the surface of the site, a quarter of which was bare ground or exposed well-weathered stones. The soil here was shallow and stony compared with the deep loams of the Lower and Upper sites.

The mixed association of *Chionochloa macra* and *C. rigida* found at the Mid site suggests that it is an example of an intermediate stage in the natural ageing of a *C. rigida* stand to a *C. macra* stand (Williams *et al.*, 1977). These authors also postulated that such sites are examples of a "run-down" system where repeated burning and grazing have caused nutrient losses in a soil system which was of low soil fertility, compared to the PHC Upper and PHC Lower sites, even before repeated burning and grazing occurred.

O'Connor (1974) has referred to this soil degradation transition as leading to a "nitrogen-losing modified system". From a study in the tall grass prairie of Kansas he postulated that a reduction in range conditions is associated with an increase in nitrifying bacteria and subsequent loss of nitrate-nitrogen in drainage. Inclusion of the PHC Mid site in this study enables the validity of this hypothesis to be tested.

One other minor site was used at Paddle Hill Creek during this study. This was on the valley floor, 500m upstream from the PHC Lower plot. At this site, referred to as the PHC Deer site, *Chionochloa rigida* on the fertile organic soil of the valley floor had been developed into a deer paddock. It was possible to compare this site with an adjacent area of *Chionochloa rigida* on the same soil type but still in intact condition (see Chapter 5).

3.3.3 Climate.

Detailed climate records from 1971-1973 for Paddle Hill Creek have been published (Williams, 1977). These climate stations were adjacent to the PHC Upper site (Station 3) and the PHC Lower site (Station 2) and only 500m from the PHC Mid site (Station 1) so a clear picture of climate regimes around these sites over the 1971-73 period is available.

Main characteristics of these climatic conditions are presented in Table 3.1 based on data from Williams (1977). No attempt was made to re-establish the monitoring programme maintained by Williams since the logistics of this were beyond the resources available to this study. However, for a short period from May to September 1978, probes from single-pen Lambrecht thermographs were installed at the ground surface and at 100mm depth to monitor freeze-thaw regimes at the PHC Lower and the PHC Upper sites. Records are presented in Figure 3.7 for the PHC Lower site and in Figure 3.8 for the PHC Upper site. At the PHC Lower site, the ground surface was subject to daily freeze-thaw conditions over most the the May to September monitoring period. At 100mm depth, soil temperatures fell steadily through May and early June and the soil was subject to freeze-thaw conditions or was frozen until early September.

Monitoring was maintained only until late July at the PHC Upper site, after which the equipment malfunctioned beneath deep snow drifts. Freeze-thaw regimes prevailed at the ground surface through autumn until mid-June. After this, a blanket of snow across the surface limited temperature fluctuations until the end of the recording period. At 100mm depth the temperature remained at or below $0^{o}C$ until monitoring ceased.

Monthly rainfall means from the Erewhon and Hakatere climate station (N.Z. Met. Service 1973; 76; 77; 78; 79) have been graphed in Figure 3.6a. Erewhon receives higher annual rainfall than Paddle Hill Creek while Hakatere receives slightly less (Williams, 1977). Nevertheless these figures give a fair indication of rainfall patterns in the area over the study period. All the Paddle Hill Creek sites receive moderate rainfall approximating 1000mm per annum for the three sites. Rainfall figures for the Hakatere and Erewhon stations indicate that February and March were the driest months between 1976 and 1978. Rainfall data gathered by Williams (1977) confirmed this to be also the case at Paddle Hill Creek during the period 1971-73.

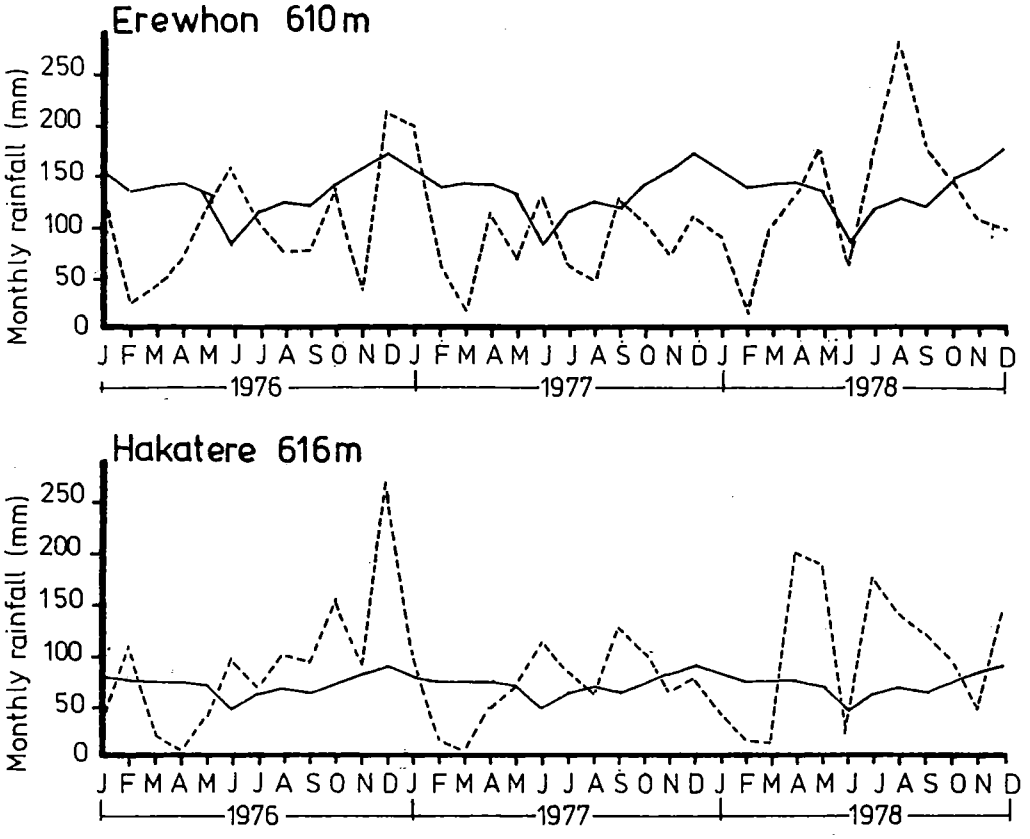

Figure 3.6(a): Monthly rainfall (mm) 1976-78 [- - - - -] and 30 year (1941-70) rainfall normals [———] Erewhon and Hakatere Stations, South Canterbury. (NZ Met Service 1973,76,77,78,79)

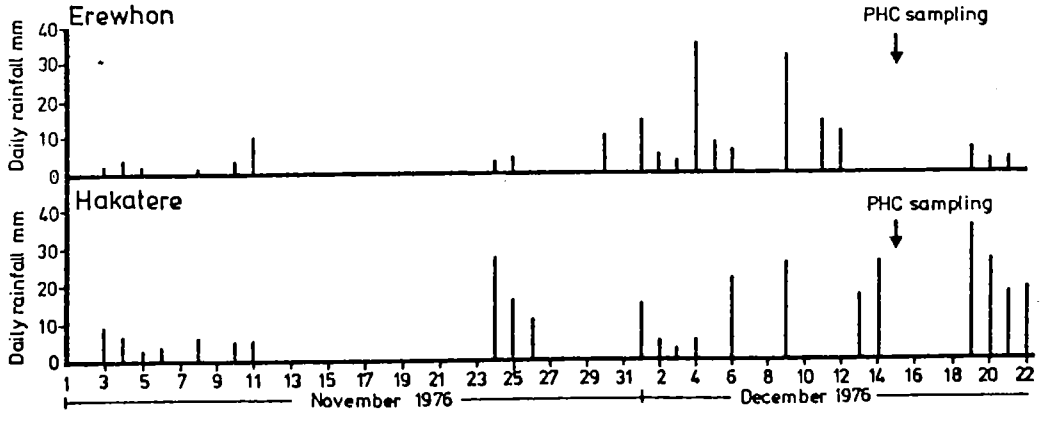

Figure 3.6(b): Daily rainfall (|) preceeding the December 1976 soil sampling at Paddle Hill Creek, South Canterbury from the nearby Hakatere and Erewhon meteorological stations (NZ Met. Service pers.comm.)

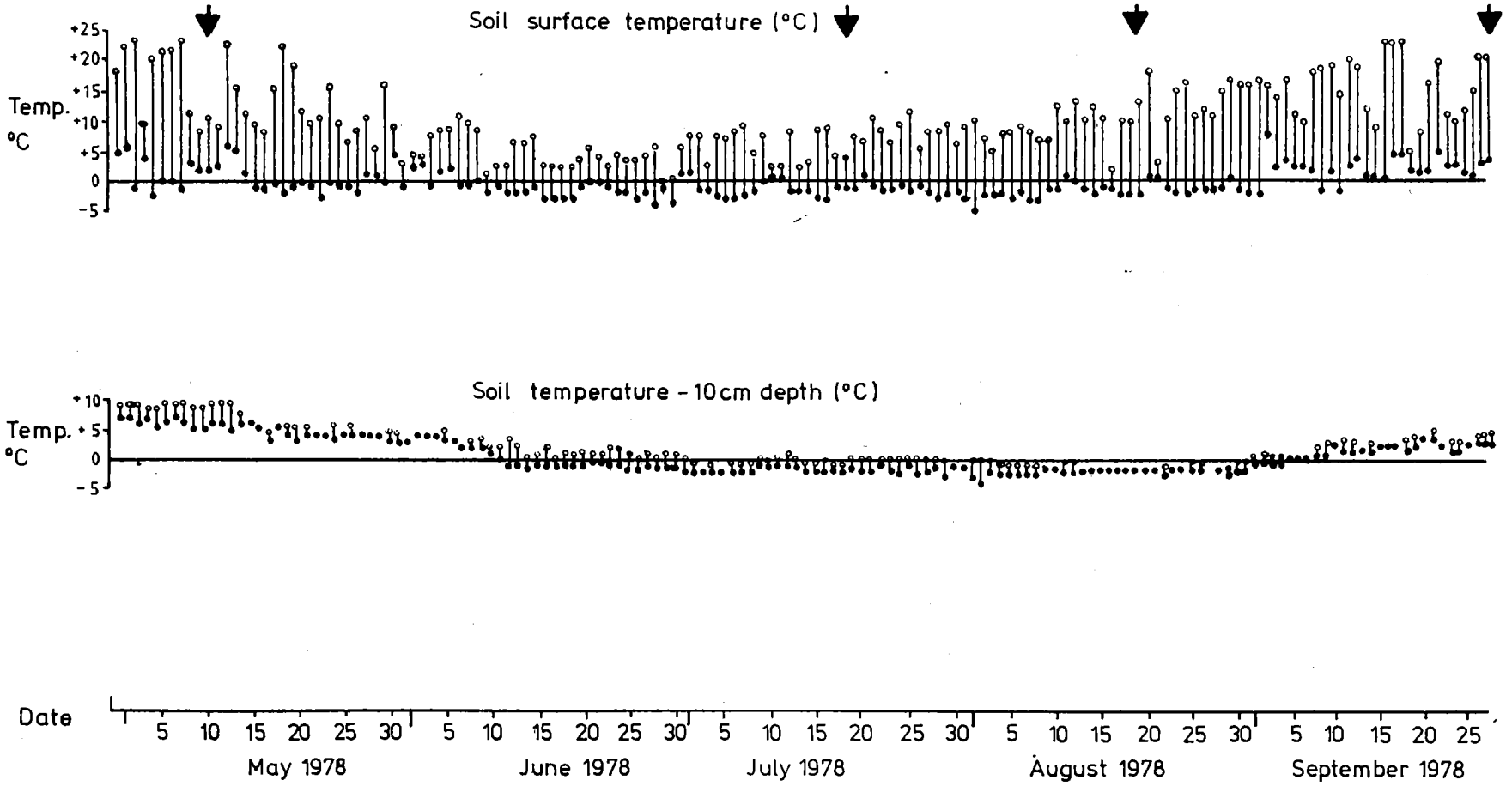

Figure 3.7: Soil sampling dates (⬇) in relation to daily maximum (o) and minimum (•) temperatures at the soil surface and at 10cm depth. Paddle Hill Creek Lower site. Intact control.

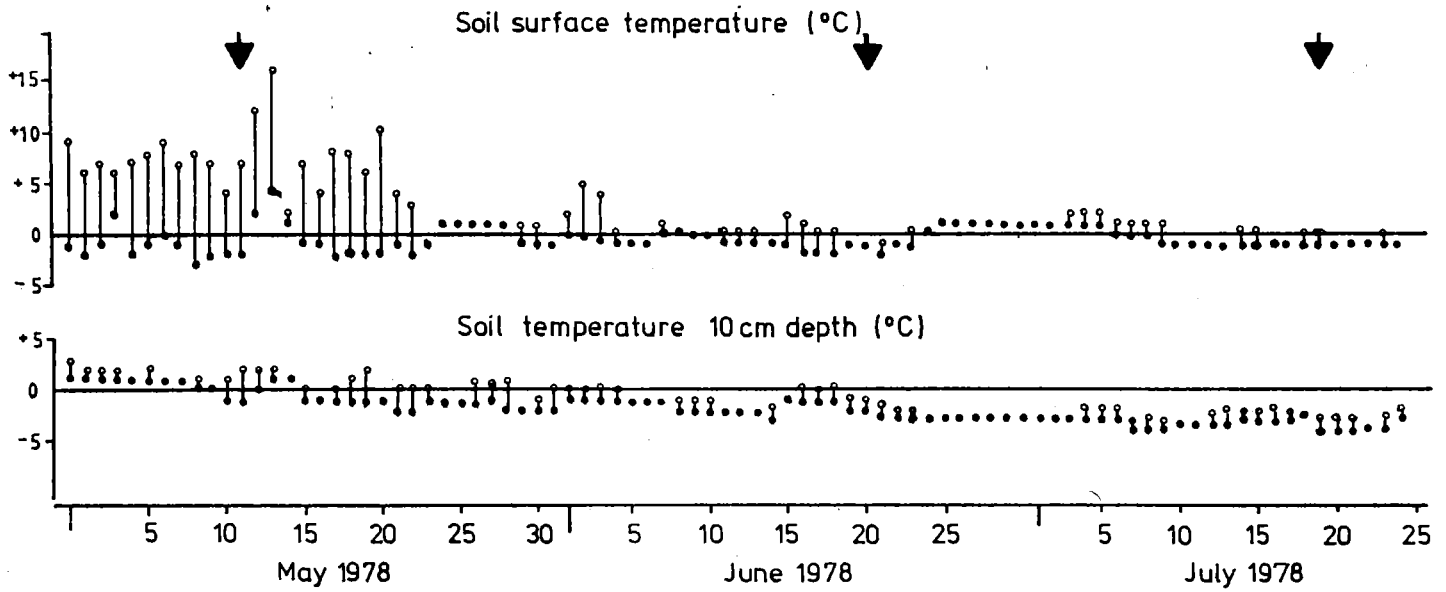

Figure 3.8: Soil sampling dates (⬇) in relation to daily maximum (o) and minimum (•) temperatures at the soil surface and at 10cm depth. Paddle Hill Creek Upper site. Intact control.

The particularly wet December in 1976 which followed a fairly dry period is evident in Figure 3.6a and in the detailed daily rainfall records for November and December 1976 shown in Figure 3.6b. This dry-wet period and its possible influence on high mineral N levels recorded in mid-December 1976 is discussed in some detail in Chapter 4.

3.4 CHEMICAL CHARACTERISTICS OF TOPSOILS.

3.4.1 Methods.

Because this study looked at mineral N transformation only in the upper soil layers (0-100mm), chemical and physical analysis was concentrated in this zone. Whole profile analyses for many of the sites are given in Williams *et al.* (1977) and Molloy and Blakemore, (1974).

In December 1976, twenty 25mm diameter soil cores from the surface 100mm of soil were sampled from around the tussock bases at each site. These were bulked into a composite sample, placed in double polythene bags and stored at approximately $4^{o}C$.

At Lincoln bulked soil samples were air-dried, crushed with a pestle and mortar after the stones had been extracted, and passed through a 2mm sieve.

Analytical procedures were as follows:-

1. *Soil Dry Bulk Density* of the 0-10cm horizon at each site was determined from the mean of 3 samples taken in a .25m x .25m square metal frame and subsequently dried, sieved and weighed at Lincoln.

2. *Soil acidity* was determined with duplicate samples using a glass electrode in a suspension of 10g of air dried soil in 25ml of water (Mountier *et al.*, 1966).

3. *Total organic carbon* was determined using the Walkley and Black method described by Allison (1965).

4. *Total nitrogen* was determined by the micro-kjeldhal method of Bremner (1965). A catalyst mixture of K_2SO_4: Cu SO_4. $5H_2O$: Se in the ratio 100:10:1 was used. Ammonia was collected in boric acid and titrated against 0.02 N sulphuric acid.

TABLE 3.3. Some physical and chemical data for 0-100 mm zone in soils studied from Otago and Canterbury.

Site	pH H_2O(1:2.5)	Dry Bulk Density g/cc	Organic Matter (%) C	N	C/N	Sulphate Sulphur µg g^{-1} soil	Phosphorus Truog-P µg g^{-1} soil	Olsen-P µg g^{-1} soil
Maungatua	4.2	0.60	12.6	0.44	29	5	0.5	3
Tawhiti	4.6	0.82	4.6	0.34	15	3	1	24
Carrick	4.6	0.80	4.9	0.32	15	3	1	23
Dunstan	4.9	0.62	5.4	0.35	15	3	3	18
Pisa	4.6	0.85	6.1	0.26	23	4	5	9
Alta 1	4.8	0.72	6.8	0.51	13	3	4	17
Alta 2	4.6	0.90	7.2	0.58	12	5	4	12
Moonlight	4.8	0.66	5.1	0.33	15	4	3	14
PHC Lower	5.2	0.81	5.8	0.38	15	3	3	34
PHC Mid	4.8	0.82	3.1	0.18	17	2	1	18
PHC Upper	4.6	0.55	9.9	0.41	24	1	4	23

5. *Truog-phosphate* was determined by the standard Ministry of Agriculture quick test (Mountier *et al.*, 1966) and Olsen - phosphate by the modified procedure of Grigg and Stephen (1974).

6. *Soluble and absorbed sulphate-sulphur* was extracted in 0.01M $Ca(H_2PO_4)_2$ at 1:5 soil to extractant ratio (Williams *et al.*, 1976) and results are presented as sulphate sulphur.

Some physical and chemical characteristics of each soil are presented in Table 3.3.

7. *Soil moisture content* was determined after oven drying to constant weight at 105°C. Soil moisture content determinations were made at each soil sampling for the duration of the study and are presented in Chapter 4.

3.4.2 Discussion of results.

(a) Soil acidity : The pH of each of the soils was low and well below the conventionally considered optimum pH of 7.0 for soil nitrogen mineralisation (Harmsen and Kolenbrander, 1965). Nevertheless mineralisation can still be slightly active at pH levels as low as 5.0 (Harmsen and Van Schreven, 1955). Dancer *et al.* (1973) found mineralisation did not alter appreciably between pH values of 4.7 to 6.6.

Increases in mineralisation with liming have been widely demonstrated in New Zealand grassland soils (White, 1959; Robinson, 1963; O'Connor, *et al.*, 1962), indicating that low pH levels limit mineralisation in New Zealand mountain soils.

Nitrification is likely to be severely limited at the low pH levels recorded at the Otago and Canterbury sites (Alexander, 1965). However, there is some evidence that acidophilic strains of nitrifiers exist that can operate at pH levels as low as 4.0 (Chase, Corke and Robinson, 1968; Walker and Wickramasinghe, 1979).

(b) Total nitrogen and total carbon: High carbon levels occur in the wet organic soils at the Maungatua, Pisa and PHC Upper sites. Total nitrogen levels are relatively high at all the sites apart from the run-down PHC Mid site. Alexander (1961) reports that a Carbon/Nitrogen (C/N) ratio below 30

is needed before net nitrogen mineralisation can take place. Harmsen and Van Schreven (1955) consider the C/N ratio should be below 20-25 before mineralisation can occur. If this is the case, mineralisation is likely to be severely restricted at the Maungatua (29), Pisa (23) and PHC Upper (24 sites).

All the lower altitude sites show a C/N ratio of 17 or less, hence mineralisation is likely to occur readily at these unless it is restricted by soil acidity.

(c) Phosphorus and sulphur: Phosphate and sulphate sulphur levels are relatively low for all sites as would be expected for the yellow brown earths. It appears that nitrification can be restricted by low available phosphorus levels. Robinson (1963) and Purchase (1974) have stimulated both mineralisation and nitrification by the addition of phosphate to soils deficient in this element.

3.5 CONCLUSIONS

1. Tall tussock grasslands are an important component of the natural vegetation of New Zealand. They are threatened in many places with clearance and there is an urgent need to study nitrogen transformations both in natural state and during cultural modification.

2. Although it is now impossible to find tall tussock grasslands in the South Island high country unmodified by grazing mammals and often also by repeated burning, this chapter has described thirteen selected sites where the effects of such modification have not been too severe and an extensive tall tussock cover persists.

3. The sites cover a range of *Chionochloa rigida* and *C. macra* grasslands considered to be broadly representative of the tall tussock cover of the eastern high country of the South Island. They range from altitudes of 850m a.s.l. to 1640m a.s.l.

4. Most of the sites are on a flat to gentle slope so that changes in soil mineral N are likely to reflect the characteristics of that site rather than external drift-regime influences.

5. Climate data gathered near or at each site gives an indication of climatic

regimes prevailing at each site. Nitrification and mineralisation are likely to be restricted at most of the sites for much of the year by cold temperatures and, in places, by waterlogged soils.

6. Topsoil chemical properties also suggest that nitrification and, to a lesser extent, mineralisation might be limited at many of the sites.

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CHAPTER 4

SEASONAL VARIATION IN SOIL MINERAL NITROGEN IN TALL TUSSOCK GRASSLANDS - A COMPARISON OF NATURAL GRASSLANDS AND THEIR RESPONSE TO SIMULATED GRAZING.

4.1 INTRODUCTION

At the eight Otago and four Canterbury natural grassland sites described in the previous chapter, a range of studies were undertaken to determine natural levels of mineral nitrogen (N) and nitrifier populations at different seasons and to see what differences simulated grazing would make to these features. In this chapter, seasonal variation in mineral nitrogen in natural and grazed pastures throughout the world and in the N.Z. tall tussock grasslands are reviewed. The studies undertaken at the Canterbury and Otago sites are presented.

4.1.1 Mineral nitrogen in natural temperate grasslands

Seasonal variation in soil mineral N levels occurs in response to changes in environmental factors and biological activity. These levels represent a balance between processes of mineralisation, nitrification, the uptake of nitrate and ammonium by plants and microorganisms, leaching of nitrate and denitrification.

In temperate grassland systems the following seasonal pattern of soil mineral N levels is predicted (Woodmansee et al., 1981; Harmsen and Van Schreven, 1955).

WINTER: Cold and wet conditions may restrict mineralisation and severely limit nitrification. It has been suggested that nitrification cannot occur below 5°C (Williams, 1969). Plant uptake and microbial activity will also be restricted by cold conditions. NH_4-N may therefore accumulate in the soils in moderate quantities. Little NO_3-N is likely to accumulate. Any NO_3-N that is produced may be leached from these waterlogged soils or lost by denitrification in the waterlogged anaerobic conditions.

SPRING: Additions of mineral N through an upsurge of mineralisation will be countered by rapid plant growth placing high demands on N supply and leaving little excess NH_4-N for nitrification. Both NH_4-N and NO_3-N are likely to be present only at low levels.

SUMMER: Mineralisation is likely to peak under favourable temperature conditions, provided soil moisture levels do not fall too low. Plant uptake of N at this time may be lower than at the spring flush period. If this is the case, soil NH_4-N levels will increase. The availability /

of NH_4-N as substrate and favourable temperatures will promote nitrification and soil NO_3-N levels should increase. In late summer or possibly thoughout the summer, drought conditions may severely limit mineralisation and nitrification.

AUTUMN: If dry conditions have prevailed through the summer and are broken by autumn rains, a rapid upsurge in mineralisation and nitrification will occur. There will be a rapid surge in NH_4-N and NO_3-N production. After rain, initiation of seed germination and seedling growth may take some time and while this occurs plant demands for soil N may be low. In time, however, plant uptake of mineral N will rapidly reduce these levels. As temperatures become colder and plant growth and hence N uptake slows down, soil NH_4-N levels may increase towards their winter levels.

Most studies of seasonal variation of mineral N in natural or induced grasslands throughout the world have involved single soil samples which give mineral N levels at one point in time. These give little indication of the magnitude of seasonal fluctuations. The few seasonal studies of mineral N fluxes in natural grassland systems have all involved sampling soils at fixed sites generally over periods of one to several years. Some, however, avoided sampling in mid-winter months (e.g. Chase *et al.*, 1968). Localities for these studies include Rothamsted Park (Richardson, 1938), Kent and London (Williams, 1969) and the Chiltern Hills (Davy and Taylor, 1974) in England, Southern New South Wales (Simpson, 1962) and Northern Territory (Wetselaar and Norman, 1960) in Australia, alpine grasslands in France (Labroue and Lascombes, 1971), semi-natural grass stands in Korea (Kim, 1976) and Southern Ontario, Canada (Chase *et al.*, 1968).

Hypothetical seasonal levels of mineral N in natural grassland soils are presented in Figure 4.1 in which the result of plant uptake and microbial activity is predicted. A situation in which no summer drought occurs is assumed in Figure 4.1a. In Figure 4.1b it is assumed that a drought occurs over the summer and is broken by autumn rains. This causes a flush of mineralisation and nitrification followed by plant growth and mineral nitrogen uptake. For both situations, it is assumed that the grasslands are temperate rather than summer growing tropical grasslands.

The aim of this study is to test the validity of this hypothetical model

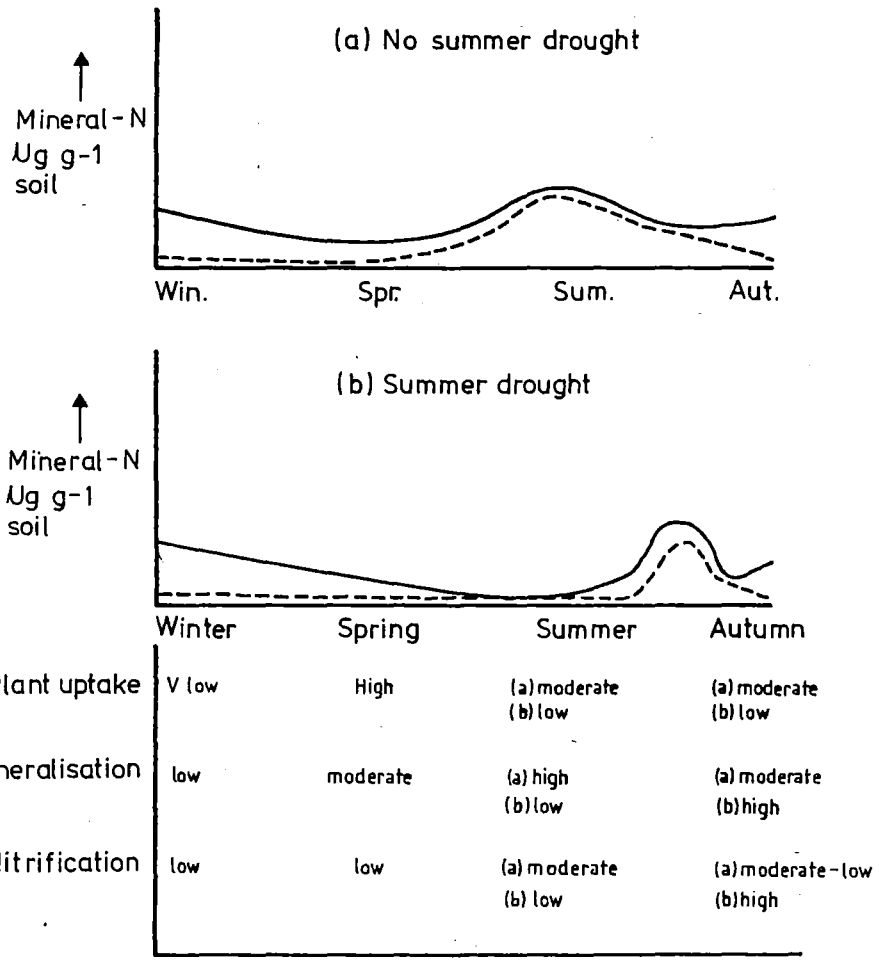

Figure 4.1 Hypothetical seasonal variation in soil mineral nitrogen levels in a temperate natural grassland under conditions of (a) no summer drought (b) summer drought.
_____ NH_4-N, _ _ _ _ _ _ _ _ NO_3-N

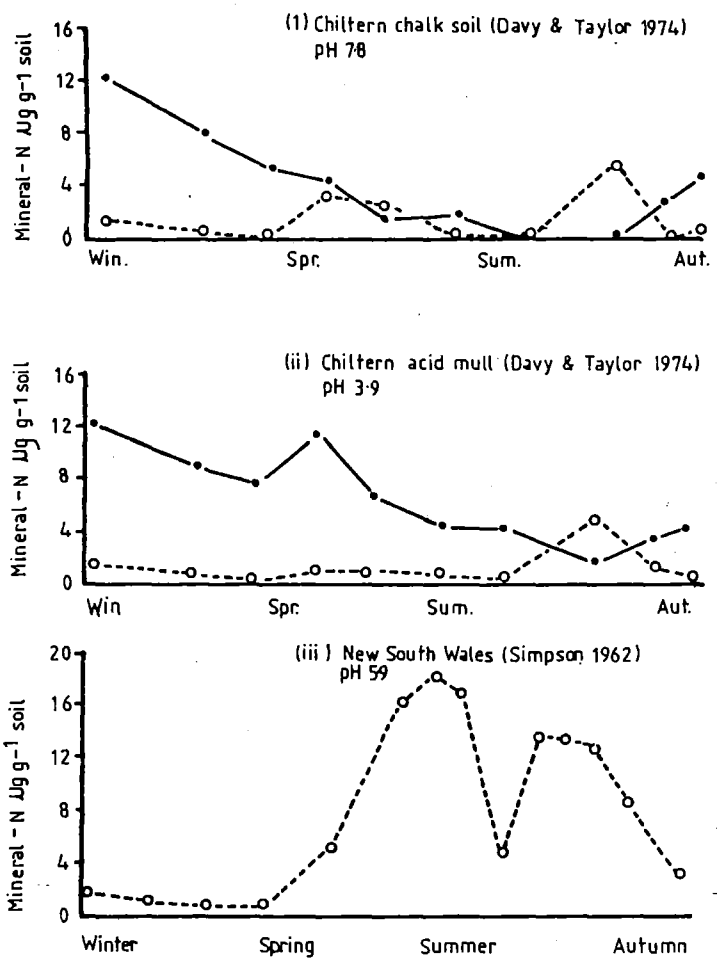

Figure 4.2 Seasonal levels of soil mineral nitrogen in three temperate grasslands •—• NH_4-N o--o NO_3-N in top 0-100mm of soil

Chiltern Soils — Note winter NH_4-N peak, late summer NO_3-N peak

N.S.W. Soil — Note summer NO_3-N peak, NH_4-N not recorded

of mineral N variation in a temperate tall tussock grassland soil. Comparison with work elsewhere is hindered by the different sampling techniques used (see Chapter 2). Results from three grassland sites studied in two surveys (Davy and Taylor, 1974; Simpson, 1962) using techniques comparable to each other and to those described in this chapter are presented in Figure 4.2 for comparison with the hypothetical model. It is clear from these examples that wide fluctuations can occur in soil mineral N levels in different seasons at any site.

Most New Zealand studies of mineral N in tall tussock grassland soils have used single or a few field soil samplings, then made conclusions on the overall soil mineral N status based on these samples, most of which have been carried out only during the summer months. (O'Connor *et al.*, 1962; Robinson, 1963; Tan, 1967; Ross, 1960). Ross (1958) investigated winter, spring and summer nitrifying activities of three tussock grassland soils through incubation experiments but did not look at field levels of mineral N in different seasons. Recently, detailed laboratory studies have shown the potential for high levels of mineral N to be present within tussock grassland soils at certain times of the year. Ross *et al.* (1979a) discovered that Cluden and Carrick soils from their Otago climosequence contained more mineralisable N in winter than in autumn samples. An allied study showed that freezing and thawing caused an immediate increase in the mineral N content of a range of soils (Ross and Bridger, 1978a).

In this and later chapters investigations are described to determine the effects of modification of tall tussock grassland, through simulated grazing, urea application, burning and cultivation, on natural mineral N levels.

4.1.2. Effects of simulated grazing on soil mineral nitrogen.

The effects of grazing upon grassland soil N transformations have been reviewed by Floate (1981), examined semi-quantatively by Woodmansee *et al.* (1981), and considered in the context of New Zealand tall tussock grasslands by O'Connor (1974; 1981; 1983).

From these reviews it may be discerned that grazing influences soil N transformations through four main processes:

a. Consumption of herbage.
b. The return or redistribution of nutrients in excreta.
c. The treading of soil and vegetation.
d. The removal of nitrogen in animal products.

The experiments described in this chapter simulated a grazing regime by tussock defoliation and urea application to small areas. They did not include formal grazing treatments although many of the sites were coincidentally grazed because all the plots were open to roaming animals. Two of the above considerations, treading and animal product removal are not taken into account in this experiment. Under actual grazing regimes, particularly with intensive stocking, treading can cause damage to plants, soil disturbance and soil compaction in localised areas throughout the range. Some effects of treading are considered in the cultivation experiments described in Chapter 5.

Removal of animal products removes N from the soil-plant system. However, under a system of extensive grazing only about 10% of above ground dry matter is likely to be utilised by the grazing animal and only about 4% of dietary N will be removed in animal products. Hence only a small proportion of the total N pool of the system is likely to be lost in this manner (Woodmansee *et al.*, 1981). Under conditions of mob sheep or cattle stocking or with high densities of rabbits, the proportion of N going into animal production will become more significant. Under these conditions, losses of N through ammonia volatisation, nitrate leaching and denitrification after animal excretions may be much more important.

a. Consumption of herbage (defoliation)

Herbage consumption can have a range of effects on soil N transformations. These depend on the level of defoliation, the animal involved, the grassland system in which it occurs and the time of the year at which defoliation takes place. Under extensive grazing management as little as 10% of plant material is consumed and the effect of grazing is less significant than in intensively grazed systems where perhaps 65-85% of plant material is consumed (Woodmansee *et al.*, 1981). Cattle tend to be less selective grazers than sheep and will often consume taller vegetation, stems and dead material while sheep select primarily for fresh growth. European pasture grasses, with meristematic tissue close to or below the ground, often respond to grazing with increased tillering and growth. Many

tussock or bunch grass species from the Americas and Australasia by contrast, have a high proportion of their biomass above ground and grazing may cause tiller death, particularly where close defoliation is repeated at frequent intervals. Grazing of these grasslands may reduce plant production and may also eliminate favoured productive species which will be replaced by lower yielding unpalatable species. The effects of grazing will be more pronounced should it occur at a time of the year when plant recovery from grazing is limited by cold temperatures or drought. The effects of defoliation on soil N transformations are summarised below:

(i) Defoliation which limits or prevents plant recovery and growth will reduce plant uptake of mineral N. The higher available levels of NH_4-N may stimulate nitrification and NO_3-N may be lost from the system through leaching or denitrification. Alternatively if tillering is stimulated by defoliation, soil mineral N levels could fall through increased plant uptake (Floate, 1981).

(ii) Defoliation may expose the soil surface to increased wetting and drying influences. More light and exposure may cause greater temperature fluctuations. Both these effects are likely to stimulate N mineralisation and nitrification.

(iii) If defoliation is severe or is maintained for sustained periods, litter accumulation will decline and mineral N inputs will come increasingly from animal excreta and less from litter breakdown. If sites are repeatedly grazed but excreta deposited elsewhere, the N pool of such a site will steadily decline as the site becomes a N losing system (O'Connor, 1974).

b. The return of nutrients in excreta (urea application)

The major proportion of the N in plant material consumed by grazing animals is returned to the soil in excreta. Between 50-80% of this N will be returned as urine. In cellulose-rich tall tussock grasslands, the proportion of urine in excreted N is likely to be even higher than 80%. Urine N is particularly significant for soil N transformations because it is generally more readily available than faeces N which is mainly bound up in relatively resistant organic fractions that break down only slowly (Floate, 1981).

Urine is not distributed evenly across the range but is concentrated in localised areas. In a comparatively intensively grazed grassland with a stocking rate of 19 sheep ha^{-1}, Jackman (1960) estimated that some 30% of the pasture might receive direct urine applications in a year. Only 15% of the pasture would be directly affected in a year by urine from cows at a stocking rate of 2.5 cows ha^{-1} because of the greater aggregation of N in cattle than in sheep urine (Ball *et al.*, 1979).

The area of soil that shows a biological response to this urea input can be more than double the wetted area. But even taking this into consideration, in an extensively grazed system where stocking densities may be as low as 0.5 sheep ha^{-1}, the proportion of the range receiving urine in a year is very small (O'Connor, 1981).

Urine applications to soil at levels of 30-60g N m^{-2} are likely to result in some or all of the following changes to conservation and redistribution of N in the soil-plant N pool.

(i) A greatly increased proportion of the large quantities of N present in most natural grasslands will enter the rapid cycling pool. This will be particularly important in perennial grasslands which often accumulate large quantities of standing dead plant material and very slowly decomposing litter layers. A study of English hill country showed that 10 times more N became "potentially" available after repeated grazing of a natural grassland compared to the N which became available through mineralisation of annually accumulated plant material (Floate, 1970). Significantly, much of the "potentially" available N is liable to be lost through leaching, volatilisation and uneven surface distribution.

(ii) N redistribution will occur as N is taken from N-donor sites and transported to N receptor sites (O'Connor, 1981). Grazing of N rich nitrogen fixing plants and at sites with N rich foliage such as flush sites, hill foot slopes and urine patches will redistribute some of this N to sites poor in this mineral (Harris and O'Connor, 1980).

(iii) Only a small proportion of the pasture benefits from urine applications. Elsewhere, N will be lost with no replacement. This problem will be particularly severe on extensively grazed pastures where stock camping behaviour may compound the uneven distribution of urine.

(iv) Volatilisation of ammonia from urine patches can remove significant quantities of urine N. Urea hydrolyses to NH_4^+ and NH_3. Soil pH may increase markedly resulting in some NH_3 volatilisation. More than 80% of the nitrogen in urine may be lost by this pathway but losses are usually 50% or less (Woodmansee, 1978). NH_3 volatilisation is greatest in hot conditions with dry, high pH soils. The risk of loss is lowest in acid soils with wide C:N ratios and a cool moist soil environment, conditions which prevail over much of the New Zealand tall tussock grasslands.

(v) The concentrations of N at the site of urine application are likely to far exceed the ability of plants to take up N at that site. Plant uptake of N in most grassland ecosystems is generally much less than 10g N m^{-2} yr^{-1} so application rates of 30-60 gN m^{-2} mean that a large pool of mineral N will be excess to the plants' requirements (Woodmansee *et al.*, 1981).

(vi) Some of the excess NH_4-N may be temporarily immobilised in the soil-root system (Kenney and MacGregor, 1978) or taken up into exchange sites in the soil.

(vii) The remaining NH_4-N excess to the requirements of plants or heterotrophic microorganisms may be nitrified. The NO_3-N produced, and not taken up by plants or microbes, may be lost through leaching or denitrification.

(viii) A secondary effect of urine application to legumes within a natural grassland is that N fixation may cease or decline as the legume host converts to mineral N uptake (Hoglund, 1973).

4.1.3 Grazing, tall tussock grasslands and soil nitrogen.
The dramatic changes in grazing patterns and other cultural modification of New Zealand tall tussock grasslands since European settlement have been reviewed in detail earlier (Chapter 1.6.1). The O'Connor hypothesis that many of the present and former tall tussock grasslands have become N losing systems (O'Connor 1974, 1981) together with the mechanisms by which such N losses might occur have also been extensively described in this earlier Chapter.

Grazing of tall tussock grasslands may lead to changes in soil N transformations in the ways already described. If grazing causes a substantial reduction in above ground green matter (O'Connor, 1971) there will probably be a short term reduction in mineral N uptake until this leaf material is restored. The resultant increase in available NH_4-N in the soil may stimulate nitrification and increase the potential for loss of NO_3-N through leaching and denitrification. If grazing causes a long term reduction in the vigour of these grasslands this potential for N loss will be sustained. Because of the reduction in tall tussock vigour there is also likely to be reduced litter deposition followed by a reduction in organic matter accumulation and possibly a longer term reduction in N mineralisation.

Grazing will certainly increase the proportion of organic N in the soil-plant pool that is converted into the rapid cycling pool should grazing animals consume much of the standing herbage. This will, in turn, increase the likelihood of leakage of N from the system by volatilization of ammonia, by nitrate loss from excretion sites and stock camps where N applications far exceed plant uptake, and through direct loss of N by excretion into waterways.

There have been no field studies that have specifically looked at the effect of grazing of tall tussock grasslands on soil N transformations although a series of laboratory studies have compared N transformations in tall tussock grasslands with the equivalent soil improved by oversowing and topdressing and subject to grazing (Ross *et al.*, 1978; Ross and Bridger 1978b; 1978c).

Factors likely to influence soil N transformations under tall tussock grassland subject to heavy grazing pressure have received attention. Mark (1955), showed from comparison of sites at Maungatua, Otago, that

heavy stocking apparently greatly reduced the canopy and "ground stratum density" of *Chionochloa rigida* in comparison with light stocking on burnt sites. There was little change in "ground stratum density" attributed to stocking rate on unburnt land.

He later made more detailed three-year studies at two sites at Maungatua and three sites on the Old Man Range, Otago (three of his sites, Maungatua 870m, Carrick 1200m, Dunstan 910m are almost coincident with those studied in this chapter), Mark (1965b). After simulated heavy grazing by clipping tussocks each spring, cut tussocks produced only approximately 67% of their original leaf length and approximately 40% of their original weight of clip compared to uncut tussocks during the first season of clipping. These yields declined in subsequent years. After clipping, an increasing number of tillers also failed to recover each year and by the end of the third season a large proportion of all the clipped tillers were dead. The detrimental effect of various management practices including burning and grazing, upon *Chionochloa* tussock vigour were also described (Mark,1965c).

O'Connor (1963), showed that *Chionochloa macra* at high altitudes on the Craigieburn range, Canterbury, was adversely affected by close defoliation without burning. There was a marked reduction in above ground production although two years after defoliation there was an apparent increase in numbers of tillers observed on the cut plants.

O'Connor and Powell (1963), studied *Chionochloa rigida* near Mackenzie Pass at 700m altitude and found that cutting of unburnt tussocks resulted in leaves on cut tussocks remaining significantly shorter than those on uncut ones for 2½ years after modification. They also found that cutting substantially reduced total herbage production over this period. Cutting promoted widespread flower production. They found that no tussock died that was burnt or cut in the 1958 trial. Tussocks were also clipped 15 months after burning and this caused a substantial reduction in total herbage production but did not cause any tussocks to die. This was a rather abnormal treatment. Generally, heavy stocking often follows spring burning and O'Connor and Powell quote the example of an adjacent trial where this had occurred resulting in considerable injury to tussocks and a lasting reduction in tussock density.

Connor *et al.* (1970) detail many field observations of intensive grazing of *Chionochloa* in the absence of burning, resulting in the death or reduction in range condition of these tall tussocks.

Payton and Brasch (1978) investigated the proposal by Mark (1965c) that the decline in tussock vigour after burning was due to a depletion of reserves through fire-stimulated flowering. They found that non-structural carbohydrate reserves in Otago populations of *Chionochloa rigida* and *C. macra* were concentrated in sheath and stem tissue and reached maximum levels in autumn. While burning initially reduced tussock carbohydrate reserves to low levels, these reserves had nearly returned to the levels of adjacent unburnt plants one season after burning. This post-fire regrowth foliage contains higher nutrient levels than unburnt tussock foliage (Williams and Meurk, 1977) and is very attractive to stock. At the only Otago site studied by Payton and Brasch which was open to grazing after burning, most of the tussocks were destroyed by the combination of burning and grazing.

The pattern which emerges from these experiments is that occasional lax browsing of tall tussock, particularly at high fertility or lower altitude sites is unlikely to cause any long term reduction in the vigour of the species. However, under conditions of repeated defoliation and particularly after burning, a reduction in range condition is almost inevitable.

The simulated grazing experiments described in the following section attempted to show how rapidly a similar condition of range degradation can be induced by repeated defoliation, and what changes occur in mineral N levels and nitrifier populations in response to this.

4.2 MATERIALS AND METHODS.

4.2.1 Site preparation.

At each Canterbury and Otago site described in Chapter 3, two 5m x 5m areas were pegged out. These were adjacent to each other across the slope and were sited on grassland of uniform slope and aspect. The areas were separated by a 2m wide buffer zone. One of these pegged areas served as the intact control, the other was defoliated. Because of the large size of each plot, no replication was done at each site. It was thought some treatment replication might be achieved by combining all plots at different sites. The study was also viewed more as a preliminary study to elucidate

general trends rather than a statistically complex study with detailed sampling to clarify a single problem (e.g. Phillips, 1981).

(a) Depletion by defoliation.

In November 1975, all *Chionochloa* plants in the defoliated plots were clipped down to the tussock stumps. Clippings were collected and discarded distant from each site. Ground litter remained undisturbed. Most plants recovered from the initial clipping and were reclipped in December 1976 and at subsequent sampling dates.

This defoliation attempted to simulate heavy repeated tussock grazing by cattle (O'Connor, 1971) and therefore no attempt was made to prevent the colonization of bare inter-tussock spaces by other plants or to exclude animal grazing.

(b) Urination.

To simulate grazing animal urination, urea was applied to 1m x 1m subplots in the lower corners of the intact and defoliated plots at each site between 10-16 December 1976. Whitehead (1970) estimates that between 30 to 60 g N m^{-2} is added in an animal urination. O'Connor (1974) calculated that each cattle urination adds about 135 g N m^{-2}. Urea (176.6g) was dissolved in water (5 litres) to give an application rate of approximately 80 g N m^{-2} to each site, a level between O'Connor's high level and Whitehead's lower level. The urea was sprayed evenly over the subplots from a plastic bottle with a perforated cap.

Urea applications were made on cool, near windless, overcast days at all sites to minimize possible NH_3 volatilization. Soil moisture levels at all sites were moderately high following a month of sustained wet weather (see Chapter 3). Such conditions in combination with the acidic soils which characterize the sites would not favour N volatilization (Ball *et al.*, 1979).

Soil pH levels were monitored immediately after application and at the first sampling. All sites showed a brief pH increase of approximately 0.5 units immediately after application, but no difference was discernible at the next sampling on 10 February 1977.

At the Paddle Hill Creek (PHC) sites a further urea application at 80 g N m^{-2} was made on 18 May 1977. By this time, mineral N levels in the urea subplots had declined almost to the levels of the unamended control plots. Soil was sampled ten days after this date to estimate how rapidly applied urea was transformed and distributed after application.

It was interesting to note that at many of the intact sites, soon after urea was applied to tussocks, the individual plants were preferentially grazed, particularly at the PHC Upper site. Most of this grazing appears to have been by hares. If the urea application increased the tall tussock foliar N concentration (see Chapter 6) this grazing selection for nitrogen rich herbage conforms to similar patterns observed by Mills and Mark (1977) in studies of the takahe in Fiordland and to the browsing of N rich legumes in tall tussock grassland noted by O'Connor (1983).

4.2.2. Soil Sampling

(a) Sampling Dates.

Otago Sites

Sampling was carried out on six occasions between November 1975 and March 1978. Three of these samples were taken in late spring (18/11/75, 10/12/76, 8/11/77) just after snow had melted from the higher altitude plots. The other three samples were taken in autumn (26/4/76, 24/4/77, 2/3/78).

The late spring samples were expected to show mineral N levels and nitrifier numbers which reflected reduced mineralisation and nitrification over the cold wet winter and spring, less any mineral N taken up by tussocks as they began spring growth.

By contrast, it was considered that the autumn samples would show the overall resultant effect of comparatively high mineralisation and nitrification activity in warm summer conditions as well as plant uptake during summer grass growth. It was expected that autumn sampling would provide the best opportunity to test the hypothesis that defoliation and urea application would affect nitrification and nitrifier numbers.

Paddle Hill Creek Sites

Between December 1976 and December 1978 soil samples were collected from these sites on 28 occasions. A much higher sampling frequency was maintained at these more accessible sites to monitor more closely the seasonal mineral N fluctuations.

Sampling every two months was initially planned at PHC for reasons of economy. Major differences between the first (15/12/76) and second (8.2.77) samplings highlighted the need for closer monitoring and from May 1977 to December 1978 approximately monthly samples were taken. Between 12 October 1977 when snow began to melt at the Upper site and 15 December 1977 samples were taken every week to clarify an apparent surge in mineralisation and nitrification in late winter and also to monitor responses to a burning and cultivation trial detailed in Chapter 5.

(b) Sampling procedure.

The sampling, extraction and storage procedure developed in Chapter 2 was used for all the sites.

Precautions to avoid soil contamination between treatments were taken. At each site those areas expected to contain the smallest nitrifier populations were sampled before sites where larger populations were expected. The following sampling sequence was observed:

1. INTACT
2. DEFOLIATED
3. INTACT UREA
4. DEFOLIATED UREA

In addition, between treatments and between sites the soil core sampler was thoroughly washed and flamed with absolute alcohol to sterilize its surface.

Soil sampling of each treatment at all the sites involved taking 10 soil cores of 25 mm diameter from the surface 0-100mm soil layer. These were selected randomly around tussock bases over the plot. The 10 cores were bulked in double plastic bags, crumbled and mixed by hand through the bag. Soils were kept at 4-10^{o}C in a polystyrene chilly bin.

Later each day, on return to Lincoln or the field base, duplicate 20g samples of field moist soil from the composite sample were each added to

200 ml 2M KCl and extracted in the procedure described in Chapter 2. Extracts were stored in sealed plastic bottles at 4°C until their mineral N was analysed the next day or soon afterwards. Soil remaining in the composite sample were sampled in duplicate for determination of soil moisture content, for the preparation of incubation tests for nitrifying bacteria and for soil pH tests.

4.2.3. Analytical Procedures

(a) NH_4-N and NO_3-N.

These were determined by the auto-analysis procedure described in Chapter 2. Steam distillation procedure was also used on the December 1976 samples as a check to confirm the unexpectedly high mineral N levels revealed by auto-analysis of these samples.

(b) NO_2-N.

A quick check was made at each sampling of each soil extract using Griess - Ilosvay reagent (Fred and Waksman, 1928) and spot plates. At no stage was any colour change recorded. It is likely that nitrite is converted rapidly to nitrate in these soils whenever nitrification occurs and that the oxidation of NH_4-N to NO_2-N is the rate-determining step (Bremner, 1965).

(c) Nitrifying bacteria most probable number (mpn).

Estimation of nitrifier mpns for each soil used samples from the chilled soil and followed the dilution procedure of O'Connor *et al.* (1966) where ammonium sulphate medium (Fred and Waksman, 1928) is used as substrate. Five dilutions with five replicates at each dilution were used to test each soil sample. Six dilutions were necessary to measure the high nitrifier populations that developed after urea applications.

Dilution tubes were incubated at 25°C for 35 days. A 50 day incubation period was tested after initial results recorded very low nitrifier mpns. However the longer incubation time caused no increase in mpn values.

A relative humidity of 92% was maintained during incubation. A fan kept air moving throughout incubation to help maintain the aerobic conditions favoured by nitrifiers. After 20 days small quantities of sterilized deionized water were added to each dilution tube to prevent these drying out.

After 35 days, dilution tubes were tested in four columns on ceramic spot plates using the development by O'Connor *et al.* (1966) of Meiklejohn's procedure (Meiklejohn, 1962), outlined in Table 4.1 below.

TABLE 4.1 Methods used in testing dilution tubes for determination of most probable numbers of nitrifying bacteria (O'Connor *et al.*, 1966).

	1	2	3	4
REAGENTS	1. Diphenylamine 2. Concentrated H_2SO_4	1. Sulphamic acid 2. Griess-Ilosvay reagent	1. Sulphamic 2. Diphenyl-amine 3. Conc.H_2SO_4	1. Griess-Ilosvay reagent
TESTS FOR:-	Presence of NO_2^- + NO_3^-	Effectiveness of NO_2^- decomposition by sulphamic acid	Presence of NO_3^- (nitrite oxidisers)	Presence of NO_2^- (ammonium oxidisers)

An estimate of mpn of both ammonium oxidising and nitrite oxidising bacteria was made by comparing positive results in columns 3 and 4 for each dilution against standard mpn tables (Harrigan and McCance, 1976).

Despite the presence of moderate quantities of NO_3-N in most intact grassland sites, nitrifier mpns were generally very low even when high NH_4-N and NO_3-N levels were recorded at these sites such as in December 1976. As well as the possibility of insufficient incubation time discussed earlier, it was also considered that the high pH (pH 7.4) of the ammonium sulphate-calcium carbonate growth medium (Fred and Waksman, 1928), might have inhibited the activity of acidophilic nitrifiers likely to inhabit *Chionochloa* grasslands (Robinson, 1963). When $CaCo_3$ was omitted from the incubation medium its acidity level increased to pH 5.8. Nitrifier mpns were even lower with this acidic medium. It was concluded that low mpns at the intact sites were not experimental artifacts but rather might indicate that NO_3-N persisted in these grasslands for some time after it was produced during short term surges of nitrification in the manner described by Belser (1979).

4.3 RESULTS

In interpreting the results presented for the different sites at different dates it is important to recognize the difficulty in attributing specific differences to specific factors when any change is in fact the resultant of a range of interacting forces as discussed in Section 4.1.1.

There is also a lack of information on what happened between sampling dates so that any interpretation of results as indicating a general trend needs to be treated with caution. This is particularly important for the Otago sites where sampling was only done in spring and in autumn. Results from the more frequently sampled PHC sites do more accurately represent the dynamics of mineral N and nitrifying bacteria populations in these tall tussock grassland soils.

4.3.1. Pooled Otago results.

Mineral N levels and nitrifying bacteria mpns are pooled for all the Otago sites at the different sampling dates in Table 4.1. Paired statistical analysis using a students t test (Snedecor and Cochrane, 1969) carried out on the data was impeded by variation between sites (used as replicates) exceeding variation between treatments and sampling dates, particularly in nitrifying bacteria mpns.

Highest NH_4-N and NO_3-N levels were recorded in the December 1976 sampling and lowest levels of these variables were recorded in autumn samples at the intact plots.

Responses to urea addition at intact plots were highly variable in nitrifier mpns with an overall significant increase in NH_4-N oxidisers only at the 2 March 1978 sample. There was no increase of overall significance in NH_4-N or NO_3-N levels in response to this urea addition.

Defoliation caused no increase of overall significance in levels of NH_4-N or NO_3-N. There was a widely variable response to defoliation in nitrifier mpns of overall significance only in NH_4-N oxidisers at the 26 April 1976 and 24 April 1977 samplings. Urea addition to defoliated plots on 10 December 1976 caused significant increases in NH_4-N, NO_3-N levels and NO_2 oxidiser mpns throughout the pooled plots at the 24 April 1977 sampling, while NH_4-N oxidiser mpns were very variable in their response compared with the intact controls.

TABLE 4.1: Mean ammonium and nitrate levels (μg g^{-1} soil) and nitrifying bacteria populations (most probable number g^{-1} soil) over eight Otago *Chionochloa* sites at six autumn and spring sampling dates.

Treatment Type & Date of Implementation	Spring 18 Nov. 1975	Autumn 26 April 76	Spring 10 Dec. 76	Autumn 24 April 77	Spring 8 Nov. 77	Autumn 2 March 78
INTACT						
NH_4-N	22.6±2.7a	18.5±1.2	57.7±6.3	14.0±1.2	16.6±1.0	7.2±1.3
NO_3-N	5.9±1.3	4.3±0.5	16.4±2.1	2.4±0.3	4.1±0.3	3.3±0.4
NH_4-ox	-	39.4±24.6	63.3±56.8	2.1±0.9	1.0±0.5	3.9±1.8
NO_2-ox	-	28.1±19.3	7.4±5.0	.7±0.3	0.3±0.2	1.0±0.4
INTACT + UREA						
(NH_4-N				15.0±1.6	17.0±1.8	7.6±1.3
80gNm^{-2}) NO_3-N				2.3±0.2	4.3±0.2	3.3±0.5
on 10/12/76						
NH_4-ox				63.2±47.1	455.0±394.2	30.1±15.2*
NO_2-ox				9.7±6.0	6.6±4.8	2.7±1.1
DEFOLIATED						
on NH_4-N		23.4±1.8	60.9±7.9	14.7±2.1	15.6±2.1	6.9±1.2
8/11/75 NO_3-N		4.6±	16.0±3.4	2.3±0.4	3.9±0.3	3.4±0.3
NH_4-ox		92.4±41.6*	112.7±64.4	5.8±2.0*	0.8±0.6	17.8±13.4
NO_2-ox		33.5±19.2	8.8±5.7	2.5±1.3	0.1±0	2.1±1.3
DEFOLIATED						
on NH_4-N				29.3±6.1**	22.4±6.6	10.8±3.5
8/11/75 NO_3-N				12.3±7.8*	6.2±0.7**	3.8±0.6
+ UREA NH_4-ox				1783.1±1624.3	64.9±58.2	122.1±63.3*
80gNm^{-2} NO_2-ox				168.8±59.7	1.2±0.7	8.5±4.1
on 10/11/76						

a = means of all eight sites ± standard error. The significance of differences between the intact control and each of the other treatments, determined by Student's t-test, is given by *,** = P<0.05, 0.01

NH_4-ox = Ammonium oxidisers
NO_2-ox = Nitrite oxidisers.

TABLE 43: Correlation coefficients (r) for soil chemical properties and environmental factors and mean mineral nitrogen levels (μg g^{-1} soil) and nitrifier mpn for all sampling dates for the pooled Otago sites.

Source of variation	Mineral Nitrogen		Nitrifier mpn	
	NH_4^+-N	NO_3^- -N	NH_4^+ oxidisers	NO_2^- oxidisers
Annual precipitation (mm)	0.37	0.31	0.20	0.11
Altitude (m)	0.19	0.10	0.53	0.08
pH	-0.51	-0.81*	-0.07	-0.07
Dry Bulk density	-0.08	-0.18	-0.63	-0.73*
Organic C	0.58	0.94**	0.07	0.01
Total N	-.24	0.49	0.62	0.43
C/N	0.41	0.65	-0.30	-0.19
$SO_4^=$-S	0.55	0.80**	0.58	-0.03
Truog P	-0.10	-0.22	-0.40	-0.39
Olsen P.	-0.55	-0.79*	-0.04	-0.02

*, ** = $P < 0.05$, 0.01. Degress of freedom = 6.

In the defoliated urea plots, at the next sampling (8 November 1977) only NO_3-N levels remained significantly higher than controls and at the 2 March 1978 sampling both NH_4-N oxidiser and NO_2-N oxidiser mpns showed significantly higher levels overall.

Correlation coefficients between soil chemical and environmental factors and mean mineral N levels and nitrifier mpns for all sampling dates at the pooled Otago sites are presented in Table 4.3. There is little overall correlation between these factors which again highlights the high variability between sites. NO_3-N levels are negatively correlated with pH and Olsen-P contrary to expectations, and positively correlated to organic C levels and sulphate sulphur.

Clearly pooling of results from each Otago site is unsatisfactory to elucidate seasonal patterns at the different sites, because site seasonal differences are masked by overall high variability. Each Otago site was then considered individually.

4.3.2 Individual Otago sites.

(a) Soil moisture content.

Soil moisture contents at each sampling date for intact and defoliated treatments at each site are presented in Figure 4.3a, and 4.3b. At the Alta 1, Moonlight, Tawhiti and Carrick sites defoliation caused virtually no change in soil moisture content compared to the intact controls. The Dunstan site showed significant ($P<0.05$) differences between the two treatments only at two of the five sampling dates.

Soils at the Maungatua site showed significant differences at four of the five sampling dates. Soils in the defoliated treatment of this site were wetter than the intact treatment soils in December 1976 and November 1977 and drier in April 1976 and March 1978.

Both the high altitude Pisa and Alta 2 sites had a comparatively low soil moisture content which became significantly lower after defoliation at the April 1977, November 1977 and March 1978 sampling dates.

Three patterns seem apparent. At lower altitude sites, defoliation seems to have caused little change in soil moisture content. Colonization of these sites by other plants was widespread and tall tussock regrowth here

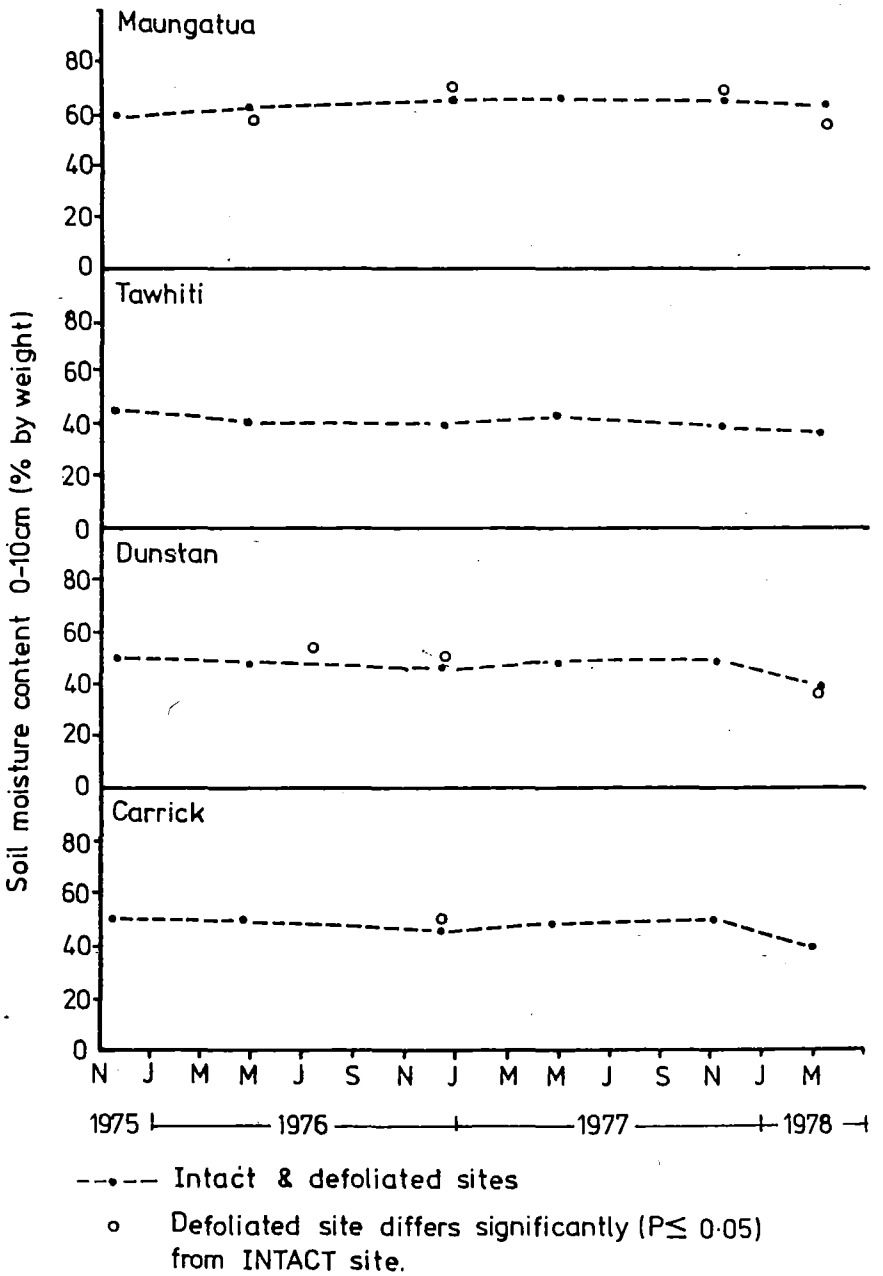

Figure 4.3a Soil moisture content - Otago sites

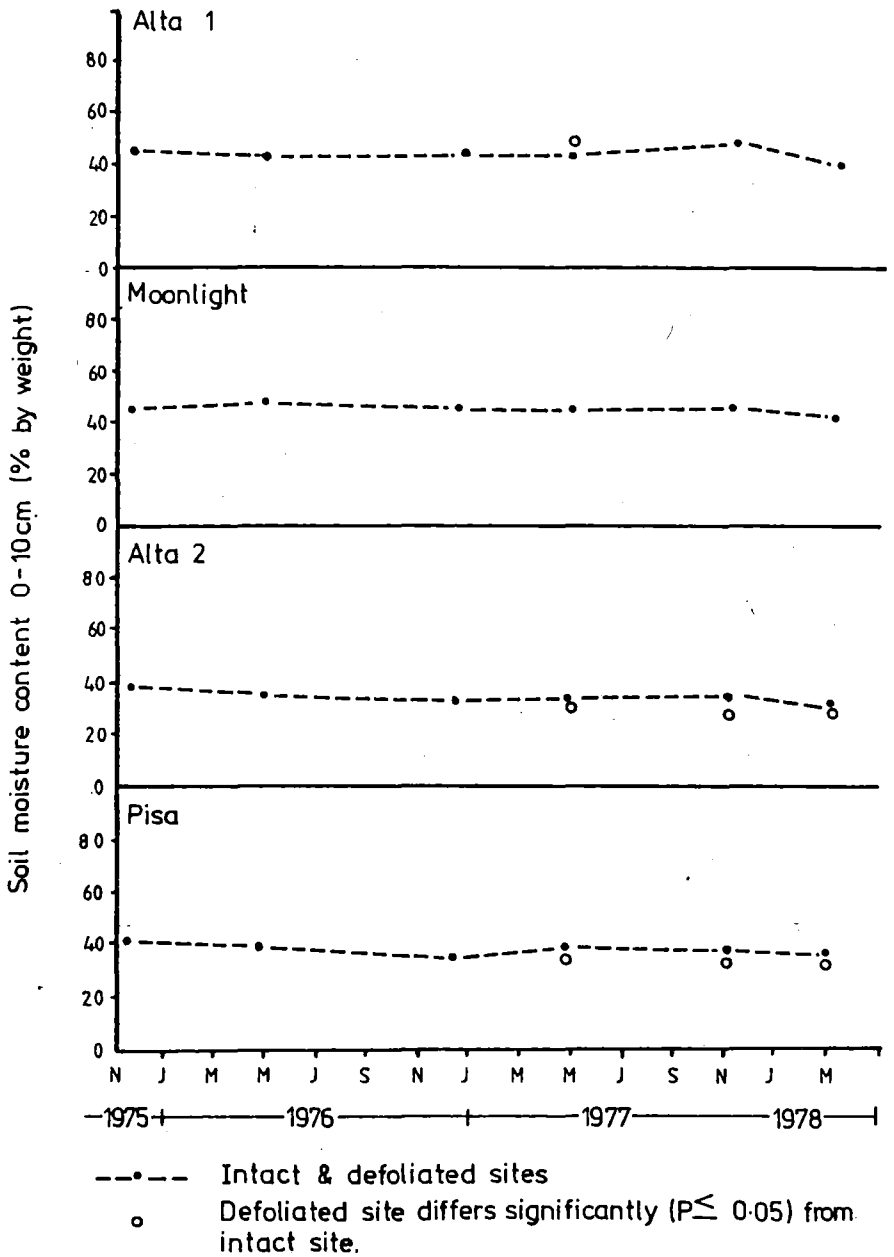

Figure 4.3b Soil moisture content - Otago sites (cont'd)

was fairly vigorous despite repeated defoliation. Plant growth at these sites is likely to have maintained transpiration rates and prevented soil moisture content increases.

Results from the Maungatua site, where only sparse recolonization of defoliated areas took place, suggest that evaporation rates may have been higher in summer from the exposed soil. Soil moisture levels increased at the defoliated treatment over winter/spring when little evaporation is likely to have occurred and transpiration losses were reduced because of tussock defoliation.

The reduction in soil moisture content with defoliation at the Pisa (1640m altitude) and Alta 2 (1530m) sites is consistent with increased evaporation from exposed soil surfaces. At these sites clipping generally caused *Chionochloa macra* tussocks to die with little subsequent colonization by other species. High evaporation rates would result from the high wind velocity at these sites. Mark (1965a) demonstrated that wind velocity increases markedly with altitude on the nearby Old Man Range where wind appears to outweigh both temperature and fog in determining how evaporation increases with altitude. Summer evaporation at 1590m altitude on the Old Man Range was 89% that recorded at Alexandra (300m altitude) while at 1220m and 910m, lower down the range, it was only 81% and 74% the rate recorded at Alexandra. Orientation of the Pisa Range and the Mt Alta Range is similar to that of the Old Man Range and wind-induced evaporation patterns are likely to be similar.

(b) Soil mineral nitrogen and nitrifying bacteria.

Results for the bulked samples from treatments at each Otago site are presented for the different sampling dates in Figures 4.4 to 4.11.

(i) Intact plots.

Soil NH_4-N levels for all the intact Otago treatments ranged generally between 10 $\mu g\ g^{-1}$ to a maximum of 82 $\mu g\ g^{-1}$ while NO_3-N levels ranged from 2 $\mu g\ g^{-1}$ to 28 $\mu g\ g^{-1}$.

Particularly high levels of mineral N were recorded in the December 1976 samples from all sites, with the peak being most pronounced at the Maungatua site and less marked at the high altitude Pisa site.

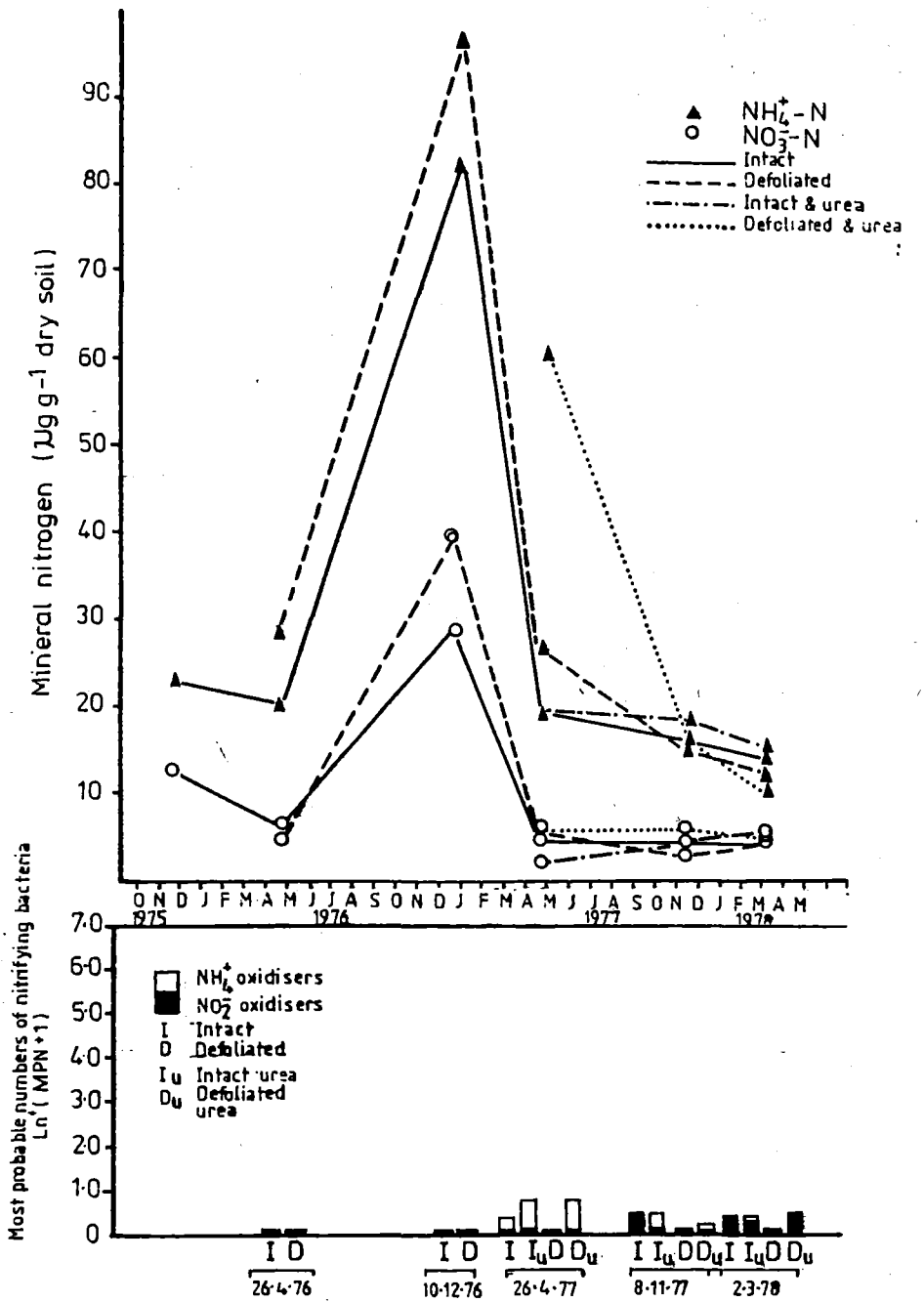

Figure 4.4 Maungatua site. Mineral -N levels and nitrifying bacteria numbers at six sampling dates 1975-1978.

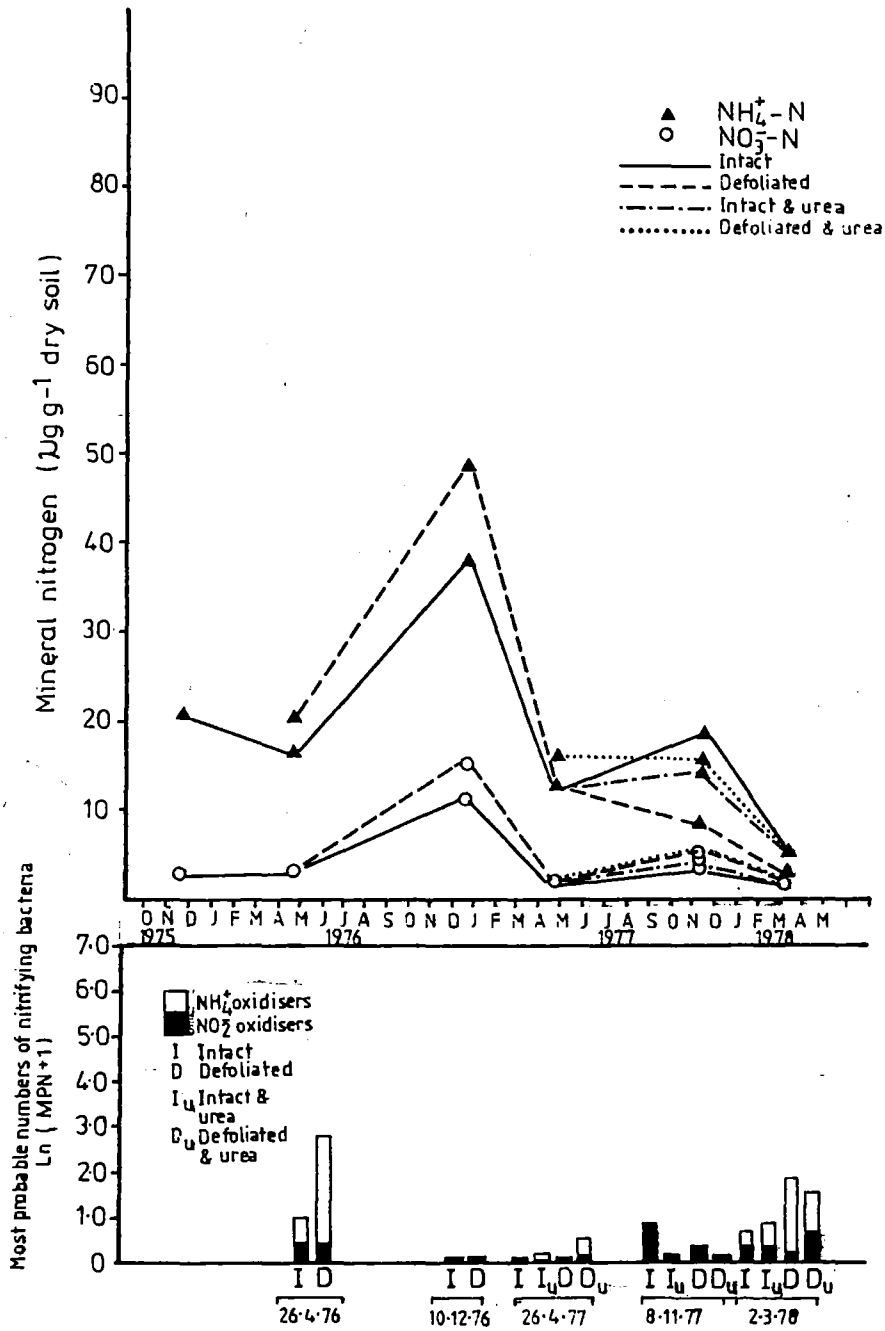

Figure 4.5 Tawhiti Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates 1975-1978.

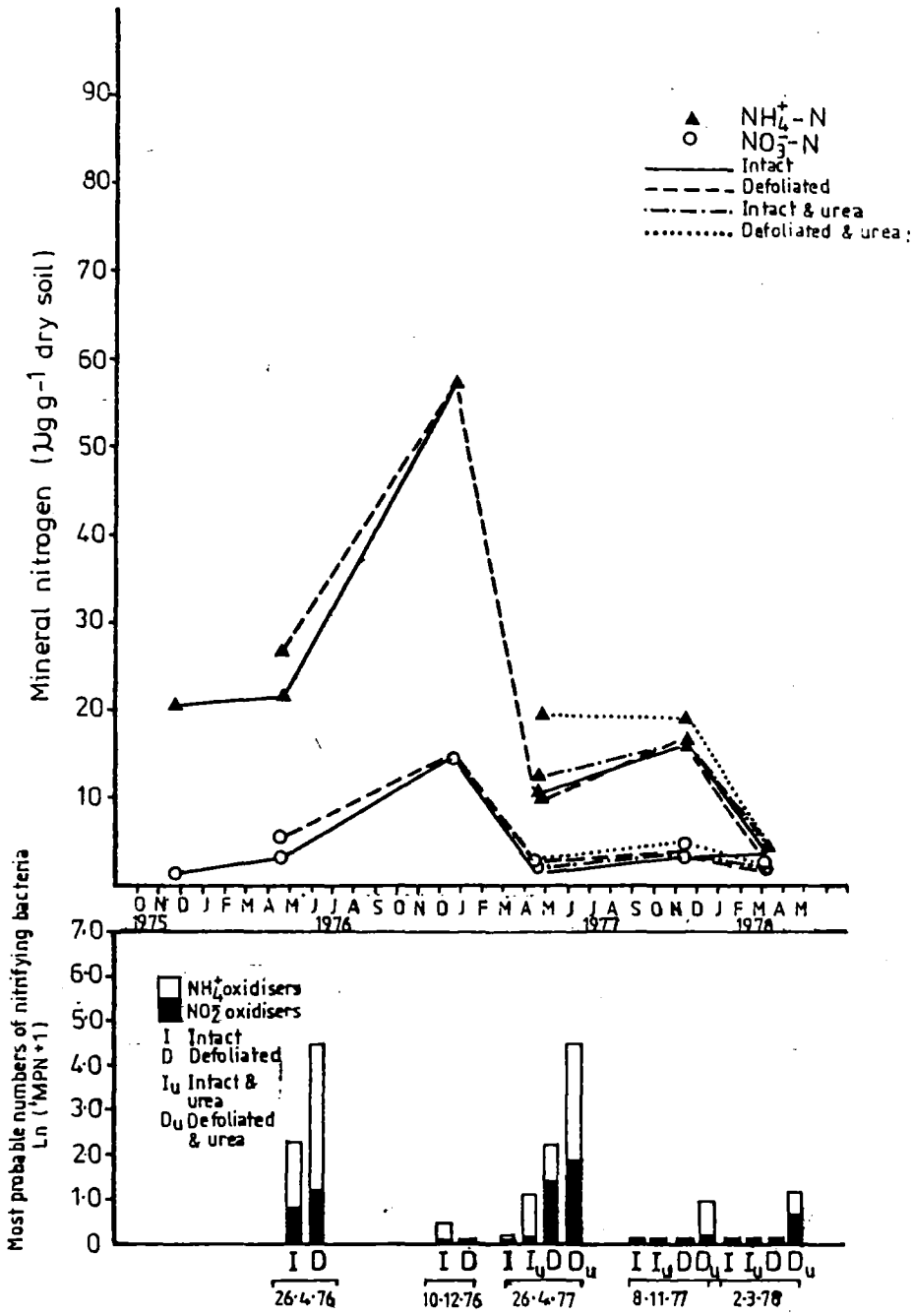

Figure 4.6 Dunstan Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates 1975-1978.

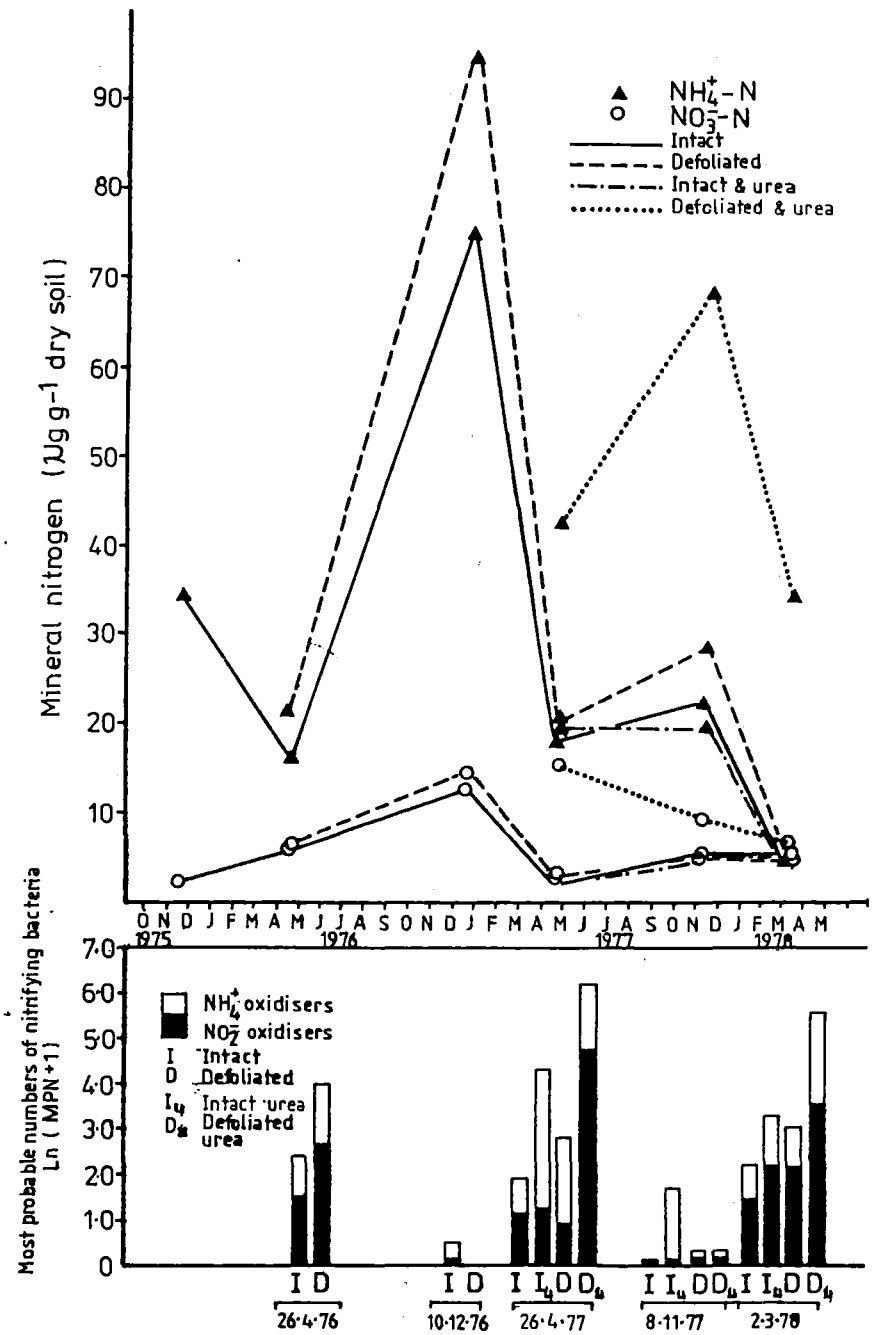

Figure 4.7 Carrick Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates 1975-1978.

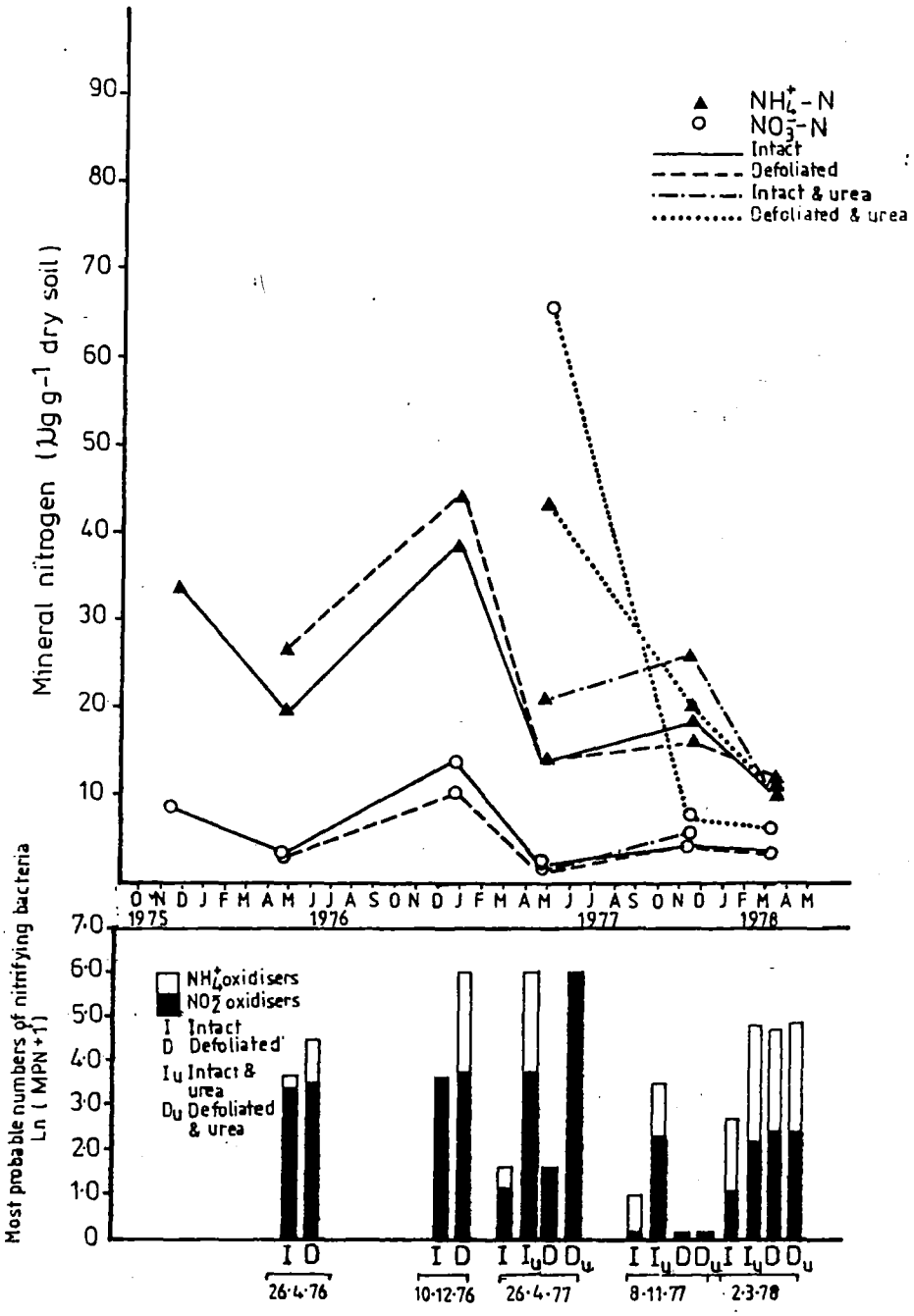

Figure 4.8 Pisa Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates 1975-1978.

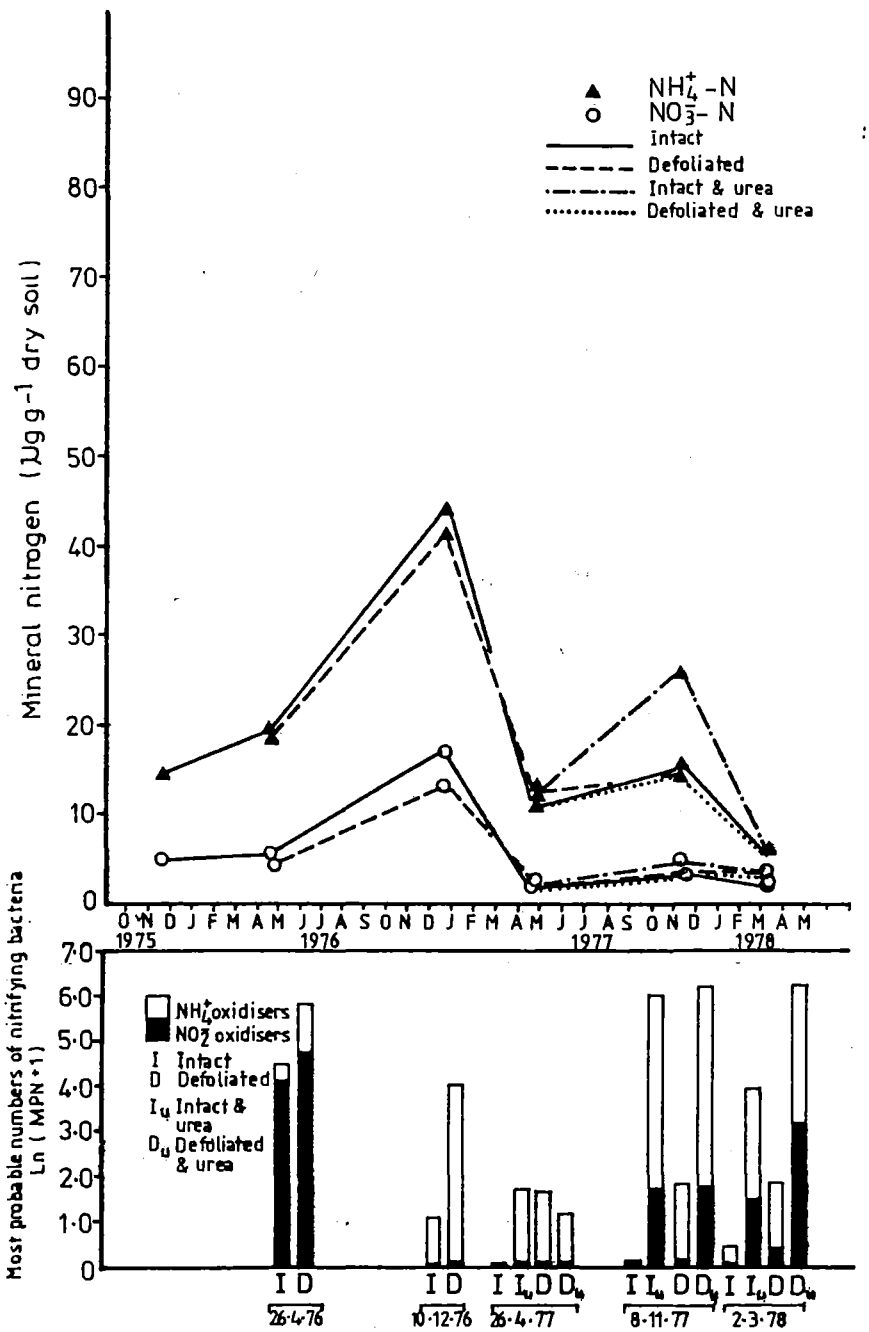

Figure 4.9 Alta 1 Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates. 1975-1978.

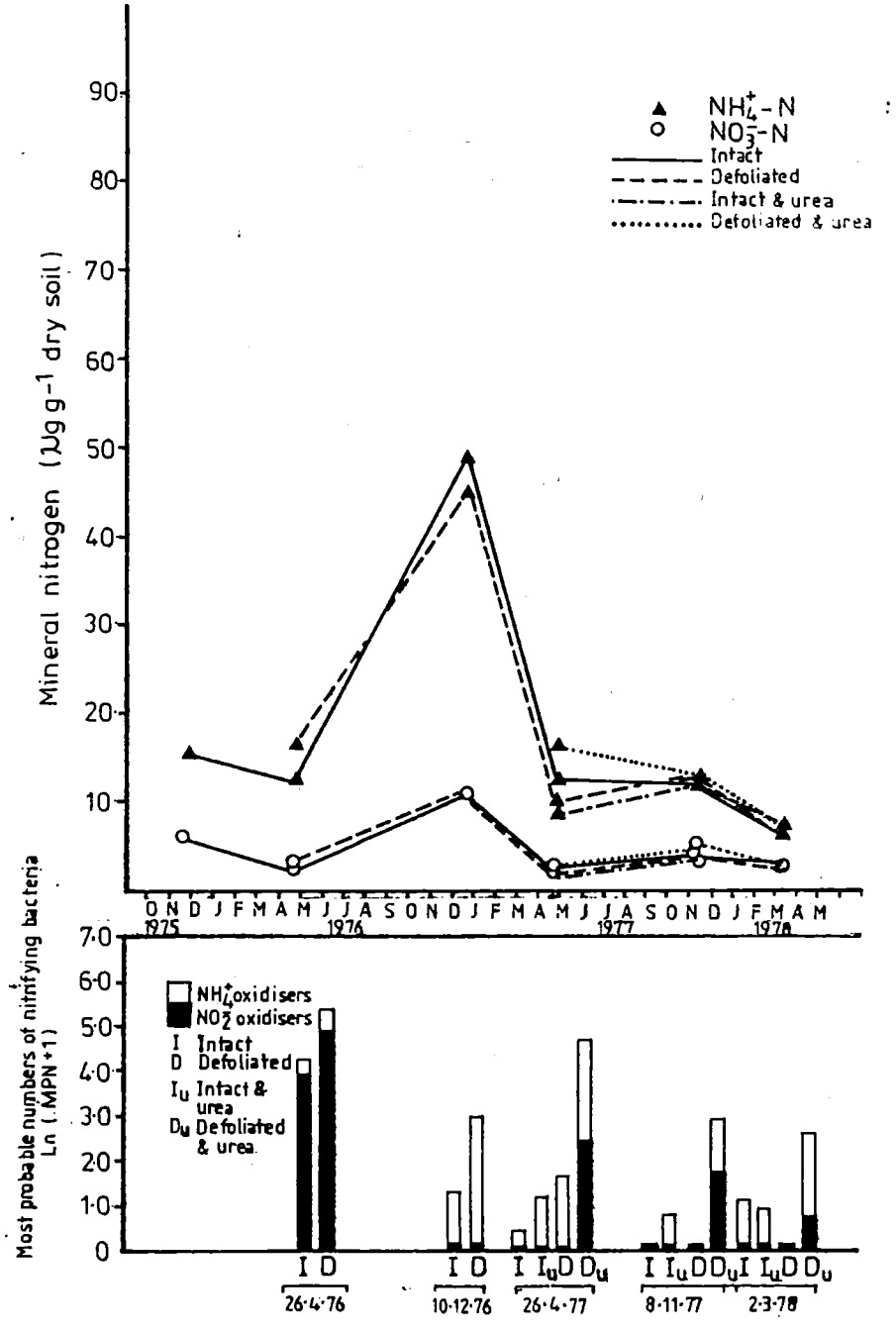

Figure 4.10 Moonlight Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates. 1975-1978.

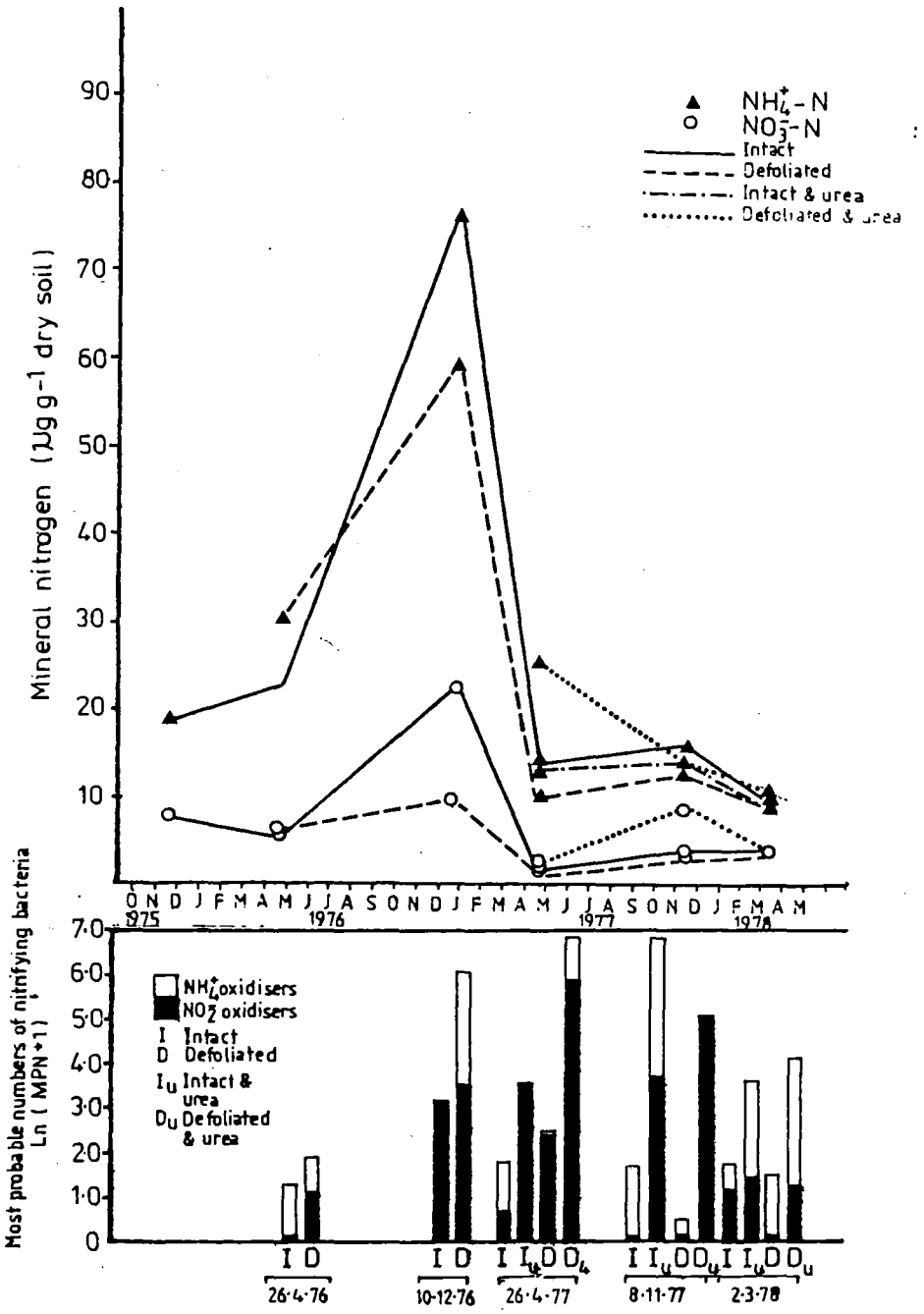

Figure 4.11 Alta 1 Site. Mineral-N levels and nitrifying bacteria numbers at six sampling dates. 1975-1978.

Data presented in Chapter 3 showed a sustained dry period over October and November 1976. Even prior to this dry period, rain and snowfalls were well below average for most of 1976 through the South Island high country. Over the fourteen days prior to the December 1976 soil sampling, steady rain fell throughout the high country. This wetting of soils previously subject to a sustained dry spell is considered likely to have caused rapid mineralisation and nitrification and produced the high recorded levels of NH_4-N and NO_3-N. A surge in mineralisation following alternate drying and wetting has been widely demonstrated (Birch, 1960; Campbell *et al.*, 1975; Ross and Bridger, 1978a).

These high levels of mineral N were not accompanied by measured high populations of nitrifying bacteria in any of the intact grasslands. This may indicate the analytical problems of the mpn technique described by Belser and Schmidt (1978) and discussed further in Chapter 8.

Alternatively the high NO_3-N levels recorded may have persisted from a flush of nitrification at the onset of the rain whereas the nitrifying bacteria which had produced the nitrate had themselves declined in number in the intervening two weeks since rain first fell. Belser (1979) describes the persistence of nitrate in soil in this manner.

Another explanation might be that some of the NO_3-N was released physically through microbial death and other disruption during the dry period in the manner described by McGill *et al.* (1981).

At the other sampling dates, nitrifying bacteria mpns in intact grasslands ranged from being generally low at the Tawhiti, Maungatua and Dunstan sites to moderate to high levels at the high altitude Pisa and Alta 2 sites. There was considerable variation between sampling dates and only the Maungatua site failed to reveal any significant levels of nitrifiers at all dates.

The overall pattern of nitrifying bacteria activity, suggests that activity is moderate to high in intact *Chionochloa macra* grasslands and low to moderate in the lower altitude *Chionochloa rigida* grasslands apart from the organic, wet Maungatua site where little nitrification activity is evident. The Carrick mixed *Chionochloa macra/C. rigida* site exhibits nitrifier activity intermediate between the high and low altitude sites.

(ii) Defoliated plots.
Soil mineral N levels showed a variable response to defoliation treatment in comparison to the intact control sites. Some sites showed a marked increase in NH_4-N levels when first sampled (e.g. Pisa, Maungatua, Carrick, Tawhiti) but these increased levels fell to the levels of the intact control as sampling progressed over the 28 month period. NO_3-N levels were slightly elevated on occasions at the Carrick, Tawhiti and Maungatua sites in response to defoliation.

The two steepland sites (Moonlight, Dunstan) exhibited little difference in NH_4-N or NO_3-N levels between intact and defoliated treatments.

At the Alta 1 and Alta 2 sites defoliation caused a reduction in NH_4-N and NO_3-N levels compared to intact controls, particularly in the 10/12/76 samples.

In contrast to the variable response to defoliation in soil mineral N levels, soil nitrifier mpns were markedly enhanced at most dates by defoliation at all sites, except the Maungatua. These enhanced numbers of nitrifiers at defoliated sites continued for the full 28 months of sampling after the initial defoliation at the Pisa, Carrick and Alta 1 sites, for 22 months at the Dunstan, Moonlight and Alta 2 sites and for 5 months at the Tawhiti site.

A priority to emerge from this study was the need to more closely monitor soil mineral N levels and nitrifier mpns immediately after defoliation. This work is described in Chapter 5.

(iii) Intact urea plots.
Soil mineral N levels did not change appreciably after urea addition on 10/12/76 at intact sites except at the Alta 1 and Pisa sites. Here, a marked increase in NH_4-N was recorded on 26/4/77 and 8/11/77. No corresponding increase in NO_3-N levels were found at these sites.

Nitrifier numbers showed a major response to urea application at all three sampling dates at the Alta 1, Alta 2 and Pisa and Carrick sites. A slight increase in nitrifier numbers was recorded at the steepland Moonlight and Dunstan sites while no response was recorded at the low altitude Tawhiti and Maungatua sites.

At the steepland sites, downslope flushing of applied urea (rapidly hydrolysed to NH_4-N) may account for the small response in nitrifier numbers. If the steepland sites are excluded, there is a clear altitudinal pattern in nitrifier response to urea applied to intact grassland. The sites at 850m altitude (Tawhiti) and 870m (Maungatua) showed no increase in nitrifier mpns. All the higher sites, both of *Chionochloa rigida* and *C. macra* grasslands, showed increases in nitrifier numbers in response to applied urea.

(iv) Defoliated urea plots.

Responses to urea addition to defoliated sites paralleled responses to urea addition at intact control sites. The three high altitude defoliated plots on flat to rolling ground; Pisa, Alta 2 and Carrick all showed moderate to high levels of NH_4-N after urea application accompanied by major increases in NO_3-N levels and nitrifier mpns.

The two steepland sites, Moonlight and Dunstan, showed slight increases in NH_4-N and NO_3-N levels and major increases in nitrifier mpns in defoliated plots after urea addition compared to the defoliated control. The Alta 1 site showed no increase in NH_4-N and NO_3-N but a major increase in nitrifier mpns. The Tawhiti site showed a slight NH_4-N and nitrifier mpn increase but no NO_3-N increase.

There was a major increase in NH_4-N only in 26/4/77 samples from the Maungatua site. This was accompanied by a slight increase in NO_3-N but no response in nitrifier mpns.

Colonization of defoliated sites by other species at low altitude sites, but not at high altitude sites, may account for much of the variation in responses. Post-defoliation colonization was vigorous at the Maungatua, Tawhiti and Alta 1 sites. These colonizing species may have mopped up much of the applied N at these sites. By the first and subsequent samplings mineral N levels would have been reduced at these sites, although elevated nitrifier numbers persisted at the Alta 1 and Tawhiti sites but not at the Maungatua site where nitrification is likely to have been limited by factors other than substrate availability.

The two steepland sites showed a major response to applied N with an increase in nitrifier mpns. Mineral N produced from the applied urea may have been flushed downhill. At the three high altitude flat sites mineral N (particularly NO_3-N) persisted at highest levels in the 26/4/77 samples then declined steadily probably as it was leached from the system since plant uptake is likely to have been limited here by sparse post-depletion colonization.

4.3.3 Paddle Hill Creek soil moisture levels.

The intensive PHC study elucidated the seasonal fluctuations in soil moisture content, mineral N levels and nitrifier populations in response to defoliation shown initially in the less frequently sampled Otago sites.

Seasonal soil moisture contents of intact grasslands at the three PHC sites are presented in Figure 4.12. Soil moisture contents of the adjacent defoliation treatments at each site are shown where these differ significantly ($P < 0.05$) from the intact controls.

Mean soil moisture content throughout the sampling period is in the order Upper > Lower > Mid sites. All sites show highest soil moisture content in mid-winter (July) and lowest levels generally in late-summer (February, March).

Defoliation caused the most frequent changes in soil moisture levels at the Lower site, soil moisture content being significantly lower than at the intact plot on 16 of the 28 sampling dates. These depressed soil moisture levels with defoliation treatment occurred in all seasons at this site.

The Mid defoliated plot had a significantly lower moisture content than its adjacent intact control at only four of the sampling dates, all during mid-summer.

The Upper defoliated plot showed significantly higher moisture content compared to its intact control plot at five of the sampling dates during the mid-winter periods of both 1977 and 1978.

Removal of dense tussock cover at the Lower site probably caused greater evaporation from the exposed surface soil here. Tussock cover at the Mid site was sparse, even prior to defoliation which may have therefore caused little increase in evaporation rates at this site.

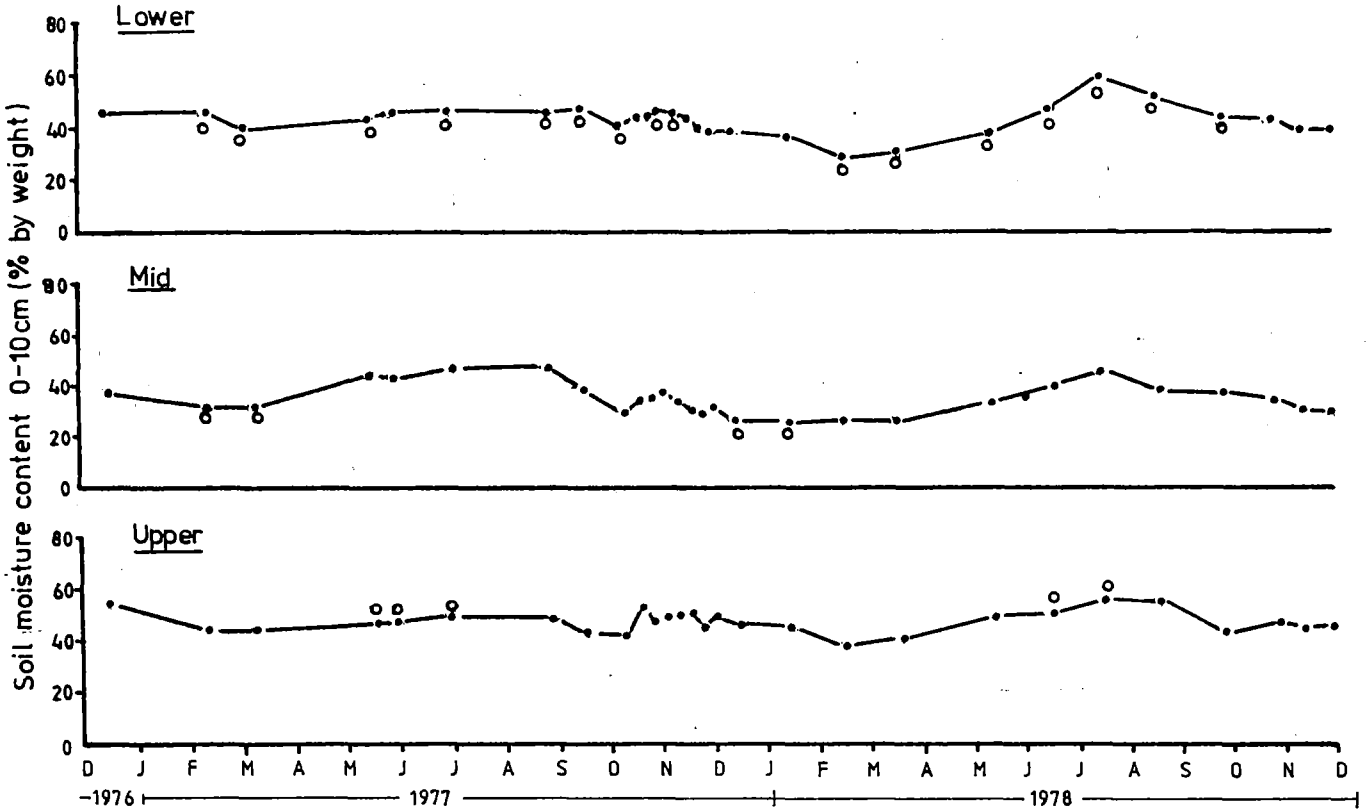

Figure 4.12 Fluctuations in soil moisture content - Paddle Hill Creek

•—• Intact and Defoliated

o o Defoliated site differs significantly (P 0.05) from Intact site.

Higher wind speeds prevail at the Upper site compared with the two lower sites (Williams, 1977). This would be expected to increase evaporation and reduce soil moisture content after defoliation as suggested for the Otago sites. However, defoliation caused little change in soil moisture content at the PHC Upper site. Possibly evaporation was prevented by the deep litter layer that persisted here even after defoliation. A deep litter layer was not present at the Otago high altitude defoliated sites. The increase that occurred in soil moisture content at the defoliated PHC Upper site in both winter seasons, prior to continuous snow cover, may result from a reduction in transpiration losses after tussock defoliation.

TABLE 4.4: Correlation coefficients (r) for soil moisture contents (% by weight) and mineral nitrogen levels ($\mu g\ g^{-1}$) and nitrifier mpn for the intact and defoliation treatments at the three Paddle Hill Creek sites over all sample dates.

	Site	Treatment	Mineral Nitrogen		Nitrifying Bacteria mpn	
			NH_4^+ -N	NO_3^--N	NH_4^+ oxidisers	NO_2^- oxidisers
	Lower	Intact	0.66**	0.42*	0.44	0.22
	Mid	Intact	0.55**	0.36	0.21	0.12
	Upper	Intact	0.58**	0.27	0.26	0.12
Soil	Lower	Defoliated	0.60**	0.55**	0.14	0.38
Moisture	Mid	Defoliated	0.60**	0.35	0.37	0.05
Content (% by weight)	Upper	Defoliated	0.61**	0.33	0.26	0.05

*, ** = $P < 0.05, 0.01$.

Degrees of freedom (a) mineral nitrogen = 28

(b) nitrifying bacteria mpn = 15

Table 4.4 presents correlation coefficients between soil moisture content, mineral N levels and nitrifying bacteria mpns. for all the PHC intact and defoliated treatments at all dates. NH_4-N levels at all sites show positive correlation with soil moisture content at these sites. NO_3-N levels show significant correlation with soil moisture content only in the intact and defoliation treatments at the Lower site.

4.3.4 Paddle Hill Creek soil mineral N levels and numbers of nitrifying bacteria.

(a) Intact sites.

Figures 4-13, 4-14 and 4-15 show mineral N levels and nitrifier mpns. for the three PHC sites at the 28 sampling dates.

Frequent samples taken between 12 October and 15 December 1977, show the short term fluctuations in NH_4-N and NO_3-N that occurred. Prominent features of the results are as follows:

1. NH_4-N and NO_3-N levels are high at all sites in the 15 December 1976 samples, a pattern also found at Otago sites sampled at this time. The particularly heavy December rainfall of this year following a dry period was outlined in Chapter 3 (Figures 3.6a, 3.6b) and high levels of mineral N resultant from this dry-wet period have been discussed earlier in Section 4.3.2.

2. Soils at all sites showed other peak levels of NH_4-N in the mid to late winter months during both years of sampling. During the winter period increases in levels of NO_3-N generally lagged slightly behind NH_4-N increases at all sites. There is, however, no evidence that nitrification of the large pool of winter-produced NH_4-N was delayed until warmer temperatures prevailed in spring or summer.

3. Nitrifier mpns were rather erratic for all sites. At the Lower site there was a moderate increase in nitrifiers in early October 1977, which coincided with peak NO_3-N levels of 10 $\mu g\ g^{-1}$. At this site nitrifier mpns. were high for most of the 1978 sampling period. At the Mid site, although there were very low nitrifier mpns throughout 1977, moderate levels were recorded in late winter 1978 which coincided with peak NO_3-N levels of 13 $\mu g\ g^{-1}$.

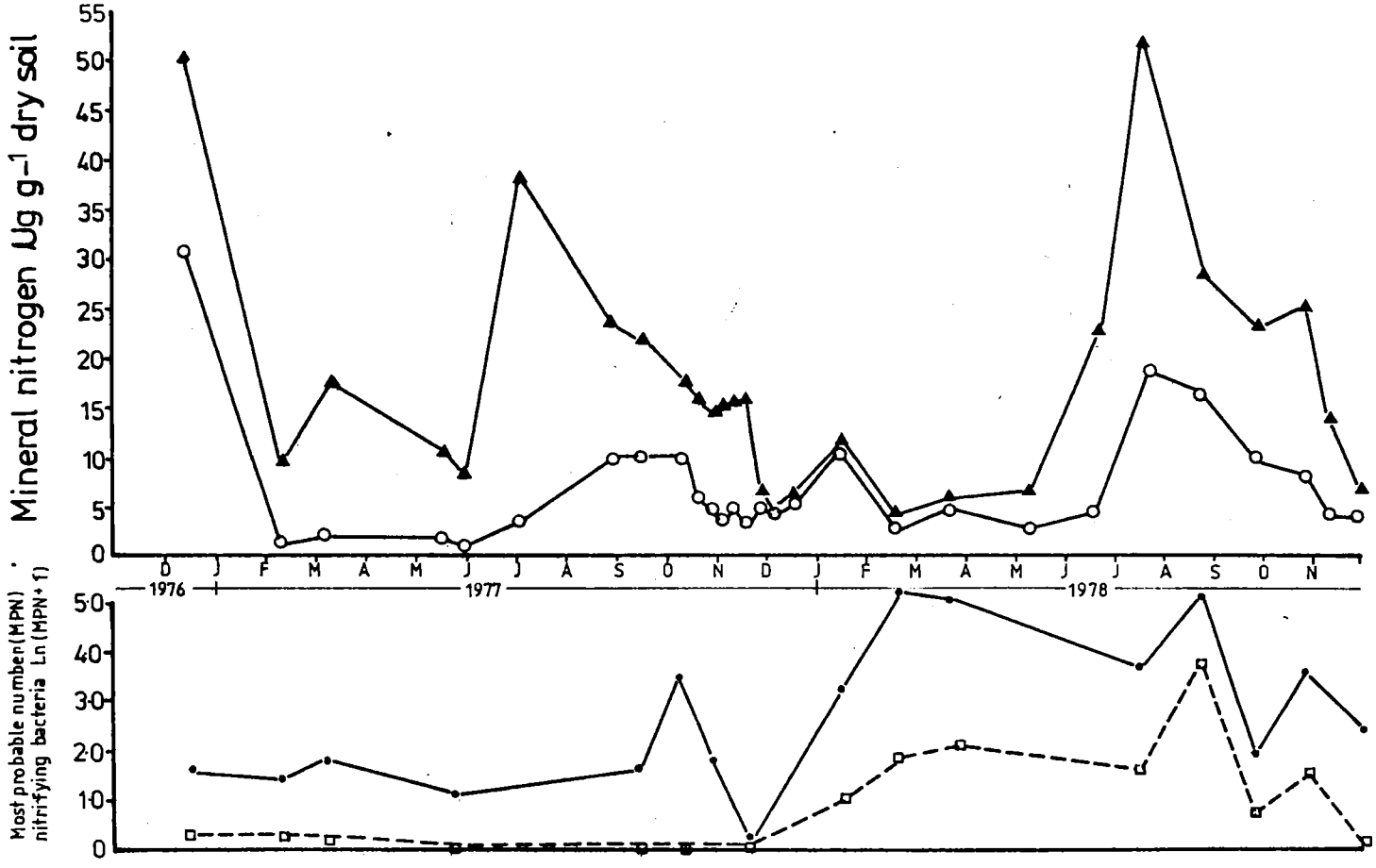

Figure 4.13 PHC Lower Site:-Intact. Seasonal variation in mineral-N levels and nitrifying bacteria numbers 1976-1978. ▲—▲ NH_4-N o—o NO_3-N •—• NH_4^+ oxidisers ▫--▫ NO_2^- oxidisers.

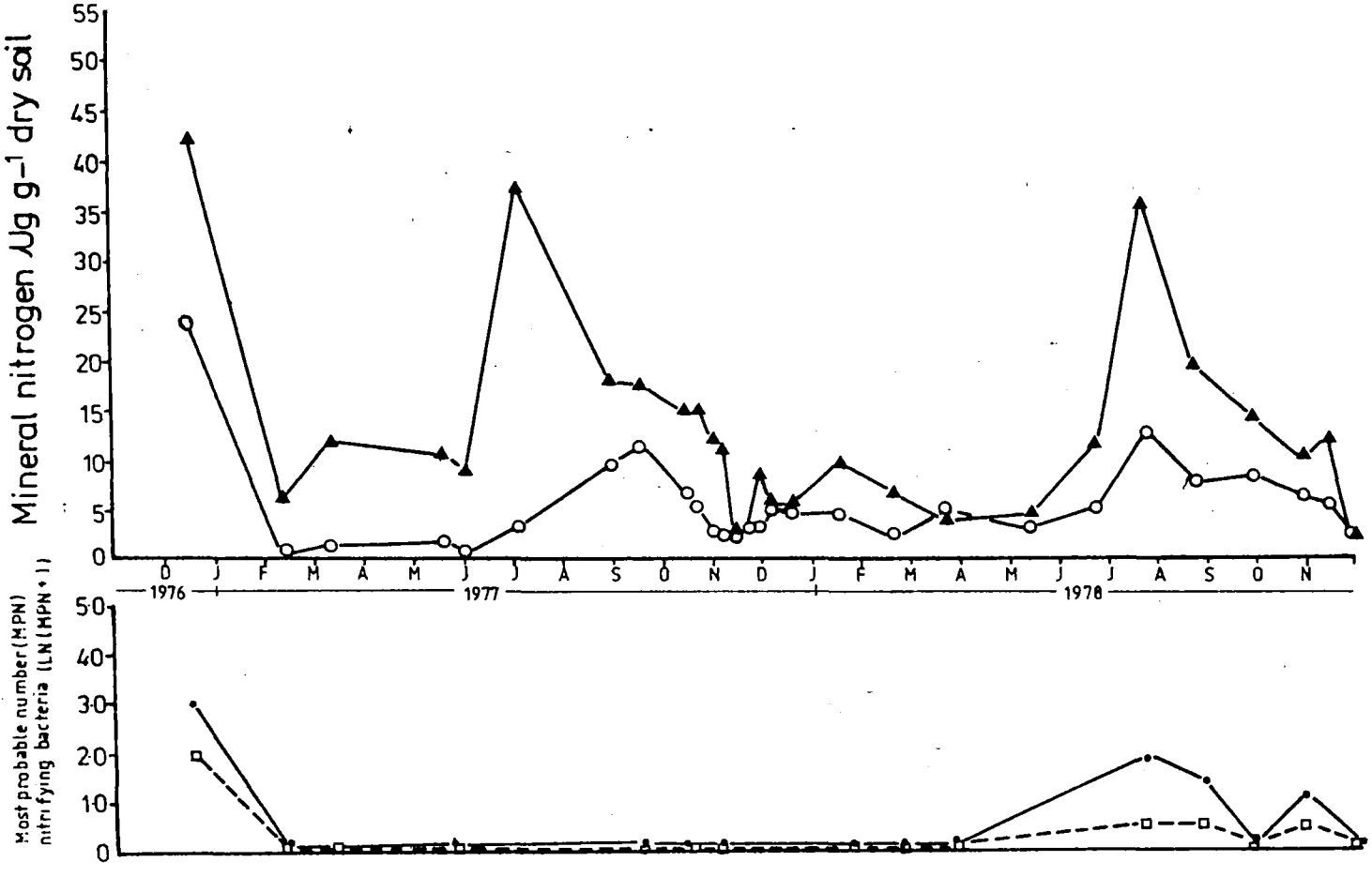

Figure 4.14 PHC Mid site:-Intact. Seasonal variation in mineral-N levels and nitrifying bacteria numbers 1976-1978. ▲—▲ NH_4-N, o—o NO_3-N, •—• NH_4^+ oxidisers, □---□ NO_2^- oxidisers.

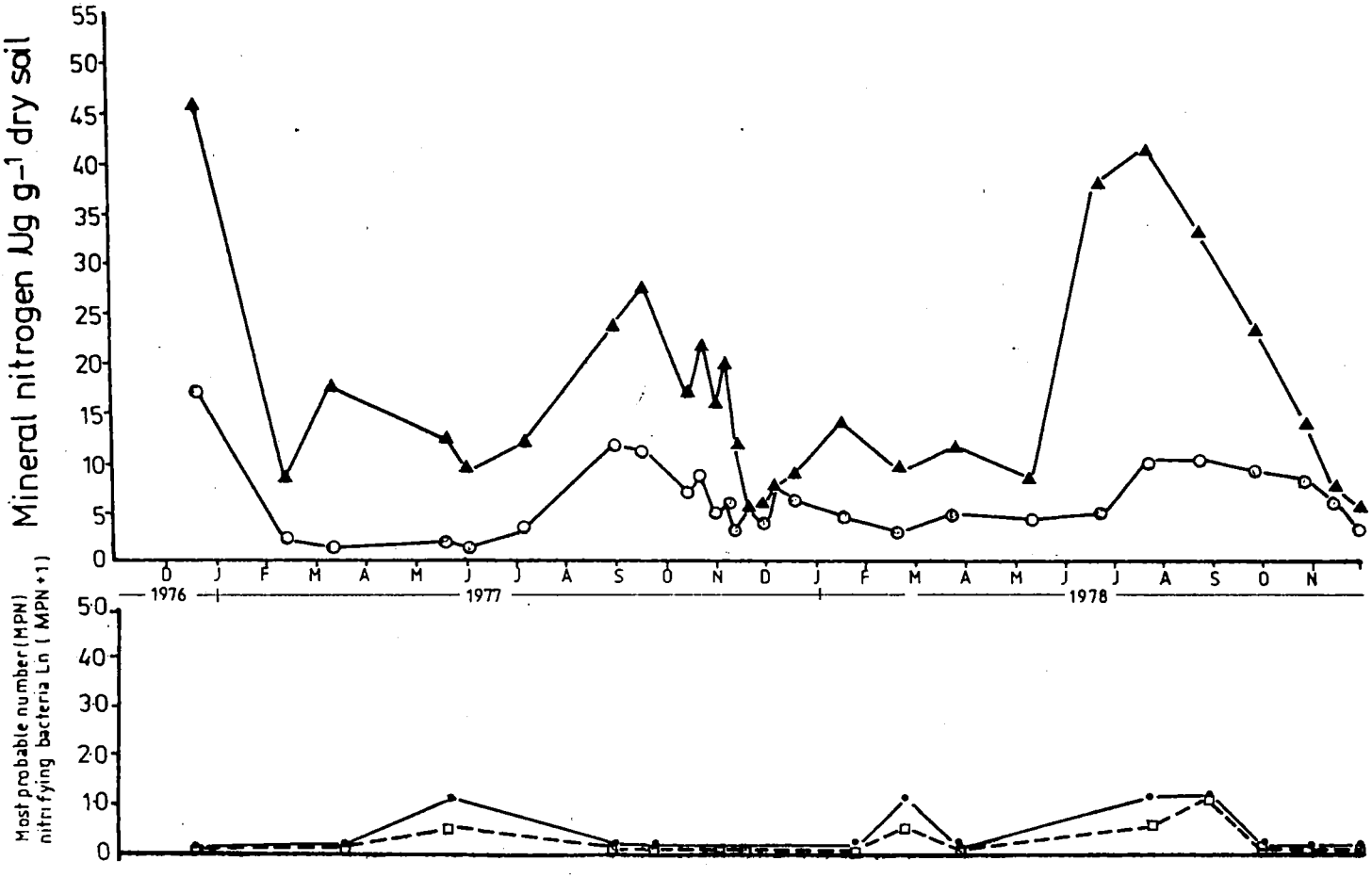

Figure 4.15 PHC Upper site:-Intact. Seasonal variation in mineral-N levels and nitrifying bacteria numbers 1976-1978. ▲—▲ NH_4-N, o—o NO_3-N, •—• NH_4^+ oxidisers, □---□ NO_2^- oxidisers.

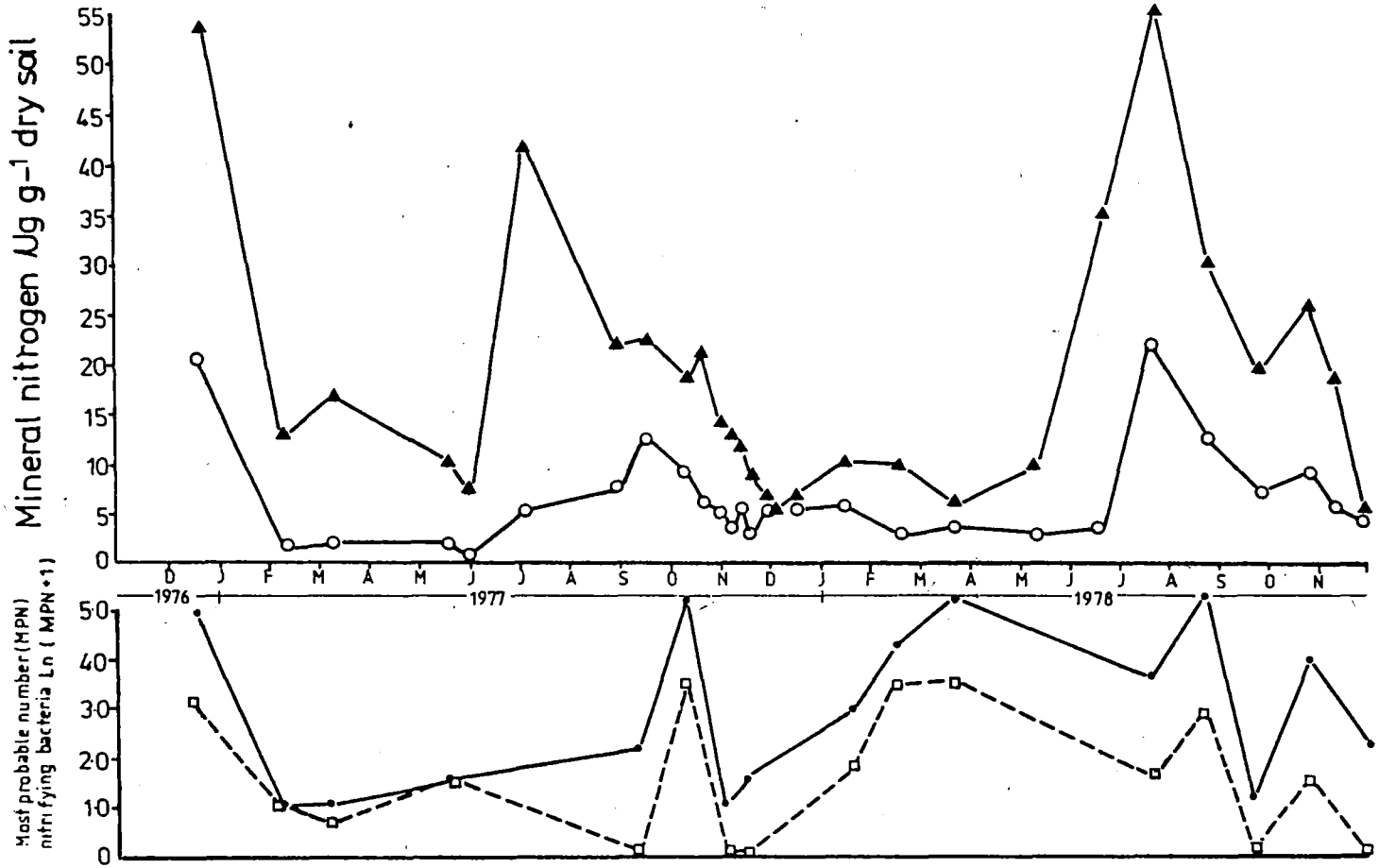

Figure 4.16 PHC Lower site:-Defoliated. Seasonal variation in mineral-N levels and nitrifying bacteria numbers 1976-1978. ▲—▲ NH_4-N, o—o NO_3-N, •—• NH_4^+ oxidisers, □--□ NO_2^- oxidisers.

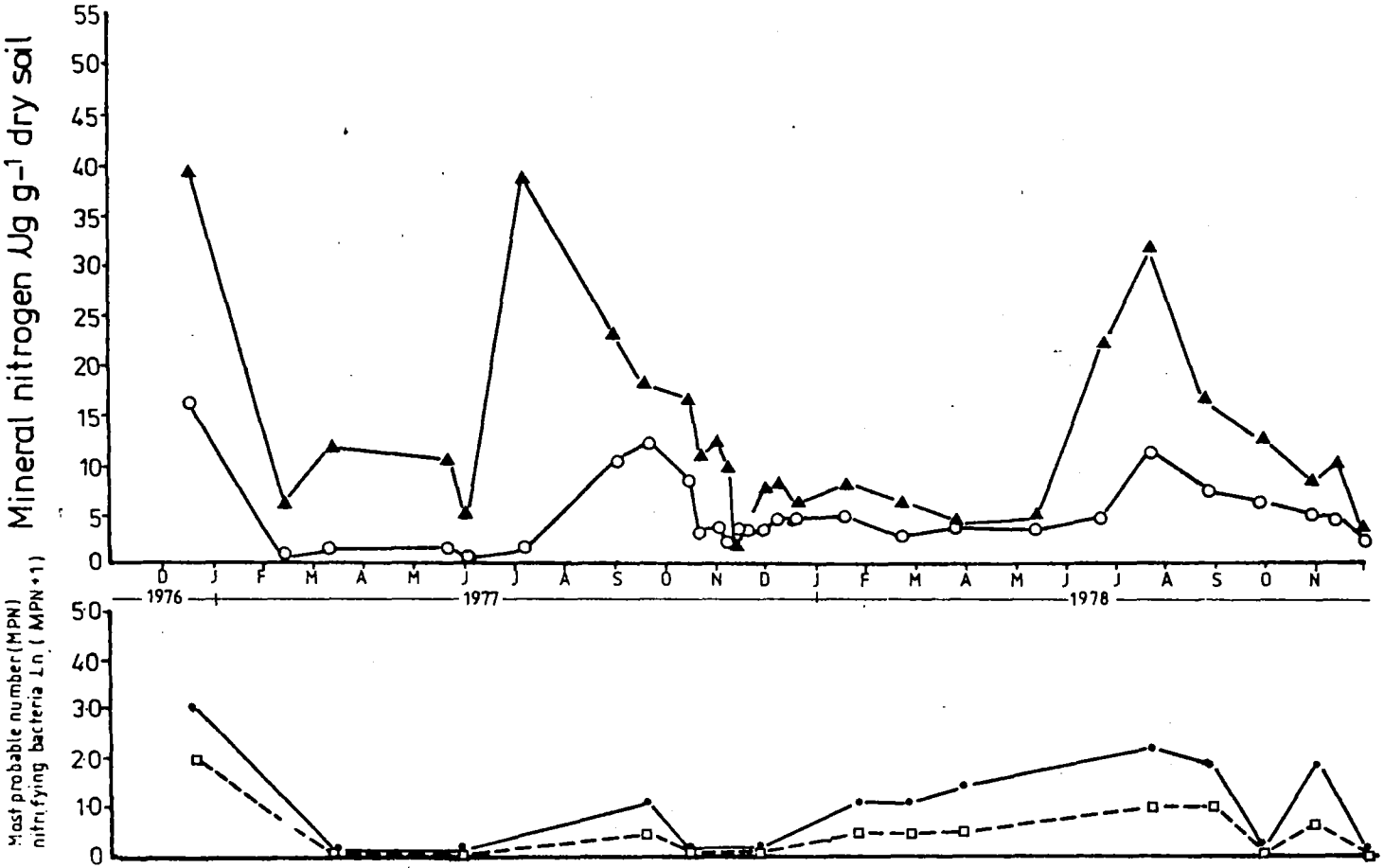

Figure 4.17 PHC Mid site:-Defoliated. Seasonal variation in mineral-N levels and nitrifying bacteria numbers 1976-1978. ▲—▲ NH_4-N, o—o NO_3-N, •—• NH_4^+ oxidisers, □--□ NO_2^- oxidisers.

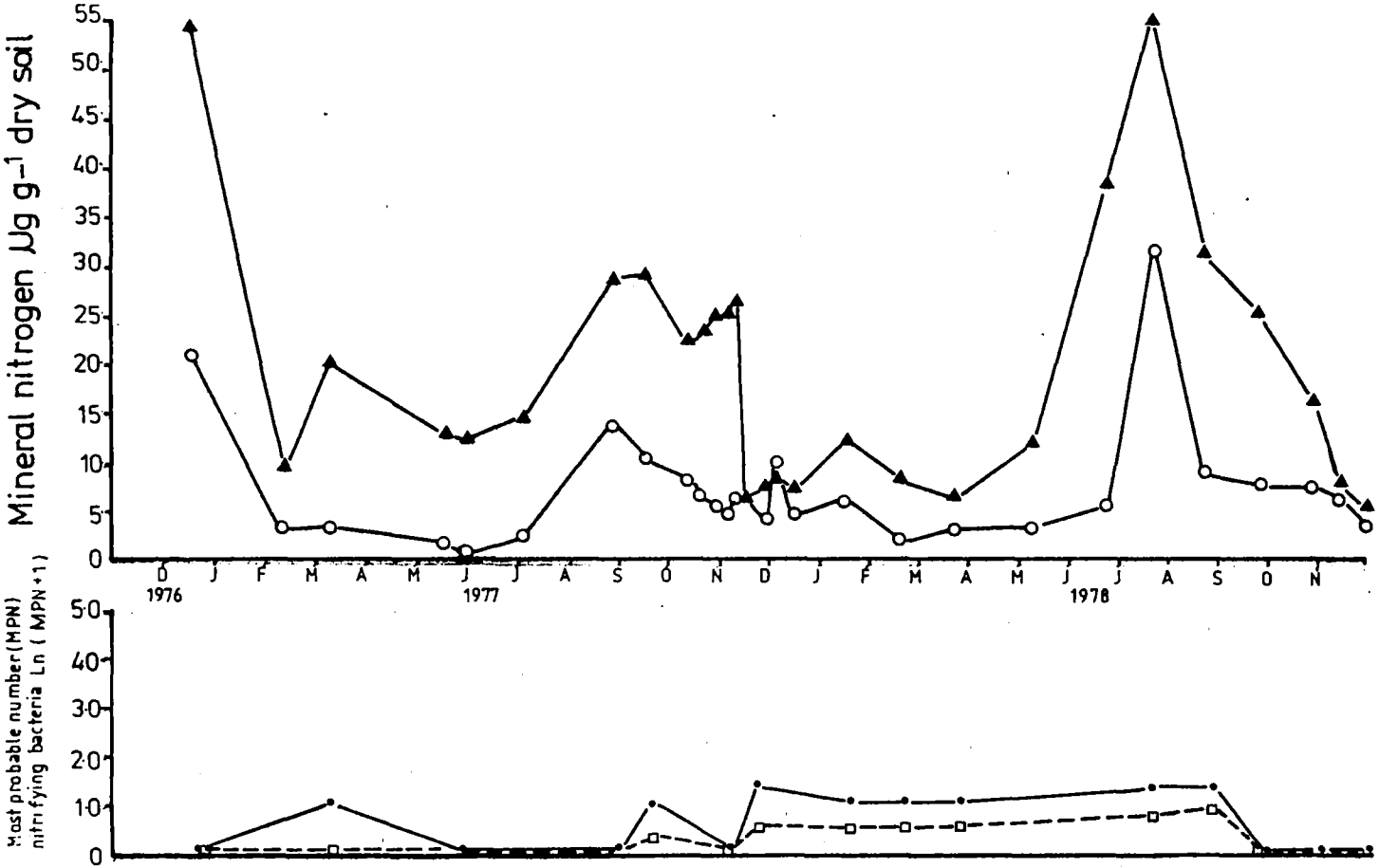

Figure 4.18 PHC Upper site:-Defoliated. Seasonal variation in mineral-N levels and nitrifying bacteria numbers 1976-1978. ▲—▲ NH_4-N, o--o NO_3-N, •—• NH_4^+ oxidisers, □--□ NO_2^- oxidisers.

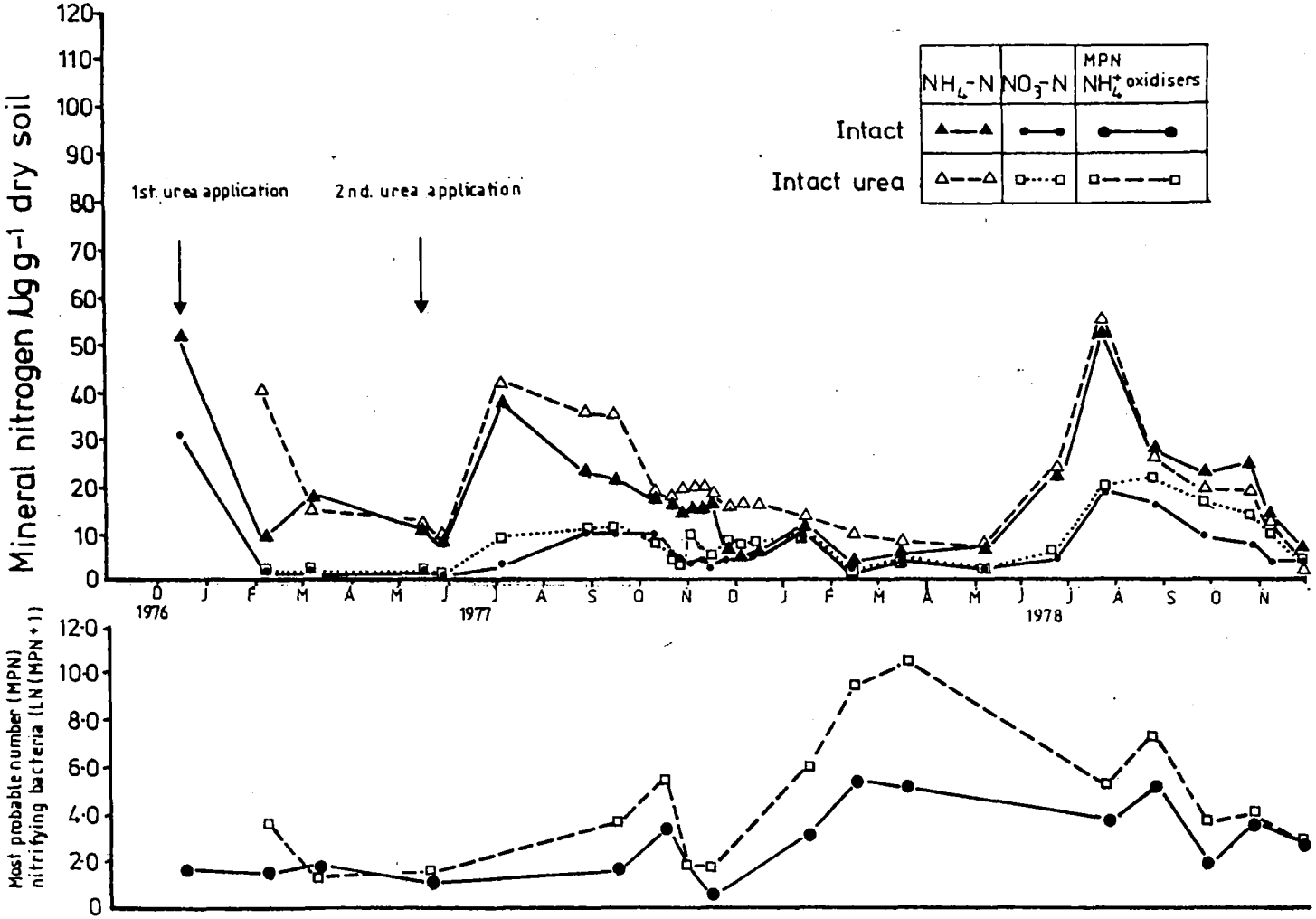

Figure 4.19 PHC Lower site:-Intact. Seasonal variation in mineral-N levels and NH_4^+ oxidiser numbers after urea application (80g Nm^{-2})

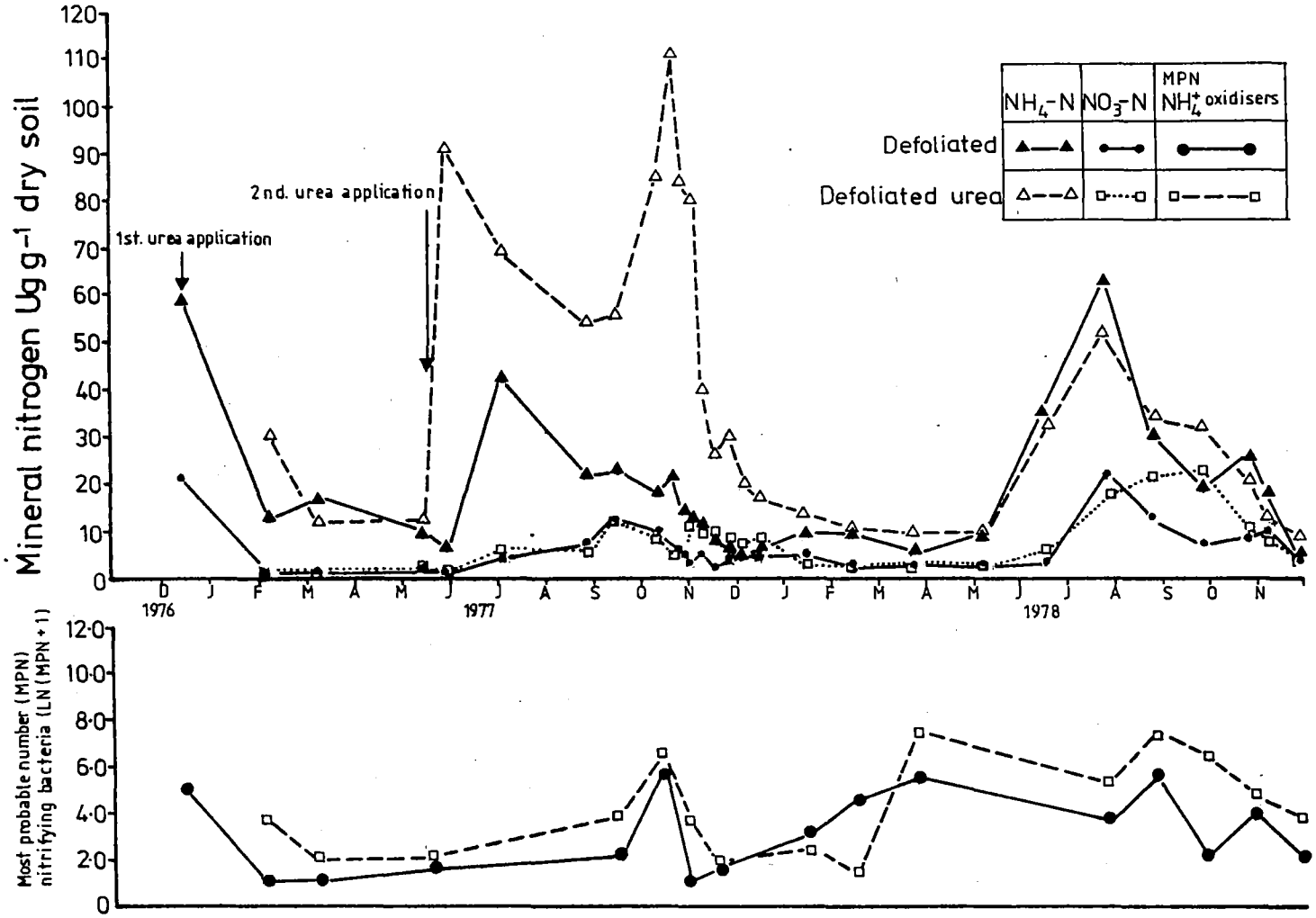

Figure 4.20 PHC Lower site:-Defoliated. Seasonal variation in mineral-N levels and NH_4^+ oxidiser numbers after urea application (80g Nm^{-2})

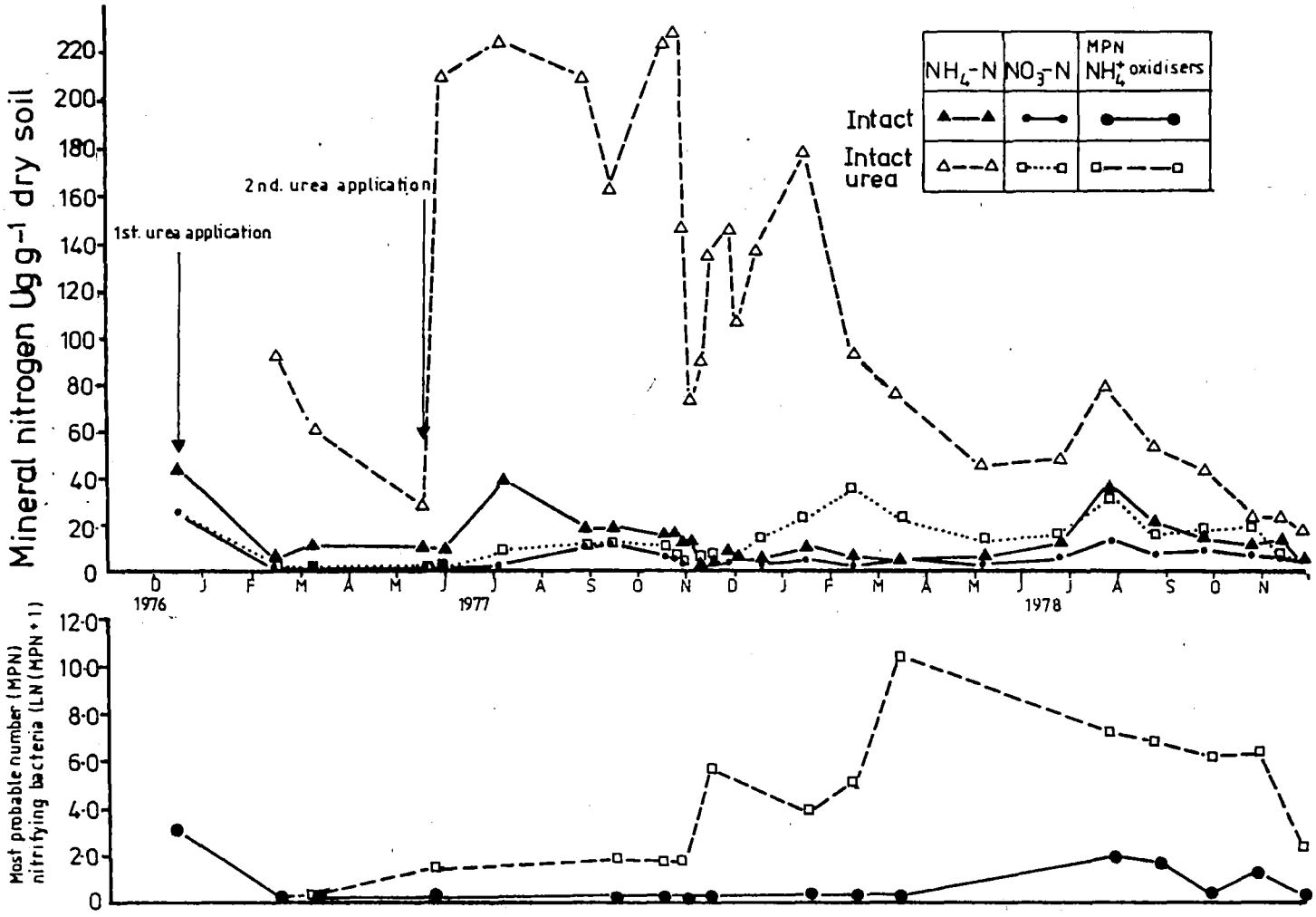

Figure 4.21 PHC Mid site:-Intact. Seasonal variation in mineral-N levels and NH_4^+ oxidiser numbers after urea application (80g Nm^{-2})

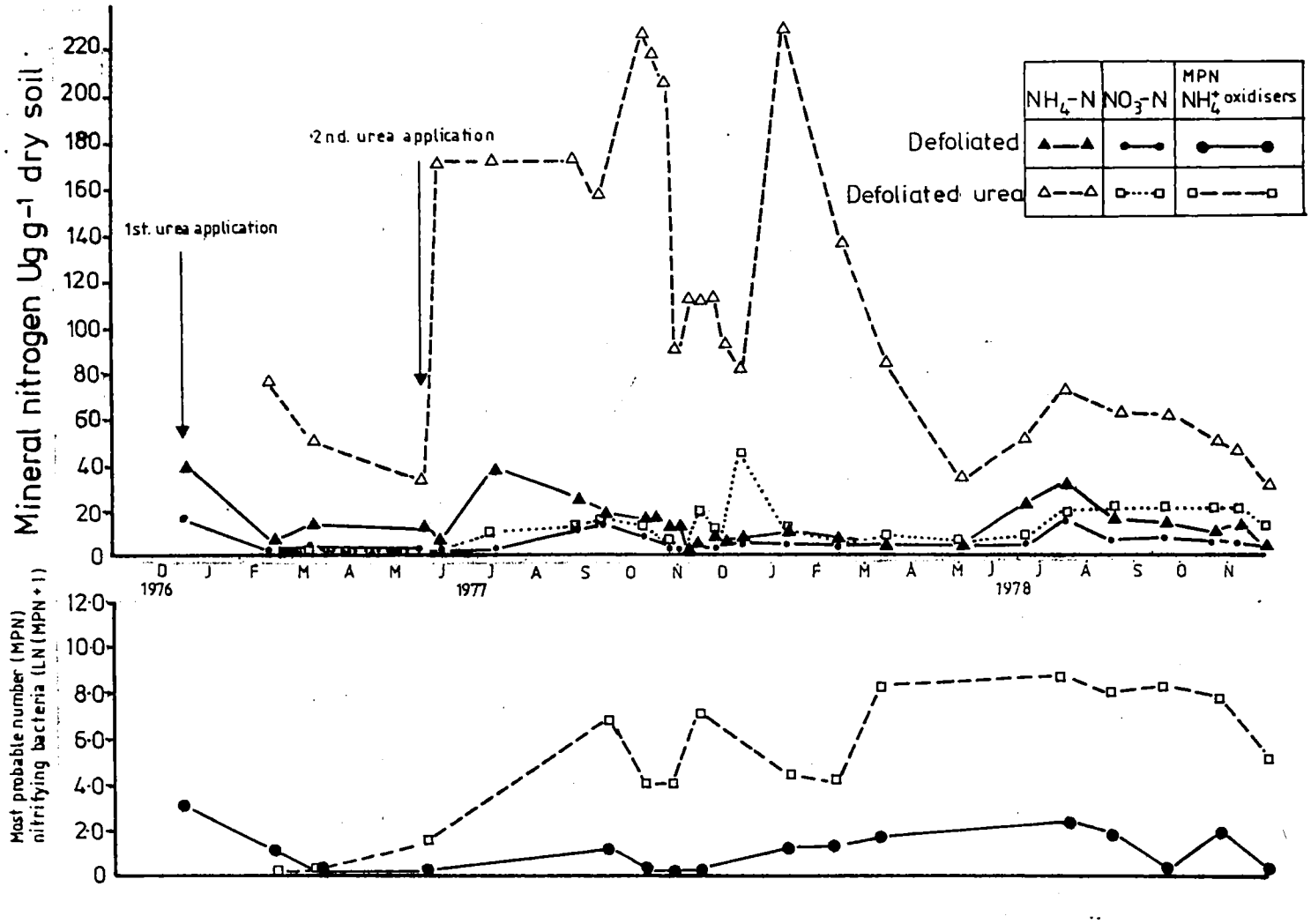

Figure 4.22 PHC Mid site:-Defoliated. Seasonal variation in mineral-N levels and NH_4^+ oxidiser numbers after urea application (80g Nm^{-2})

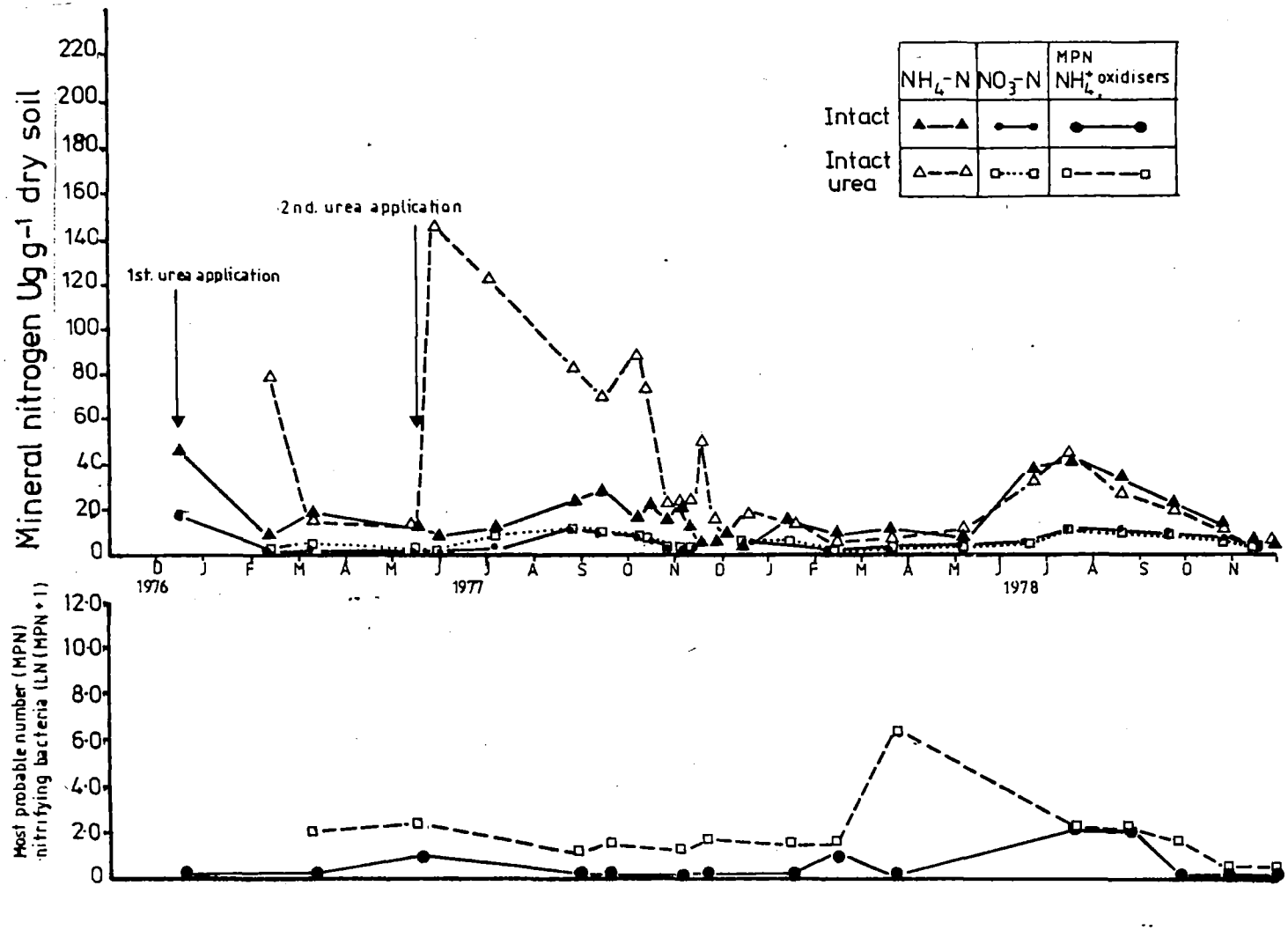

Figure 4.23 PHC Upper site:-Intact. Seasonal variation in mineral-N levels and NH_4^+ oxidiser numbers after urea application (80g Nm^{-2})

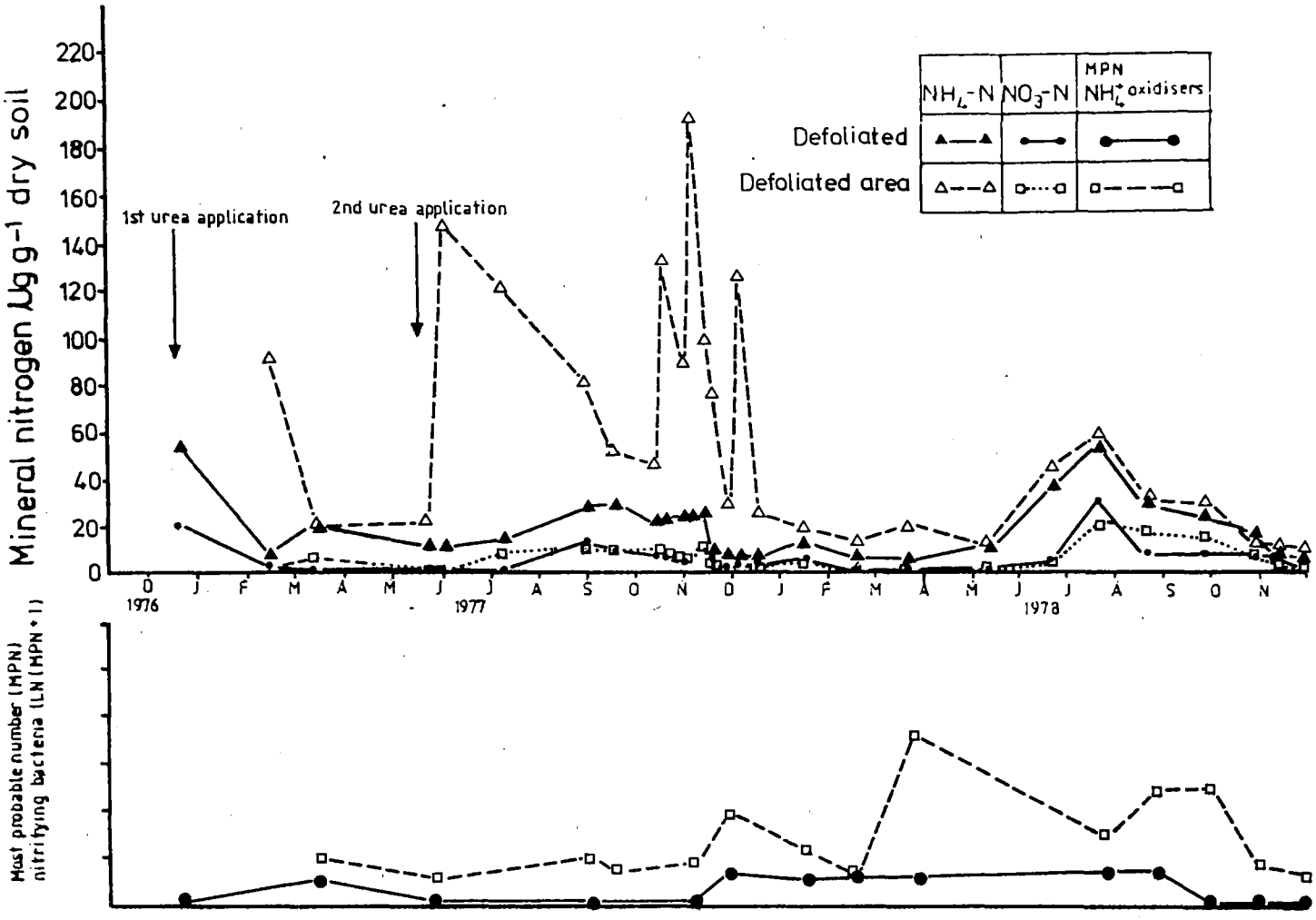

Figure 4.24 PHC Upper site:-Defoliated. Seasonal variation in mineral-N levels and NH_4^+ oxidiser numbers after urea application (80g Nm^{-2})

4. Lowest levels of both NH_4-N and NO_3-N and NO_3-N occurred in the summer - autumn period at all sites in both years. Similar levels of both NH_4-N and NO_3-N were recorded at all sites during these periods. NH_4-N ranged at or just below 10 µg g^{-1} while NO_3-N levels at all sites ranged at or below 4 µg g^{-1} soil. Nitrifier mpns were low at all sites for the summer-autumn periods except at the Lower site where levels incresed rapidly in January 1978 and remained high for the rest of that year.

5. The intensive weekly sampling carried out from 12 October, 1977 to 15 December, 1977, revealed generally declining levels of NH_4-N and NO_3-N which may have coincided with the commencement of spring plant growth and rapid N uptake by plant roots. Weekly fluctuation in NH_4-N and NO_3-N levels was greatest at the Upper site.

(b) Defoliation treatment.

Mineral N levels and nitrifier mpns for the PHC defoliated treatments at the 28 sampling dates are shown in Figures 4-16, 4-17 and 4-18. Because there was a gap of a year between defoliation and the first soil sampling in this study, a further more closely monitored study is described in Chapter 6.

Defoliation caused few measured changes in mineral N levels at any of the sites compared to the intact control plots. A slight variation between the two treatments was apparent at the Lower and Upper sites where defoliation treatment resulted in slightly higher NO_3-N and NH_4-N levels both in the December 1976 samples and in the winter mineral N peaks of 1977 and 1978.

Nitrifier numbers were generally increased by defoliation at all sites.

(c) Urea application.

Urea application to all sites at Paddle Hill Creek caused changes in mineral N levels and nitrifying bacteria mpns (NH_4+oxidisers only) which were markedly different between the Lower, Mid and Upper sites as shown in Figures 4.19, 4.20, 4.21, 4.22, 4.23 and 4.24.

Each of the three sites is considered below:

(i) Lower site. (Figures 4.19 and 4.20).

Monitoring after the first urea application was not as frequent as the

later sampling programme, but revealed a slight increase in NH_4-N levels which was not sustained, only a slight increase in nitrifier mpns at both intact and depletion treatments in response to urea application and no apparent increase in NO_3-N levels after urea addition.

The second urea application on 18 May 1977 revealed a dramatic difference between the intact and defoliation plots. Ten days after urea application, NH_4-N levels in the defoliation plot had increased dramatically and these levels remained well above levels in the unamended defoliation control until February 1978. However, NO_3-N levels in the defoliation urea plot did not increase above control levels until five months after urea application. Nitrifier mpns in the defoliation urea plot were slightly higher than in the defoliation control plot for much of the sampling period.

After the second urea application, the Lower intact plot recorded similar NH_4-N levels to those of the intact control plot. NO_3-N levels were also similar for the two treatments.

Clearly, most of the urea applied to the Lower intact plot was either lost before it was hydrolysed to NH_4-N or this NH_4-N had been immobilized through plant or animal uptake or lost by some other pathway (e.g. leaching).

Nitrifier mpns were consistently higher at the intact urea plot than at the intact control and reached very high levels in February and March 1978 (13,524 and 36,480) compared to levels at the intact control (335 and 156) and also compared to those at the defoliated urea plot (3 and 1506).

(ii) Mid site (Figures 4.21 and 4.22).
Both the intact and defoliation treatments responded in a similar manner to each other after urea addition at this site. The second urea application caused a rapid major increase in NH_4-N levels which maintained for much of the subsequent 18 months of sampling.

NO_3-N levels were not increased by May urea addition to both defoliation and intact plots until late spring then remained generally higher than control treatments until the end of sampling. Nitrifier mpns at both intact and defoliation plots also were markedly increased by urea addition.

(iii) Upper site (Figures 4.23 and 4.24).
The first urea application caused a brief surge in NH_4-N levels at both the intact and defoliated plots at this site, but caused only a slight increase in nitrifier numbers and no increase in NO_3-N levels.

The second urea application caused a rapid major increase in NH_4-N levels at both intact and defoliated plots. At the depleted urea site, after the 28 May peak level of NH_4-N (145 µg g^{-1} soil), levels again soared in an erratic fashion from October to December 1977 and reached a peak of 195 µg g^{-1} soil on 3 November. NH_4-N levels fell dramatically at the 15 December 1977 sample to 26 µg g^{-1} soil and remained slightly higher than levels at the defoliated control for most of the remainder of sampling. The second urea application caused no measured or sustained increase in soil NO_3-N levels at either the intact or defoliated plots, however, both these plots showed slightly elevated nitrifier mpns in response to urea addition.

4.4. GENERAL DISCUSSION

4.4.1 Mineral nitrogen levels in tall tussock grasslands.

Levels of NH_4-N and NO_3-N recorded at the Paddle Hill Creek and Otago sites in most seasons were markedly higher than mineral N levels generally recorded in other studies of N.Z. tussock grasslands and grasslands elsewhere.

Verstraete (1981) states that:

> *"in grassland soils NH_4^+ levels are quite low (<10ppm) and the nitrifiers appear to compete ineffictively with grass roots and with heterotrophic micro-organisms in particular."*

Campbell and Biederbeck (1982) found NH_4-N levels generally below 10ppm in Saskatchewan wheat fields as did Chase *et al.* (1968) in Ontario grasslands. Robinson (1962) found levels of NH_4-N and NO_3-N in Craigieburn short tussock grassland soil were generally below 10ppm and a similar finding was made for Southern Chilean rangeland soils. (O'Connor *et al.*, 1966). Recent studies by Soil Bureau, D.S.I.R., in Otago tall tussock grasslands, have concentrated on the study of nitrogen mineralisation largely through laboratory incubation of soils. These studies recorded "field" levels of NH_4-N over several seasons which were well below 20ppm at all sites in soils adjusted to 60% water holding capacity in the laboratory (Ross and McNeilly, 1975). Field cores sampled

in March 1977 and analysed immediately showed NH_4-N levels below 5.9 ppm and NO_3-N levels below 1.5ppm for these grassland sites (Ross *et al.*, 1979a).

4.4.2 Winter surges in mineral nitrogen levels.

Some studies overseas have detected surges in winter mineral N levels comparable to those found at the PHC sites. Davy and Taylor (1974) found that NH_4-N levels peaked during winter in three Chiltern Hills soils. Williams (1969) found NH_4-N levels up to 64 ppm and NO_3-N levels up to 62 ppm in winter soil samples from playing fields in London. Kim (1976), recorded winter NH_4-N levels up to 80 ppm and NO_3-N levels up to 18 ppm in studies of semi-natural grass stands in Korea.

Winter peaks in mineral N levels at all the PHC sites cannot be accredited simply to a reduction in plant uptake during this period, because defoliated sites where vegetation had been destroyed, also showed a peak in mineral N similar to that recorded at intact sites.

If the surge in NH_4-N levels that occurred in all intact and defoliated PHC plots in June/July of both 1977 and 1978 is not related to plant cover other environmental factors need to be considered.

Soil moisture levels increased at all PHC sites slightly in mid-May of both 1977 and 1978. These increases were most pronounced at the Mid site, but even here did not represent a major change in soil moisture content which might account for the rapid increase in NH_4-N levels.

The most likely factor causing sharp increases in NH_4-N levels, accompanied or followed by NO_3-N increases is considered to be alternate freezing and thawing of the surface layers of the soil.

Daily temperature readings at the soil surface and at 60mm depth at the PHC Lower and Upper sites in 1978 showed that freezing and thawing of the upper soil profile occurred through much of late May, June and July, Comparison can be made between the NH_4-N and NO_3-N levels recorded at these sites and the surface soil temperature fluctuations presented in Chapter 3 (Figures 3-7, 3-8). The surge in NH_4-N levels is greatest in June at the PHC Upper site which experienced freeze-thaw effects earlier than the warmer Lower site where the major mineral N surge was delayed until a month later in July.

Freeze-thaw activity is likely to occur at most of the Otago and PHC sites every year. Soil temperature data presented by Williams (1977, pers. comm.) showed that daily freeze-thaw of surface soil at PHC was recorded for much of the late May-July period over three winters from 1971 to 1973 at meteorological stations adjacent to the Upper, Mid and Lower sites described here. Data presented by Mark (1965a) shows that early winter freeze-thaw in surface soil layers occurred in both mid and high altitude snow tussock grassland on the Old Man Range, Otago. However, the Otago soil sampling described in Section 4.3.2 of this chapter did not occur at a time when any freeze-thaw stimulation of mineral N production was likely to have been recorded.

The effects of freeze-thaw on soil physical properties in the New Zealand hgih country have been studied in greatest detail by Gradwell (1954, 1956) at Molesworth Station, Marlborough. This study showed the major influence freeze-thaw has upon soil structure and the modification of freeze-thaw influences that result from continuous snow or vegetation cover. Tall tussock vegetation had the greatest effect of all plant cover types studied in limiting temperature extremes. Freeze-thaw, however, still occurred in inter-tussock spaces. Freeze-thaw behaviour is likely to be characteristic of surface soil layers in most of New Zealands tall tussock grasslands for certain periods each year. Many laboratory studies of the effects of freezing and thawing on soil mineral N have now been undertaken.

Allen and Grimshaw (1960); Harding and Ross (1964) and Hinman (1970) all showed that laboratory soil freezing causes major increases in both soil NH_4-N and NO_3-N. They attributed this to the release of previously non-exchangeable NH_4-N from organic or inorganic soil colloids through disruption of these by freezing and thawing. It is likely also that the substrate available for mineralisation will increase.

Ross *et al.* (1979b) showed that storage of a range of Otago tall tussock grassland soils at -20°C for 24 hours caused a significant increase in NH_4-N contents in all soils and a significant increase in NO_3-N contents in most soils. A similar result was shown for the Craigieburn soil in Chapter 2 of this study. Ross and Bridger (1978a) showed that a single freezing and thawing stimulated subsequent mineral N production appreciably during subsequent incubation in Carrick soil from Otago, and slightly in the Tawhiti and Obelisk soils from the same region.

A further study of the Carrick soil (Ross *et al.*, 1979a) suggested that this soil contained more mineralisable N in winter than in autumn.

None of these New Zealand studies can really be applied to a field situation. They have all involved studies of soils from single sampling dates. The freezing to which the soils have been subjected ($-20^{o}C$) is well below that experienced in nature and would be expected to cause major disruption to soil biological activity.

Studies in Canada have explored the field influence of seasonal soil freezing and thawing to a greater extent. Mack (1963) found that repeated freezing and thawing of two organic soils resulted in a surge of biological activity upon thawing and increased the mineralisation of nitrogen. The peak of increased activity decreased with each successive freezing and thawing. Soulides and Allison (1961) showed that multiple freezing and thawing caused a small release of NH_4-N but not of NO_3-N. Biederbeck and Campbell (1973) found that with marked downward shifts in soil temperature, microbial population levels decreased markedly whereas mineralisation and nitrification rates increased significantly resulting in a temporary flush of mineral N This "kill" of microbial cells was much more pronounced with flunctuating than with constant temperature conditions. The validity of this phenomenon was supported by four year field data that showed that the onset of the first cold spell each autumn caused a sudden flush in mineral N production. A later study (Campbell and Biederbeck 1982) gave further field support to this finding as did an incubator trial simulating growing season conditions which showed that pronounced increases or decreases in temperature led to flushes in N mineralisation (Campbell *et al.*, 1974). Alternate freezing and thawing has been shown to cause widespread disruption of soil aggregates (Hinman and Bisal, 1968) and wide fluctuations in soil moisture content (Bisal and Pelton 1971). Both of these physical effects would be expected to increase mineralisation and nitrification. Campbell and Biederbeck (1972) postulated that during transient cold spells vegetative cells are killed and their protoplasm then serves as a source of readily available N substrate for the surviving and adapting microflora which results in an enhancement in mineralisation and nitrification. Their 1973 paper confirmed the validity of this theory which was also given support in findings by Ivarson and Sowden (1970) who showed that the total amount of free amino acids and sugar content of a soil markedly increased with repeated freezing and thawing.

Further laboratory testing of repeated freezing and thawing tall tussock grassland soils is described in Chapter 7.

4.4.3 Tall tussock depletion and soil mineral nitrogen at Paddle Hill Creek.

Defoliation caused no consistent changes in soil mineral N at any of the PHC defoliated plots. This result contrasts with the marked increases in NH_4-N found at half the Otago sites 5 and 12 months after defoliation. Sampling at PHC, however, did not commence until 12 months after the first defoliation, and it is therefore possible that any change in mineral N had occurred before this date.

The general increase in nitrifier mpns after defoliation at all the PHC sites, particularly the Lower site where soil chemical properties favoured nitrification, was in agreement with similar findings at most Otago sites. The increase in nitrifying bacteria with defoliation might be explained by a drying effect at the Lower and Mid sites. It does not however, account for the increase at the Upper site where no soil drying occurred after defoliation.

Urea applications served to enhance differences between intact and defoliation treatments. At most sites, nitrifier mpns were considerably higher with the defoliated urea treatment than with intact urea treatment.

Eventually all sites, both defoliated and intact, supported high nitrifier populations after two urea applications. Variation in nitrifier activity seemed dependent on the initial nitrifier population, something also noted by Robinson (1963) in his study of tussock grassland soils. The Lower site nitrifiers responded to the first urea application but the Mid and Upper sites did not. Nitrifier mpns, prior to the first application, were higher at the Lower site than at the other two sites and were therefore more capable of immediately using a vastly increased substrate level. After the second urea application, all sites showed a marked response in nitrifier activity. The Mid defoliated site showed a particularly marked response in nitrifier activity to applied urea.

Clearly, all the PHC sites have a capacity to nitrify NH_4-N provided sufficient quantities of this are available in the soil. Nitrification will proceed at any time of the year including winter, and appears more dependent on substrate availability rather than any other factor such as the presence of vegetation cover, low pH and low temperatures. These

other factors do however, influence nitrification activity. Removal of vegetation caused a general increase in nitrifier mpns, which would be consistent with the theory that substrate competition exists between plant roots and nitrifying bacteria. (Robinson 1963). Nitrifying activity at the wet, acidic Upper site (pH 4.6) was always lower than at the free-draining less acidic Lower site (pH 5.2).

Results from defoliation trials at the three PHC sites conform to the hypothesis of O'Connor (1974) that degradation of tall tussock grassland systems leads to increased losses of soil nitrogen through increased mineralisation, nitrification and leaching of nitrate. It seems possible also, however, that soil N losses may also occur from intact grasslands at certain times of the year such as winter and after dry/wet periods.

4.4.4 Urea application and tall tussock nitrogen uptake.

Two unusual responses to applied urea were observed at Paddle Hill Creek.

(i) There were major variations in NH_4-N levels at the Lower intact and Lower defoliated plots after the second urea application. The major difference between these two plots was the vegetation cover. In Section 4.1.2 it was stated that the concentrations of N in the urine application ($30\text{-}60 gNm^{-2}$) are likely to far exceed the plant N uptake ability (about $10 gNm^{-2}yr^{-1}$). There is some evidence that some slow growing species can absorb nutrients in excess of immediate growth requirements ("luxury consumption") during nutrient flushes and use these reserves later to support growth after soil reserves are exhausted (Clarkson 1967, Grime 1979, Grime and Hunt 1975).

Such an adaptive capacity might be advantageous in *Chionochloa* by enabling it to capitilize on the winter and dry/wet flushes of mineral N shown to occur in these grasslands. The development of such a capacity in *Chionochloa* in relation to pulses in phosphorus availability has been discussed by Chapin *et al.* (1982).

(ii) During the intensive sampling period from 12/10/77 to 15/12/77 at PHC, spectacular changes in NH_4-N levels were recorded for the defoliated urea treatments particularly at the Mid and Upper sites (see Figures 4.22 and 4.24).

e.g. Mid defoliated urea NH_4-N 28/10/77 205.5 $\mu g\ g^{-1}$,
3/11/77 87.1 $\mu g\ g^{-1}$.
Upper defoliated urea NH_4-N 28/10/77 87.7 $\mu g\ g^{-1}$,
3/11/77 195.3 $\mu g\ g^{-1}$.

These major changes were bidirectional and were most pronounced at the Upper sites where plant colonization after defoliation was very sparse. They are therefore not considered attributable to variation in plant uptake. Possibility they reflect short term variation in microbial or physical immobilization of NH_4-N at this site. An alternative explanation is that they are simply an anomaly caused by the sampling technique used, although the bulking of 10 cores from each treatment at each sampling date should have eliminated most sampling variation resulting from uneven distribution of applied urea.

This anomaly remains unexplained. Campbell *et al.* (1970) observed similar large and unexplainable decreases in exchangeable ammonium in a brown loam soil following a steady autumn build up in NH_4-N.

4.5 CONCLUSIONS

1. Intact tall tussock grasslands in Otago and at Paddle Hill Creek, Canterbury, showed levels of mineral N which are high in comparison with those generally reported from grasslands elsewhere. These levels fluctuated within and between seasons. Nitrifying bacteria were present at low to moderate levels at all sites. Moderate to high nitrifier populations were detected in high altitude *Chionochloa macra* grasslands in Otago while low to moderate populations occurred in lower altitude *Chionochloa rigida* grasslands.

2. All Otago and Canterbury sites exhibited a peak of NH_4-N and NO_3-N production in December 1976. This is attributed to the alternating dry/wet conditions that prevailed at all sites prior to sampling.

3. All PHC sites showed a major surge of mineral N production during the winters both 1977 and 1978. This surge is attributed to alternating freezing and thawing of the soil in the May-June-July period releasing large quantities of mineralisable N.

4. Lowest levels of mineral N at all PHC sites occurred in the summer-early autumn period when plant uptake may be moderate and N mineralisation may be restricted by dry soil conditions. This may also be the period of lowest microbial mortality resulting in low inputs of substrate for mineralisation.

5. Tall tussock defoliation caused changes in soil moisture content at most sites which tended to vary with altitude. It caused a marked reduction in soil moisture content at the high altitude Pisa and Alta 2 sites in Otago but not at the Upper site in Canterbury. At the lower altitude Otago sites and the Mid PHC site there was little change in soil moisture content while the Lower PHC site showed a general reduction in soil moisture content with defoliation.

6. Defoliation caused a general increase in the numbers of nitrifying bacteria at most sites at most sampling dates, but caused no consistent changes in soil mineral N levels.

7. Urea application generally caused major increases in NH_4-N and NO_3-N levels at defoliated plots in Otago and Canterbury. It also caused a marked increase in nitrifier numbers at these plots. These effects were particularly sustained at higher altitudes where post-defoliation plant colonization was sparse.

8. Urea application did not, however, cause substantial increases in NH_4-N or NO_3-N at most of the Otago or Canterbury intact plots, although nitrifier numbers at these plots increased markedly in response to urea. It is postulated that *Chionochloa* species may possess the ability for luxury uptake from the soil of large quantities of mineral N which would enable the plants to utilise periodic surges in soil mineral N production.

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CHAPTER 5

SEASONAL VARIATION IN SOIL MINERAL NITROGEN IN TALL TUSSOCK GRASSLANDS - SOME EFFECTS OF BURNING, CULTIVATION AND FERTILISER ADDITION.

5.1 INTRODUCTION

5.1.1 Burning of tall tussock grasslands.

Since first human settlement in New Zealand and until comparatively recent times burning of tall tussock grasslands has been widespread. Even before Polynesian settlement of New Zealand natural fires, probably triggered by lightning, have occurred at irregular intervals in the eastern high country of the South Island (Molloy *et al.*, 1963). Polynesian colonisation of the country caused a marked increase in the frequency and extent of burning. Several explanations are advanced to explain the extent of Polynesian burning throughout the country and particularly in eastern parts of New Zealand:-

Fire is likely to have been used to flush out moa from forest, shrubland and grassland. Periodic burning to promote fresh growth to attract moa may also have been used in much the same way that deerhunters today burn cutover forests and shrublands to attract animals. Burning would have facilitated foot access through dense forests and *Discaria, Coprosma* and *Leptospermum* shrublands particularly *enroute* to alpine crossings to the Westland greenstone areas. Fires are likely also to have accidentally spread from campfires.

This combination of causes resulted in extensive burning of forest areas throughout eastern New Zealand. In the Cass region of Canterbury, a detailed chronology of these Polynesian fires and their effects on the vegetation has been described, (Molloy, 1977). This points to a cluster of fires occurring 500 to 600 years ago. In the Cass district and over much of the eastern South Island, forest was destroyed. Close to the Main Divide, where rainfall exceeded 1500mm, the forest regenerated. Further east, in drier zones, the forest was replaced by tall tussock *(Chionochloa)* grasslands. It is likely that revegetation to grasslands was rapid on intact soils or on those accumulating downslope waste containing abundant fine material. However, where only infertile subsoil or coarse detritus was present, revegetation occurred much more slowly and in places erosion initiated (O'Connor, 1980).

After the initial drastic transformation from forest, periodic fires would have served to maintain grasslands, probably mainly of tall tussock, against forest recovery. Tall tussock species withstood this periodic burning because

it was not accompanied by intensive grazing. By this time most of the moa were likely to have become extinct. Only burning in combination with intensive grazing can eliminate tall tussock and lead to the development of short tussock vegetation. (O'Connor and Powell, 1963).

Nitrogen losses over the period of Polynesian burnings are likely to have been large. Much of the nitrogen lost in smoke or leached as nitrate formed by nitrification, may have been replaced through stimulation of nitrogen fixation by native plants such as *Carmichaelia, Swainsona* and *Discaria,* particularly on youthful soils in the manner described by Woodmansee and Wallach (1981). After European burnings, however, large numbers of introduced grazing animals selectively grazed and eliminated many of these native nitrogen fixers, especially *Carmichaelia.* Because of this on unimproved grassland post-fire nitrogen fixation is likely to have been severely limited and the whole system may have steadily been depleted in nitrogen. (O'Connor, 1974).

European settlement of the high country heralded an era of widespread burning of tall tussock grassland in combination with heavy stocking by sheep. The settlers burnt the tussock grassland to encourage:-

> *"the delicately green and juicy grass which springs up after burning and is far better for sheep than the rank and dry growth of summer after it has been withered by winter frosts".*
>
> *Butler (1863)*

Burning was widespread throughout Otago (Beattie, 1947), Canterbury and Marlborough (O'Connor, 1983). The result of this burning and grazing was widespread depletion and deterioration of tussock grasslands. Tall tussock grasslands, particularly in the lowland and lower montane zones, were eliminated over extensive areas and replaced by short tussock and low herbs (Cumberland, 1945).

Today burning of tussock grassland country still occurs but on a much smaller scale than in the early days of European settlement. Burning permits are issued to runholders by Catchment Boards and fires are primarily used to control scrub at lower altitudes although in Southland and Otago in particular, tussock burns are still common. In addition, accidental fires have in recent years engulfed thousands of hectares of tall tussock rangeland. (e.g. 1972 Mt White, 1977 Eyre mountains; 1981 Mt Somers; 1982 Haldon Station; 1983 Kaimanawa red tussock).

5.1.2 Burning and soil nitrogen.

The effects of burning upon soil nitrogen have recently been comprehensively reviewed by Woodmansee and Wallach (1981). The degree to which burning changes the nitrogen pool of an ecosystem depends to some extent on the type of fire that occurs. An intense burn can consume standing plant matter, litter and much of the organic material in the upper layers of the soil. This is particularly marked in forest fires. Grassland fires often simply race across the surface consuming only standing plant material. An intensive burn may totally kill the roots and shoots of plants impeding the recovery of vegetation. Such a burn may also destroy soil biota.

It has been pointed out that in the N.Z. tall tussock grasslands, loss of nitrogen in gaseous form during burning can be quite substantial because of the large quantity of nitrogen tied up in above ground standing crop (O'Connor, 1983) i.e. the Paddle Hill Lower site described in this chapter had 14.3 ± 0.9 gNm^{-2} in its above ground nitrogen pool (Williams, 1977).

There are many factors likely to stimulate soil nitrogen mineralisation and nitrification after a fire:-

(i) Soil temperature increases are likely because of greater absorption of sunlight by fire blackened surfaces and the elimination of plant shading. Stanford *et al.* (1973) found that the rate of N mineralisation in a number of soils increased two to threefold for each $10^{o}C$ increase in soil temperature in the $5^{o}C$ to $35^{o}C$ range. Ross and Bridger (1978) showed a similar marked increase in nitrogen mineralisation with increasing temperature when they incubated a range of Otago tussock grassland soils.

(ii) Soil acidity usually decreases after burning. In grassland soils which tend to have a greater buffering effect than forest soils, the increase in pH levels after burning is usually small.

(iii) Exchangeable bases such as potassium, magnesium and calcium often increase in level after burning which may stimulate nitrogen transformations.

(iv) Soil water levels can alter after burning. Burning may evaporate considerable quantities of water from the exposed soil surface. Transpiration

losses will obviously cease. It is likely that burnt sites will be more subject to wetting and drying regimes known to stimulate nitrification (Birch, 1960).

(v) Destruction of plant cover is of great importance because it eliminates competition for NH_4-N between soil biota and plant root systems. Nitrification is therefore likely to be stimulated by an increase in substrate levels.

5.1.3 Cultivation, soil nitrogen and tall tussock grasslands.
The effects of cultivation on soil nitrogen depends on the type of cultivation, its frequency and the fate of plant residues growing on the soil surface prior to cultivation.

Many of the effects of cultivation closely parallel those of burning such as effects upon water relations, soil temperature, light regimes and the elimination of plant competition for soil nitrogen. The major difference between them is that whereas burning volatilises much of the plant organic matter and releases many mineral salts on the soil surface as ash without general disturbance to underlying soil, cultivation incorporates plant residues into the soil system and disturbs the physical arrangement of the soil. This has a significant effect on soil nitrogen transformations.

Nitrogen transformations within the cultivated ecosystem have been comprehensively reviewed by Power (1982). These can be briefly summarised as follows:-

(i) Soil water relations: Cultivation exposes the soil to sunlight and to the drying effects of the wind. In general, tillage tends to dry the soil. The lack of plant cover reduces transpiration loss from the soil and eliminates the surface sponge-like litter which intercepts rainfall. During rainfall, the cultivated soil may become more waterlogged than its undisturbed analogue. Thus the cultivated system is likely to be more sucsceptible to the wetting and drying cycles described by Birch, (1960).

(ii) Soil aeration: Tillage is an oxidative process which reduces bulk density, increases porosity and exposes more soil surface to the atmosphere. Consequently tillage enhances aerobic processes such as organic matter oxidation, organic nitrogen mineralisation and nitrification.

(iii) Soil temperature: The soil is more exposed which leads to greater extremes of temperature than beneath a plant mantle. Sunlight will heat the soil in the daytime enhancing the rate of microbial activity. In winter, the soil will be more exposed to freeze - thaw effects described in Chapter 7.

(iv) Soil organic matter increases rapidly once cultivation and incorporation of plant residues occurs. There may be an initial decrease in mineral N caused by microbial uptake. Allison (1973) reported that soil organic matter and organic nitrogen content decreased for the first 25-50 years after a range of natural grasslands were cultivated. This was attributed to increased biological activity and turnover of organic matter within the soil system.

(v) Plant competition for mineral N is obviously eliminated by cultivation. This is likely to lead to a major upsurge in nitrification caused by the increased levels of NH_4-N available as substrate.

Cultivation is not widespread in N.Z. tall tussock grasslands. In much of the country these grasslands now occur at sites that are too high or too steep for cultivation to be economic. There are, however, extensive areas of *Chionochloa rigida* grassland in eastern Otago where cultivation is taking place. In Southland, Otago and Canterbury there are some *Chionochloa rubra* grasslands being cultivated for the first time. Some small scale cultivation of other *Chionochloa* grasslands is occurring through parts of the South Island high country.

In addition, vast areas of short tussock *Festuca* grasslands induced from *Chionochloa* grassland by fire and grazing, are undergoing cultivation for the first time (Dunbar and Hughes, 1974). These still represent only a small proportion of the total area of natural grassland because it has long been recognised that the most economical and effective way to "improve" natural tussock grasslands is not by cultivation but by oversowing and top-dressing (O'Connor *et al.*, 1962).

O'Connor *et al.* conducted one of the few published studies of tussock grassland cultivation and its effects on N transformations and soil bacteria. A Craigieburn soil supporting short tussock grassland was examined and it was found that after cultivation very little mineralisation took place unless soil acidity was ameliorated by liming. After cultivation nitrification

was negligible in virgin soil, increased slightly with the addition of lime and only increased substantially with the addition of urea to provide a substrate for nitrifying bacteria. This result suggests that N.Z. tussock grassland soils may behave differently under cultivation compared to grassland soils elsewhere.

5.1.4 Soil nitrogen transformations and phosphate fertiliser.
Soil phosphorus levels are of major importance to processes such as nitrogen fixation, plant uptake, nitrogen immobilisation, nitrification, denitrification and mineralisation.

Cole and Heil (1981) have provided a comprehensive review of the role of phosphorus in terrestrial nitrogen cycling. O'Connor (1974; 1983) has attempted to integrate phosphorus and soil nitrogen interactions in N.Z. tussock grasslands. The role of phosphorus on nitrogen transformations is summarised below. Many of these processes are linked to each other.

(i) Nitrogen fixation activity is determined by the level of available phosphorus in the soil which in turn is dependent on the stage of soil pedogenesis. Youthful systems with high available (mainly calcium-bound) soil phosphorus exhibit high rates of nitrogen fixation. As soil systems mature, levels of organic matter production and nitrogen accumulation are closely correlated with total phosphorus levels in the soil.

(ii) Plant uptake of mineral nitrogen is closely linked with phosphorus levels. This occurs both because of greater fixation of nitrogen in high P systems and from an increased ability of plants to scavenge mineral N from the soil probably because they develop a more vigorous and extensive root system. (Black and Wright, 1972).

(iii) Nitrogen mineralisation rates increase with an increase in the supply of soil phosphorus. It has been shown that phosphorus is the limiting factor for the growth of mineralising microorganisms in many rangeland soils such as those in Colombia (Munevar and Wollum, 1977) and New Zealand (Ross and Bridger, 1978).

(iv) Nitrification activity increased in response to phosphorus additions to soils low in natural phosphorus in Zimbabwe (Purchase, 1974) and in New Zealand tussock grasslands (Robinson, 1963; Ross and Bridger, 1978) although both the New Zealand experiments were conducted in artificial laboratory conditions.

5.1.5 Aims of the study.

The range of studies of burning of tall tussock grasslands described in section 5.1.1 have focused on the effects of burning upon tall tussock plant growth and have been less concerned with the effects of burning on soil biological activities and soil chemical properties. Payton and Brasch (1978) concluded that the factors that stimulate growth in tall tussocks immediately after a fire remain uncertain. They speculated that burning, by increasing soil temperatures, may accelarate the rates of mineralisation in the soil and thereby increase nutrient availability. This would accelerate the regrowth of tussocks after burning compared to unburnt plants and might also account for the higher concentrations of nutrients present in regrowth foliage compared to unburnt tussock foliage (Williams and Meurk, 1977).

The small scale burning experiments described here were to determine whether this caused any stimulation of soil nitrogen mineralisation. Cultivation studies were also to determine whether the very small change, after cultivation in soil nitrogen transformations demonstrated by O'Connor *et al.* (1962) in the comparitively depleted Craigieburn soil, applied also in soils supporting dense tall tussock vegetation.

These studies supplemented the major study of mineral nitrogen transformations in natural grasslands described in Chapter 4 and therefore did not involve the same range of sites or sampling frequency as this earlier study. Nevertheless it was hoped that they would provide an indication of changes in soil mineral N levels in response to the drastic modifications of range-land that have been widespread in the past in the N.Z. high country and continue in many areas today.

5.2 MATERIALS AND METHODS.

5.2.1 Sites and soils.

Field work was carried out at Paddle Hill Creek at sites adjoining the study sites described in Chapter 3.

(i) Cultivation was done at the Paddle Hill Creek Lower, Mid and Upper sites.

(ii) Burning was conducted at the Lower and the Upper sites. There was insufficient plant material in the stunted scattered tussocks and litter free intertussock spaces at the Mid site for a successful burn.

(iii) Cultivation with phosphate fertiliser application was at a site adjoining the Lower site where the local farmer had established a deer trap.

5.2.2 Modification techniques.

(i) Cultivation: a 3m x 3m area was pegged out at each site adjacent to the intact control described in Chapter 4 but located downslope and separated by a 2m zone of unmodified grassland.

On 18 October 1977, in fine weather, the area was dug with a spade to a depth of .5m so that all clods were broken up and plant and litter residues were mixed throughout the soil. Over the 14 month course of the experiment there was little regrowth at any of the three sites.

(ii) Burning: A 3m x 3m area was pegged out at the Lower and Upper sites downslope from the intact control treatments and separated from each of these controls by a 2m unmodified buffer zone.

On 18 October 1977, after a period of dry weather lasting 10 days, both sites were burnt by quickly setting the perimeter of the plot alight and allowing the fire to burn to the centre. A thorough burn was achieved in the manner of spring burns described by Butler (1863). All intertussock litter was consumed and tussocks were reduced to blackened leafless stumps which sprouted new green leaves within a month. These new leaves at both sites were killed by severe late frosts in early December 1977. Tussock at the Lower site resprouted again in March 1978 and many of these tillers recovered and grew. Heavy browsing of fresh shoots by cattle and hares occurred throughout the experiment. Tussocks at the Upper site died under this burning, frost and grazing treatment.

(iii) Cultivation and fertiliser: On 20 November 1976, Mr Bill Dobbs, manager of Mt Possession Station, disced a one hectare area on the valley floor at Paddle Hill Creek close to the Lower site. On 15 December this

was harrowed to an even texture, sown with clover and turnip seed and 300 kg of superphosphate fertiliser applied. A high deer fence was erected around the plot and trip wires were stretched across the tilled area to create a deer trap.

A 5m x 5m area inside the fence was marked out for regular sampling.

An area of equal size was pegged out beyond the fence in dense unmodified tall tussock to act as a control. A sustained dry period followed sowing. Although seeds germinated, most of the turnip plants succumbed to the dry spell. The clover plants developed slowly and did not show widespread vigour until March 1977 when they covered about half the plot. The cover died back through the winter then spread in spring 1977 to cover most of the plot.

On 18 May 1977 nitrogen as urea was applied to a 2m x 2m sub-plot in the cultivated and fertilised area. Urea (176.6g) was dissolved in water (5 litres) to give an application rate of approximately $80gNm^{-2}$.

5.2.3 Sampling frequency and methods.

Sampling at the burning and cultivation treatments began on 18 October 1977, then took place at weekly intervals until 15 December 1977 after which soils were sampled monthly until 1 December 1978. At the fertilised site (referred to from now on as Deer site) sampling began on 20 December 1976 and continued at the same sampling frequency as that described in Chapter 4 until 1 December 1978.

Identical methods to those used in the natural grassland survey described in Chapter 4 were used to measure soil moisture content, mineral N and most probable numbers (mpn) of nitrifying bacteria. Soil pH was measured at all treatments every second sampling period. Soil temperature was not monitored.

5.3 RESULTS

5.3.1 Soil pH.

Levels of soil acidity recorded under the burning, cultivation and cultivation with superphosphate treatments showed no discernable deviation from pH levels recorded for the intact control treatments at each site (see Table 3.3). This confirms the strong buffering effect characteristic

of grasslands (Woodmansee and Wallach, 1981).

Soil pH at the cultivation treatment of the Deer site where urea was applied increased from 5.3 on 18 May 1977, the date of urea application, to 5.6 on 28 May. By the next sampling date on 2 July, pH level at this site had returned to pH 5.2, the level recorded in soil without urea amendment.

5.3.2 Soil moisture content.

Mean soil moisture contents from duplicate samples for each of the different treatments at the Lower, Mid, Upper and Deer sites are presented in Figures 5.1, 5.2, 5.3 and 5.4.

(i) Burning:-

At the Lower site (Figure 5.1) no immediate soil moisture loss was apparent in response to burning. By mid-November, one month after burning took place soils with the burning treatment showed a lower moisture content than the control soils. This lower moisture content was sustained until mid-December after which levels with the burning treatment and at the intact control became similar. At the Upper site (Figure 5.3) moisture levels with the burning treatment were similar to those of the intact control soils until mid-January after which substantially higher moisture levels were recorded with burning treatment until the August 1978 sampling when both treatment and control levels became similar once again. At both Upper and Lower sites, soil moisture content was comparatively high. The decrease in moisture level after burning at the Lower site over the summer period was not accompanied by any comparable decrease at the Upper site and may reflect the greater evaporation potential of bare soil at this lower altitude site (Williams, 1977). The increase in soil moisture content at the Upper site after burning treatment may result from the elimination of transpiration losses.

(ii) Cultivation:-

Changes in soil moisture content were much more apparent with cultivation than with burning.

At the Lower site (Figure 5.1) cultivation caused a rapid reduction in soil moisture content compared to soils at the intact control site. Over the first three months, soil moisture content under cultivation treatment averaged 34% against 42% for the intact control soils. Moisture levels under both treatments were similar for the next three months. Through the

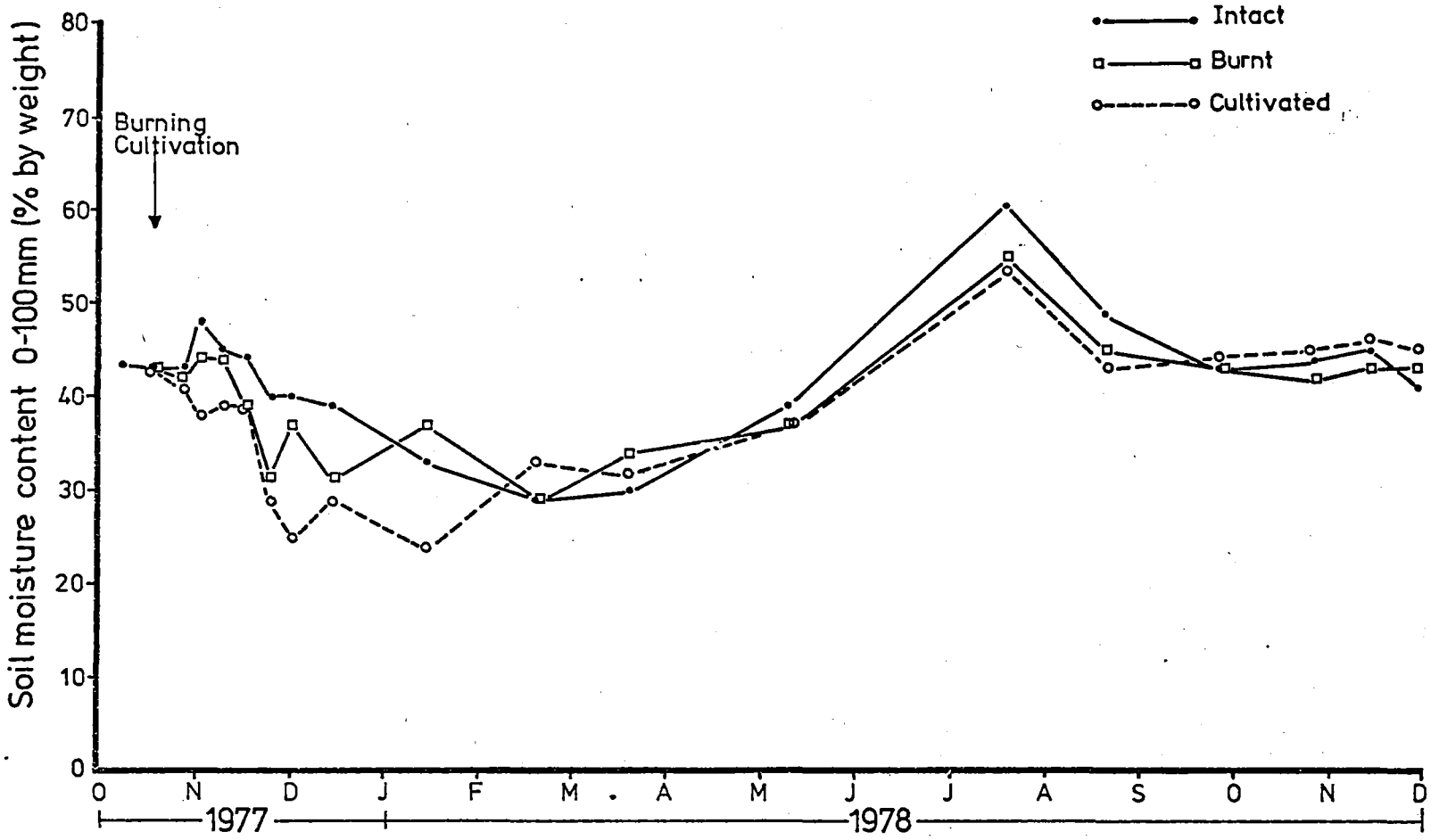

Figure 5.1 Fluctuations in soil moisture content after burning and cultivation. Paddle Hill Creek Lower site.

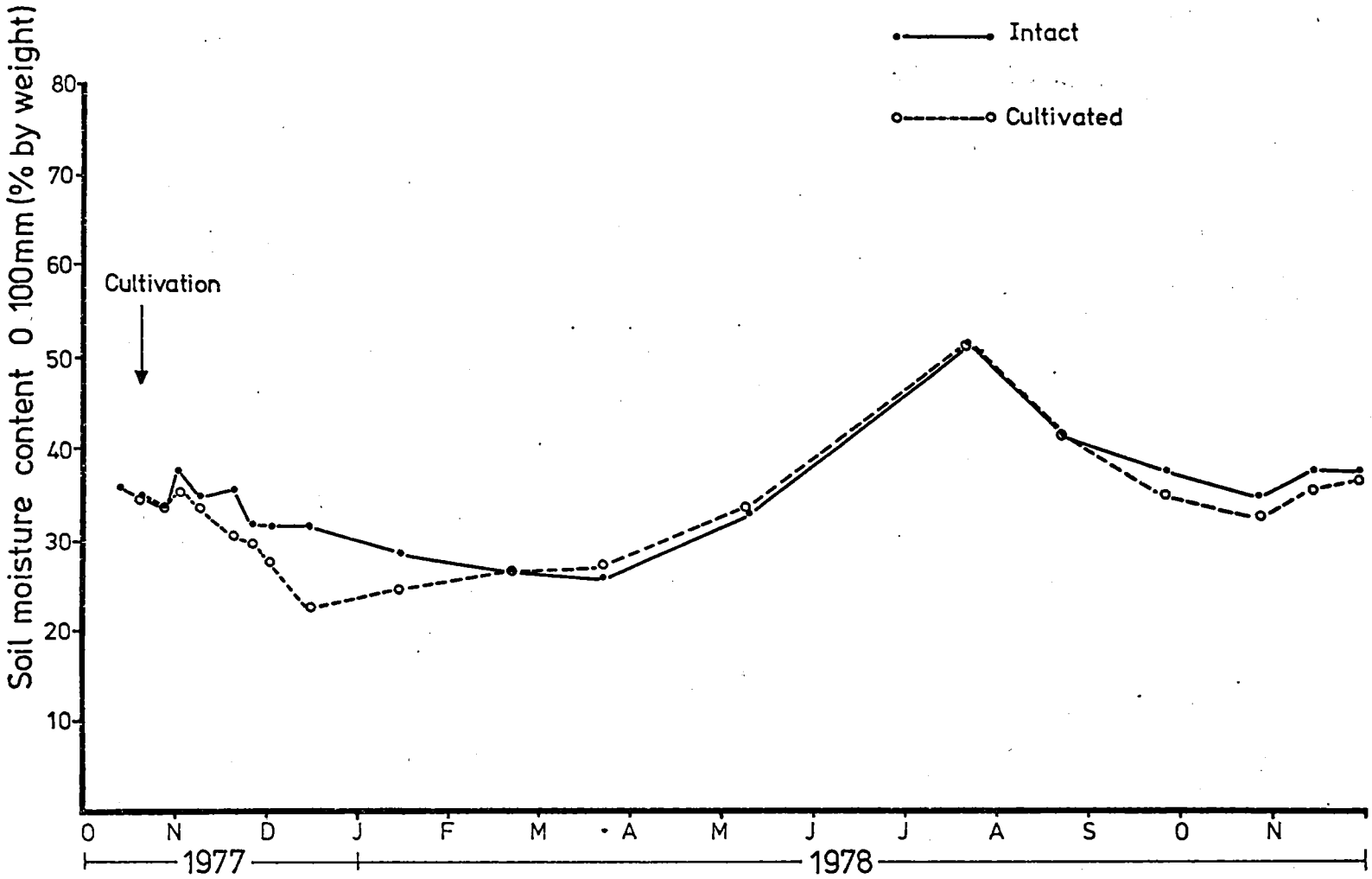

Figure 5.2 Fluctuations in soil moisture content after cultivation. Paddle Hill Creek Mid site

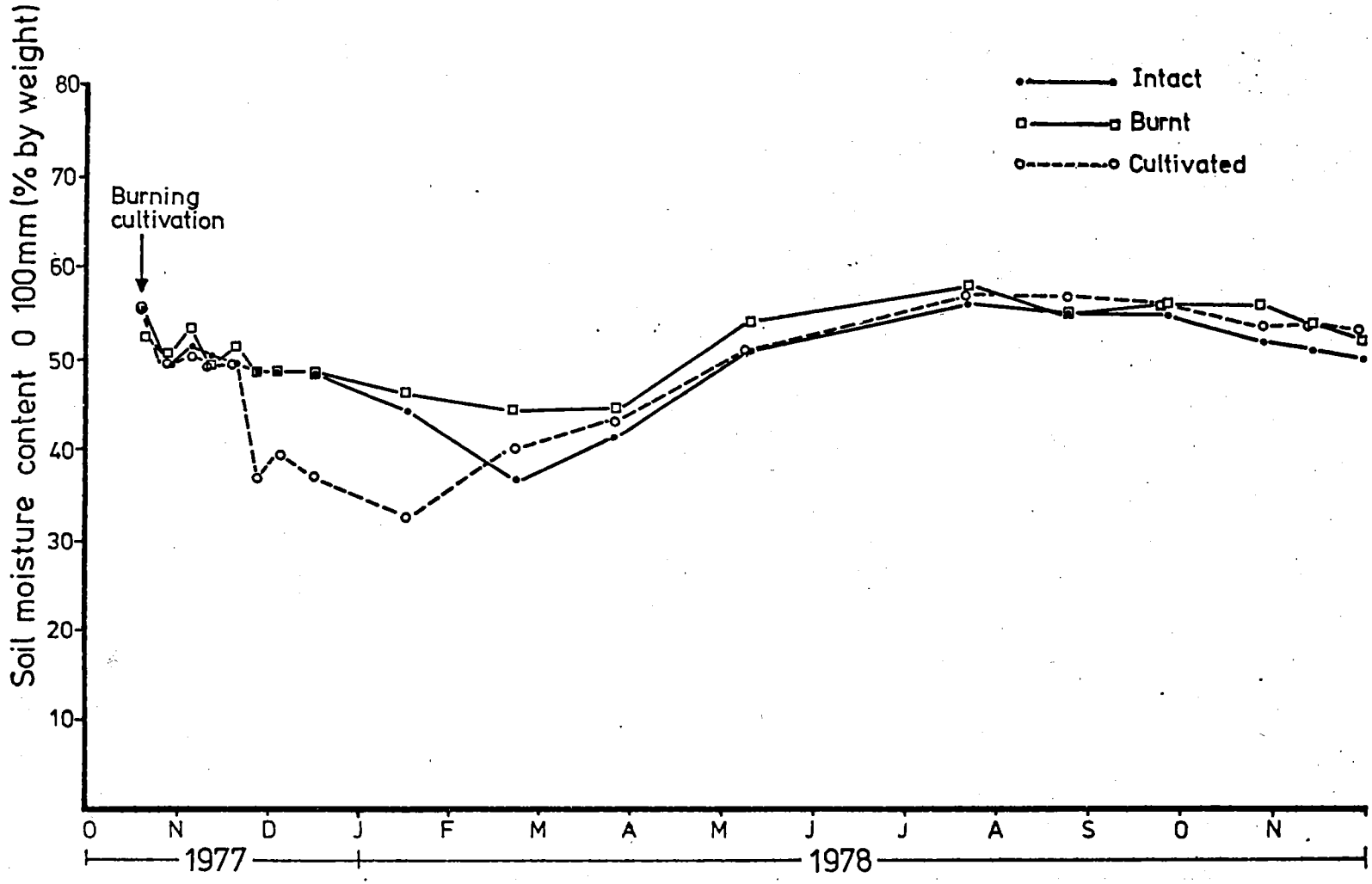

Figure 5.3 Fluctuations in soil moisture content after cultivation and burning. Paddle Hill Creek Upper site

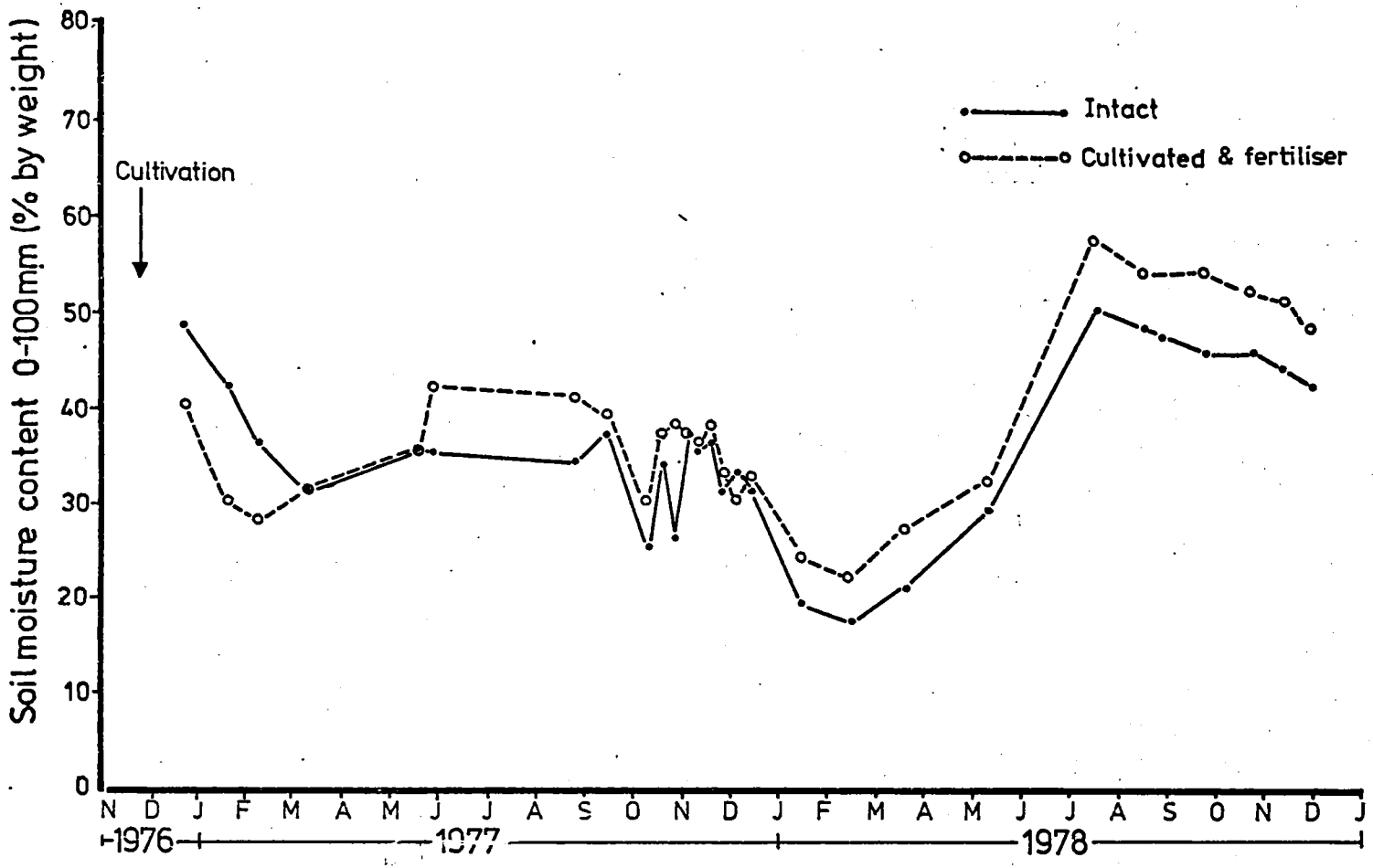

Figure 5.4 Fluctuations in soil moisture content after agricultural development by cultivation, fertiliser and seed addition. Paddle Hill Creek Deer site

winter of 1978 (May, July, August, samples) soil moisture content under cultivation treatment averaged 45% while in the intact control soils it averaged 50%.

On the drier soils of the Mid site (Figure 5.2) soil moisture content also fell soon after cultivation and for the next three months mean soil moisture content was 30% against 34% for the intact control soils. Levels under both treatments then remained similar until the end of sampling.

At the Upper site (Figure 5.3) intact control and cultivation treatment soil moisture levels were similar for the first month after treatment. Cultivation treatment soil moisture content then dropped markedly for the next two months and averaged 36% moisture content against 45% for the intact control soils. From January 1978 onwards, levels for both treatments were similar.

Soil moisture levels at the Deer site (Figure 5.4), cultivated in November 1976, were also lower for the first two months after cultivation compared to those in the adjoining intact control soils. However, for almost all samples over the next 18 months the cultivation treatment showed higher soil moisture levels than the intact control. This difference is difficult to explain. Possibly evapo-transpiration losses from a grass/clover sward are lower than those from tall tussock grassland.

In summary, cultivation caused a steady decline in soil moisture content at all sites for the first two to three months following treatment. After this period, moisture levels under cultivation treatment returned to those of the intact controls except at the Deer plot where cultivated soil retained a higher moisture content than the intact tall tussock grasslands.

5.3.3 Mineral nitrogen levels and nitrifying bacteria numbers.

(i) Burning:-

LOWER SITE (Figure 5.5): Soil samples immediately after burning had considerably higher NH_4-N levels (26 $\mu g\ g^{-1}$) than the same soil sampled just before the fire and soil from the adjacent intact control (16 $\mu\ g\ g^{-1}$). No decrease in soil moisture content was recorded to account for this increase either here or at the Upper site. The increase is attributed to NH_4-N

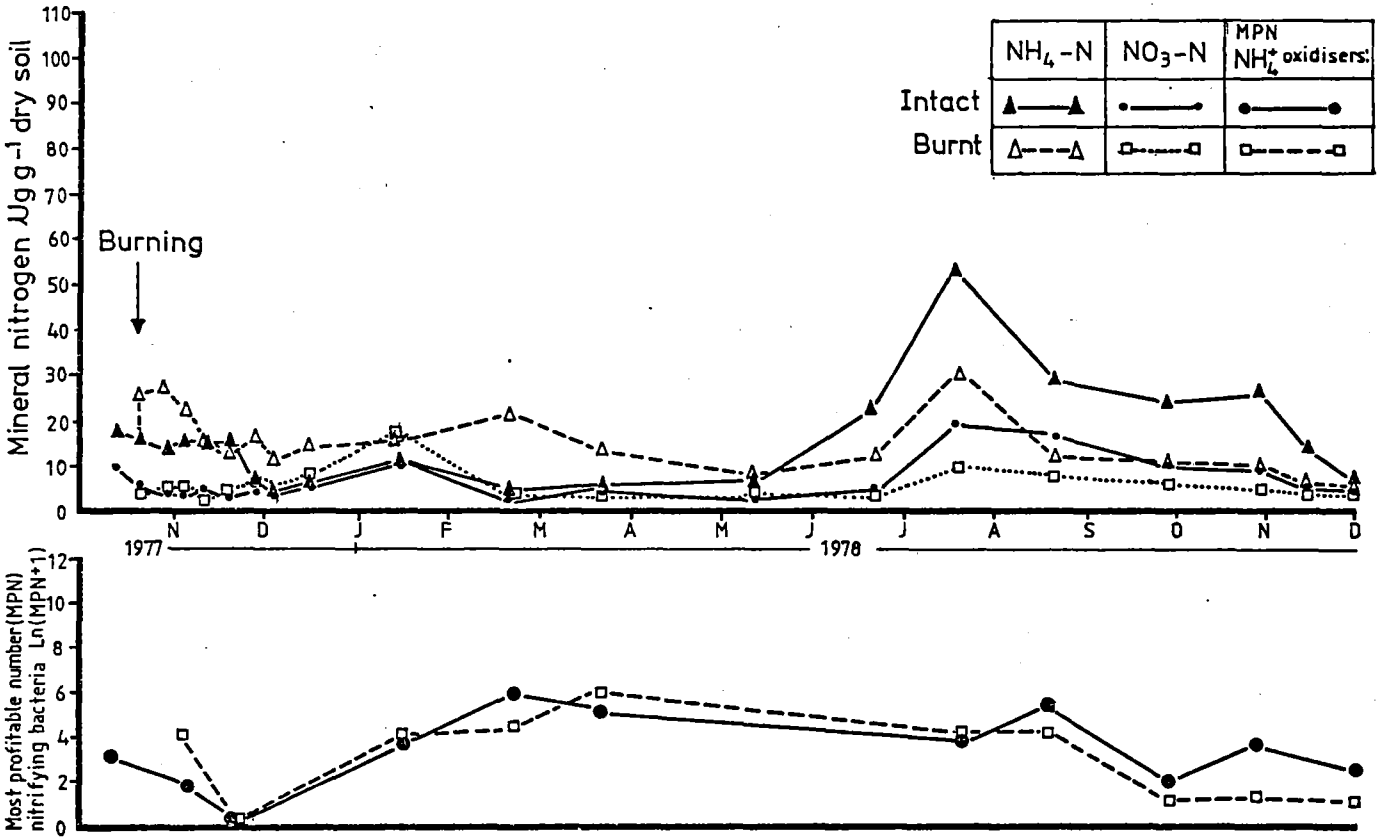

Figure 5.5 PHC Lower site. Comparison between burnt and intact tall tussock grasslands in seasonal variation in mineral-N levels and nitrifying bacteria numbers (NH_4^+ oxidisers only).

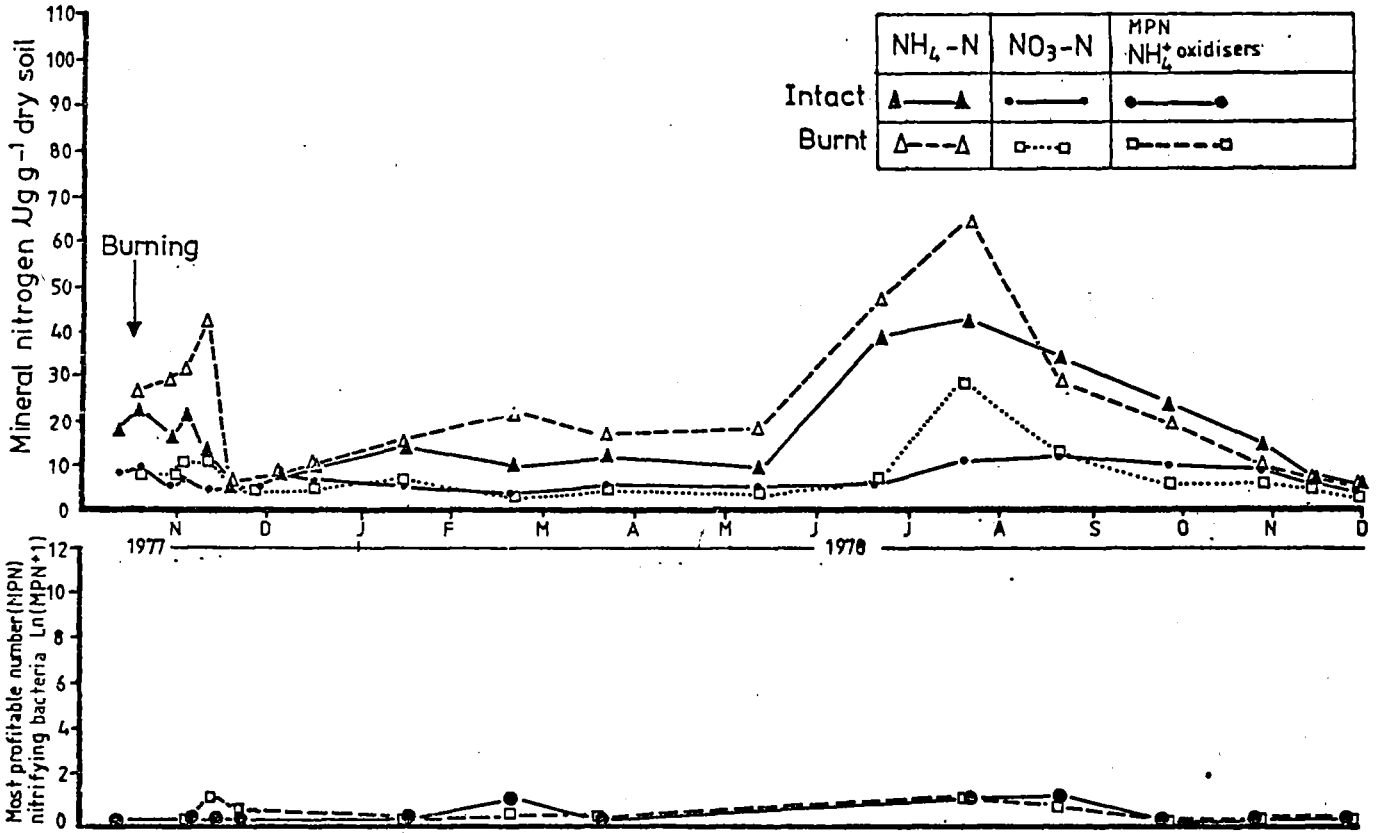

Figure 5.6 PHC Upper site. Comparison between burnt and intact tall tussock grassland in seasonal variation in mineral-N levels and nitrifying bacteria numbers (NH_4^+ oxidisers only).

released from micro-organisms killed during the fire in the manner described by Woodmansee and Wallach (1981).

The higher NH_4-N levels after burning, compared to NH_4-N levels in the intact control, were sustained for most of the next seven months after which they dropped well below the NH_4-N levels at the intact control.

NO_3-N levels after burning treatment lagged behind the increased NH_4-N levels recorded during this period but increased slightly from mid-November to mid-January after which they fell to the levels of the intact control soil. They later fell below those levels from July 1978 until the end of sampling. Few changes in nitrifying bacteria numbers were recorded in response to burning.

UPPER SITE (Figure 5.6): An immediate increase in NH_4-N levels (22 $\mu g\ g^{-1}$ to 27 $\mu g\ g^{-1}$) occurred after burning. NH_4-N levels with burning increased steadily for 24 days after treatment. They were matched by a small increase in NO_3-N levels with burning treatment from 28 October to 10 November. By 18 November both NH_4-N and NO_3-N levels had returned to the levels of the intact control. A minor increase in nitrifying bacteria was recorded on 10 and 18 November.

NH_4-N levels with burning treatment increased above those of the intact controls again from 18 February to 19 July. There was no corresponding increase in nitrifier numbers during this period and NO_3-N levels in response to burning increased above the intact control levels only on 19 July.

From August 1978 until the end of sampling NH_4-N and NO_3-N levels in soils from the burning treatment fell slightly below soil levels from the intact control.

The main influences of burning tall tussock at PHC upon soil nitrogen levels and possible explanations for these effects are detailed below:-

1. At both sites burning caused a same day increase in NH_4-N which is attributed to destruction of micro-organisms.

2. At the Lower site, burning was followed by an upsurge in mineralisation and a small upsurge in NO_3-N production for the next six months by which time there was vigorous growth of grasses and herbs between the burnt tussocks. Demand for NH_4-N and NO_3-N from these plants may be responsible for lowering mineral N levels at the burning treatment below those of the intact control.

3. An upsurge in mineralisation also occurred at the Upper site after burning causing a sustained increase in NH_4-N levels and a brief increase in NO_3-N levels. Invasion by introduced grasses and herbs did not occur at this high altitude acidic, wet site. Plant demand for NH_4-N after the burning treatment may therefore have been much less than that at the intact control site which may account for the maintenance of higher NH_4-N levels here after burning. NO_3-N levels after burning treatment did not match the upsurge in NH_4-N production possibly because of the poor nitrifying capacity of soils at the Upper site.

(ii) Cultivation:

LOWER SITE (Figure 5.7): Mineral N levels showed no response here until six weeks after cultivation. Nitrifier mpns. however rose dramatically four weeks after tillage.

The major surge in NH_4-N production, six weeks after cultivation, was accompanied by a corresponding major increase in NO_3-N levels and nitrifier mpns. These higher levels at the cultivated site compared to the intact control were maintained until the end of sampling 12 months later.

MID SITE (Figure 5.8): There was no response in mineral N levels or nitrifying bacteria numbers here until five weeks after cultivation when on 25 November and again on 2 December, a major increase in NH_4-N levels was recorded in response to cultivation treatment. This was accompanied by a slight increase in NO_3-N levels.

After this date, NH_4-N levels remained slightly higher with cultivation than in the intact control for most of the remaining sampling period. NO_3-N levels soon returned, however, to the levels of the intact control.

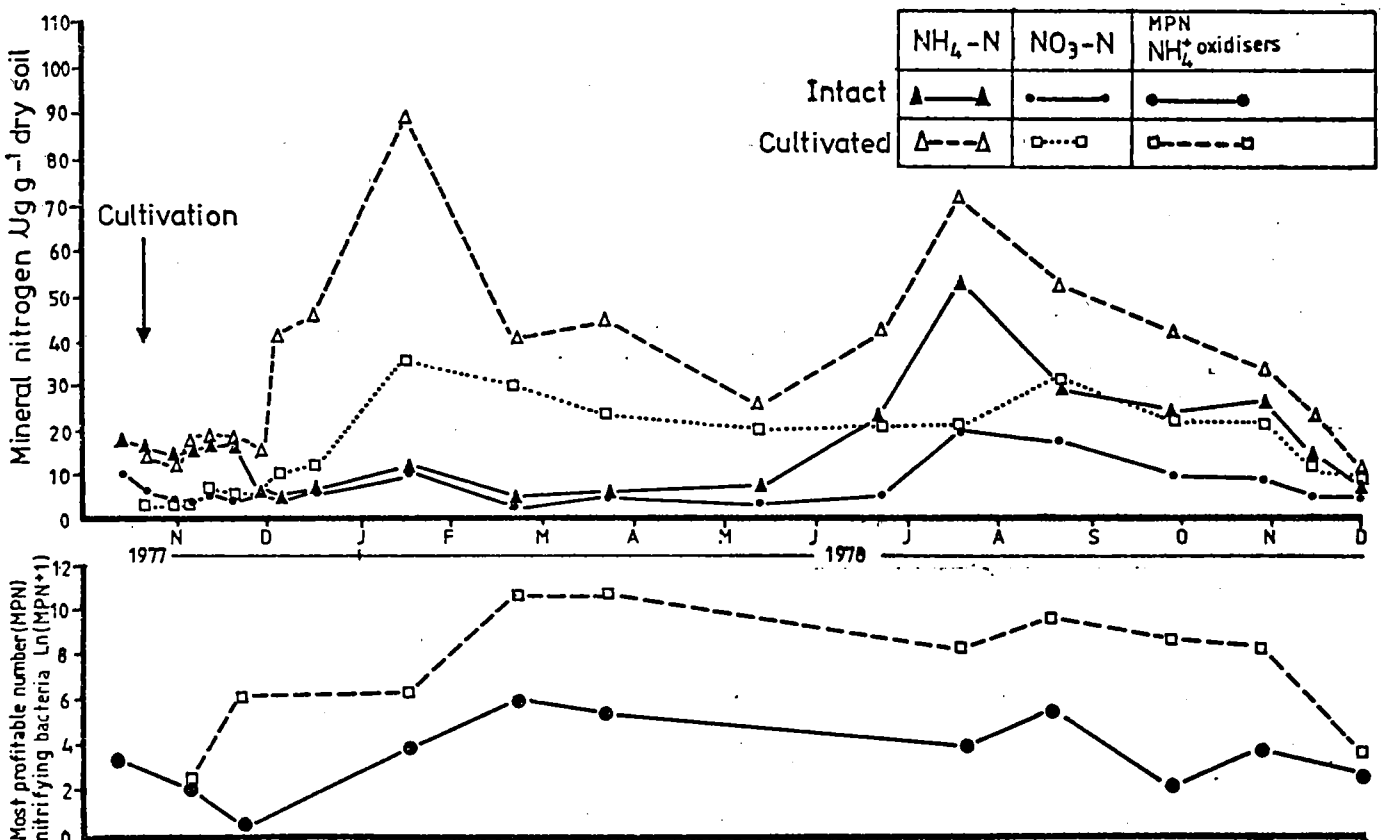

Figure 5.7 PHC Lower site. Comparison between cultivated and intact tall tussock grassland in seasonal variation in mineral-N levels and nitrifying bacteria numbers (NH_4^+ oxidisers only).

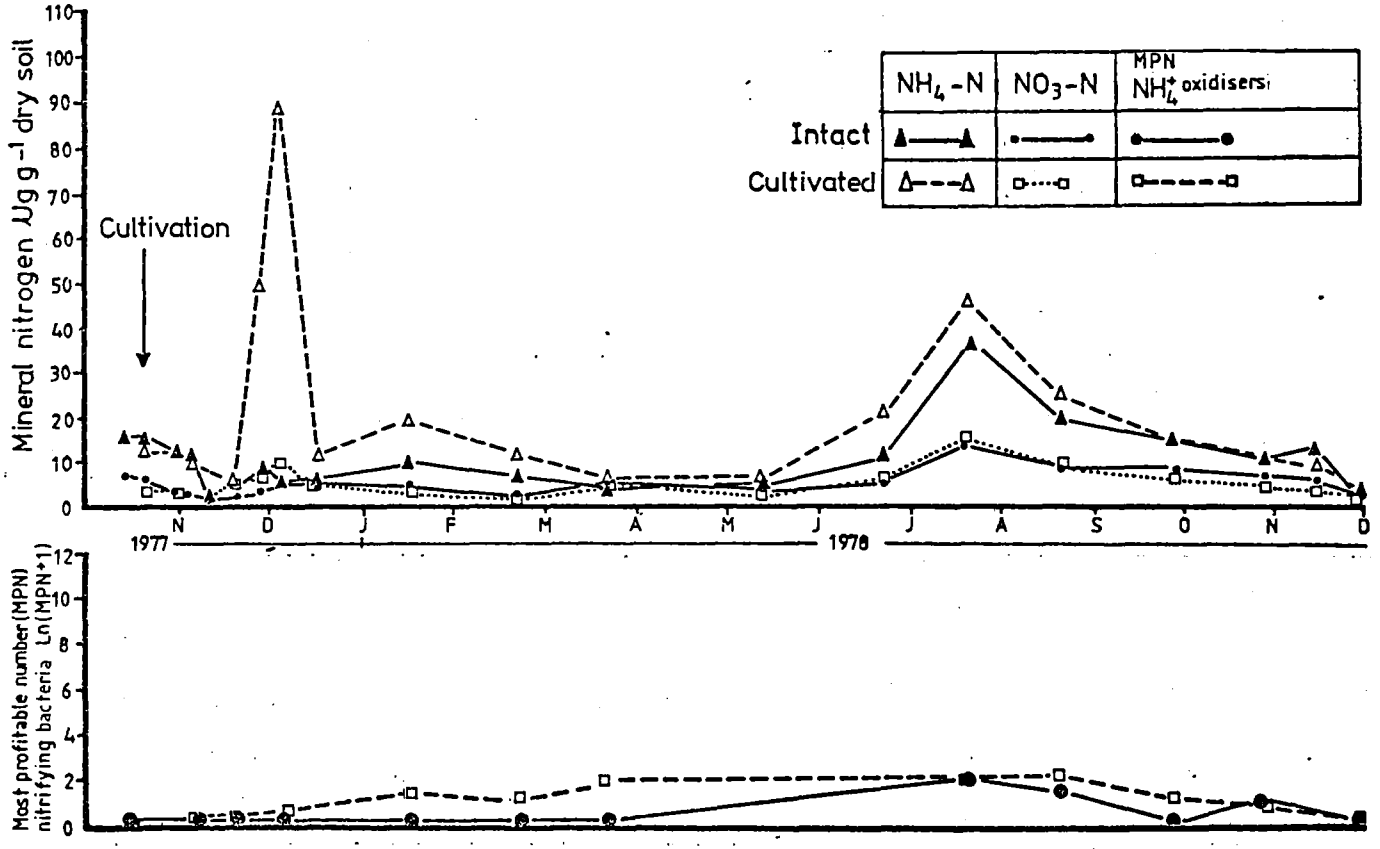

Figure 5.8 PHC Mid site. Comparison between cultivated and intact tall tussock grassland in seasonal variation in mineral-N lvels and nitrifying bacteria numbers (NH_4^+ oxidisers only).

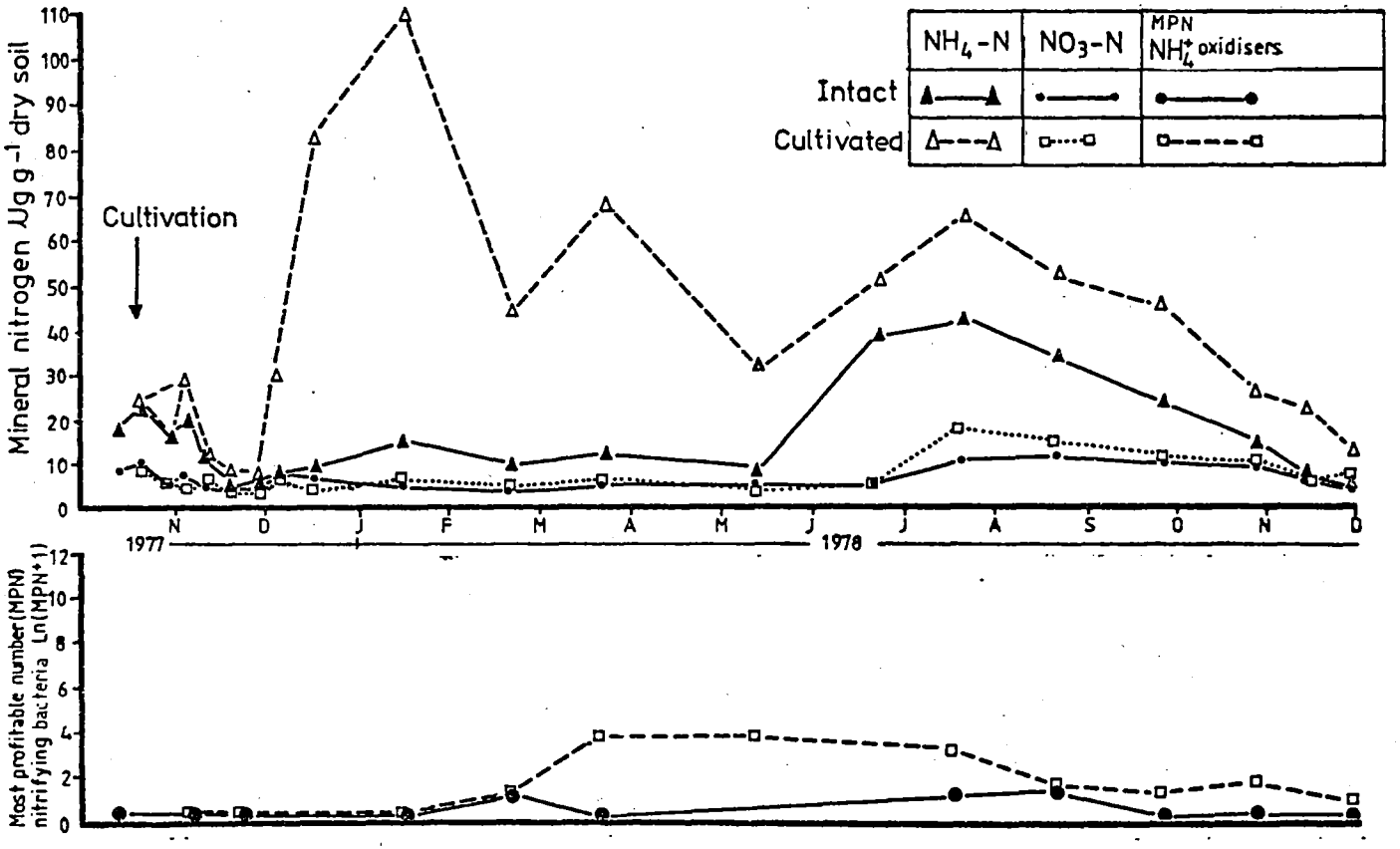

Figure 5.9 PHC Upper site. Comparison between cultivated and intact tall tussock grassland in seasonal variation in mineral-N levels and nitifying bacteria numbers (NH_4^+ oxidisers only).

Nitrifier mpns. with cultivation remained slightly higher than at the intact control for most of the duration of the experiment.

UPPER SITE (Figure 5.9): Like the Lower site, cultivation at this site caused no change in mineral N or nitrifier levels for six weeks after tillage. An enormous surge in NH_4-N levels then occurred. Higher NH_4-N levels were then recorded with cultivation compared to the intact control until sampling ceased.

There was no increase in NO_3-N levels to match the NH_4-N increase with cultivation apart from a brief small surge at the July and at the August 1978 winter samplings. Nitrifier numbers showed no apparent response to cultivation until five months later on 20 March 1978. From this time onwards nitrifier numbers were steadily higher with cultivation treatment than at the intact control treatment.

The main effects of cultivation of tall tussock grassland on mineral N transformations at PHC and possible explanations for these effects are detailed below:

1. The 5-6 week lag in NH_4-N production at all sites after cultivation was probably caused by microbial immobilisation during decomposition of the large quantity of litter and plant residues incorporated into the soil.

2. Cultivation treatment at all sites then caused a major surge in NH_4-N production which was sustained until the end of sampling at the Upper and Lower sites where a large quantity of plant residues were incorporated into deep soils already high in organic matter. The surge at the Mid site was more brief. This response is likely to result from the small quantity of plant residues at this site and its natural low soil organic matter content. Less substrate is therefore available here for mineralisation to take place after cultivation treatment.

3. The moderate nitrifier population already present at the Lower site responded rapidly to an increase in NH_4-N substrate with cultivation and nitrifier numbers increased rapidly resulting in sustained high NO_3-N production.

4. Some nitrifiers were initially present at the Mid site. These responded to cultivation and increased in numbers slightly. A brief surge of NO_3-N production accompanied the surge of NH_4-N production but lack of substrate possibly prevented this NO_3-N surge from being sustained.

5. The Upper site had very low nitrifier numbers prior to cultivation. These were therefore unable to capitalise on the major increase in NH_4-N substrate until nitrifier numbers could build up. This seems to have taken about five months after which a brief increase in NO_3-N levels was recorded under cultivation treatment.

(iii) Cultivation and superphosphate fertiliser (Figure 5.10).
At the Deer site, as at the other cultivated sites described in the previous section, there was a lag of 4-7 weeks before sharp increases in NH_4-N, NO_3-N and nitrifier mpns. were recorded.

By the mid-March sample date, clover and introduced grasses covered about half the cultivated area. The marked drop in mineral N levels recorded at this date and later in May was attributed to plant uptake. Clover and grasses died back after the frosts and snow of June 1977 and a July surge in NH_4-N and NO_3 levels at the intact control treatment was matched and exceeded with cultivation treatment. This pattern continued until November after which both cultivation and control treatments recorded similar mineral N levels. By November grass and clover growth was prolific and these plants covered the entire surface of the cultivated treatment. Demand for mineral N from this extensive plant cover at the cultivation treatment is considered the reason why NH_4-N and NO_3-N levels remained at the same level as at the intact tussock control, even though nitrifier numbers remained higher with cultivation treatment for the duration of the experiment.

The winter 1978 surge of mineralisation was considerably less at the cultivation treatment than at the intact control possibly because by this stage the cultivation treatment contained less organic nitrogen vunerable to freeze-thaw effects.

Because cultivation at the Deer site occurred in a different season, with different cultivation techniques and with the addition of both fertiliser and seeds to its soil, it is not considered valid to directly compare

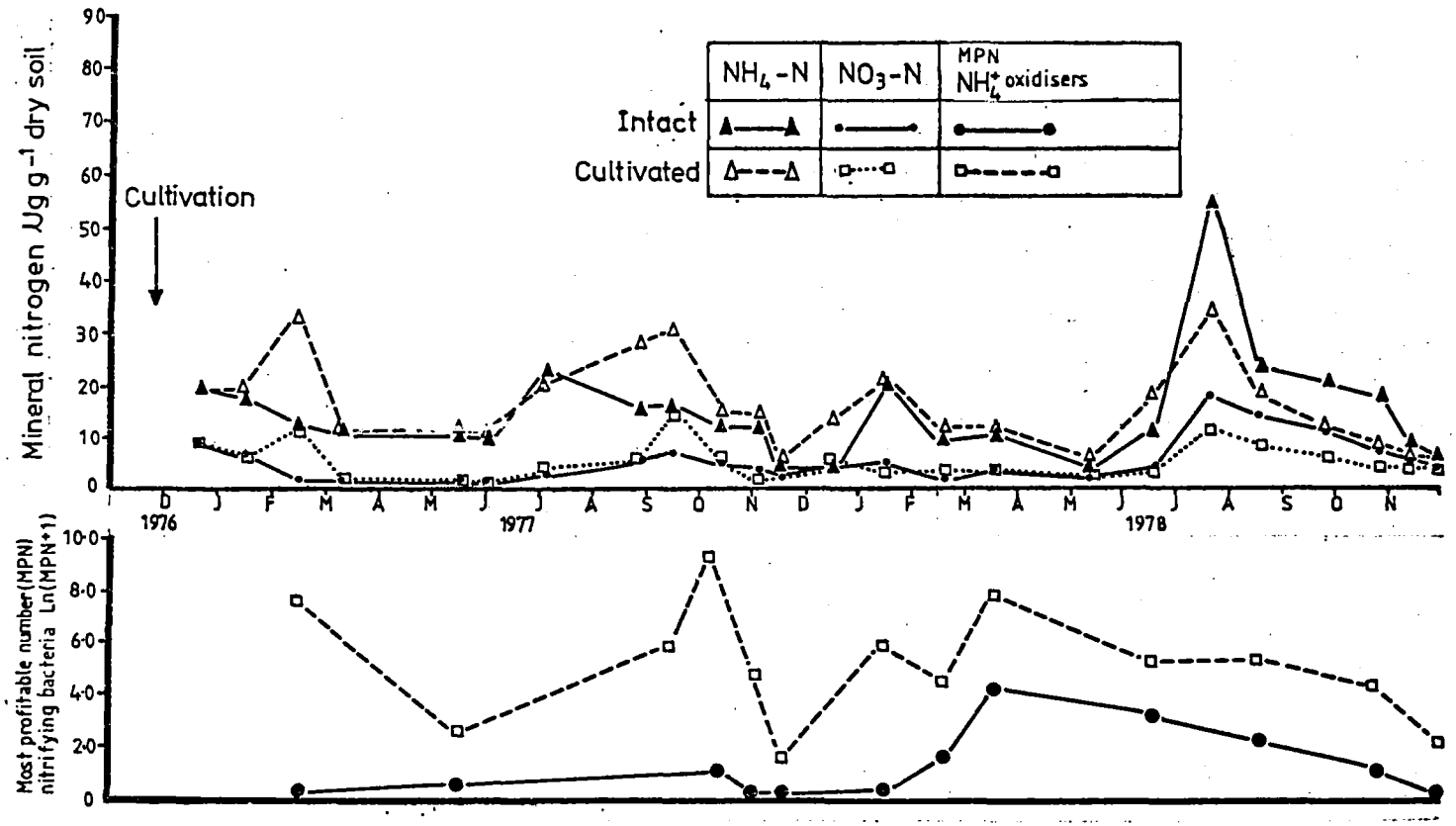

Figure 5.10 PHC Deer site. Comparison between cultivated and intact tall tussock grassland in seasonal variation in mineral-N level and nitrifying bacteria numbers (NH_4^+ oxidisers only).

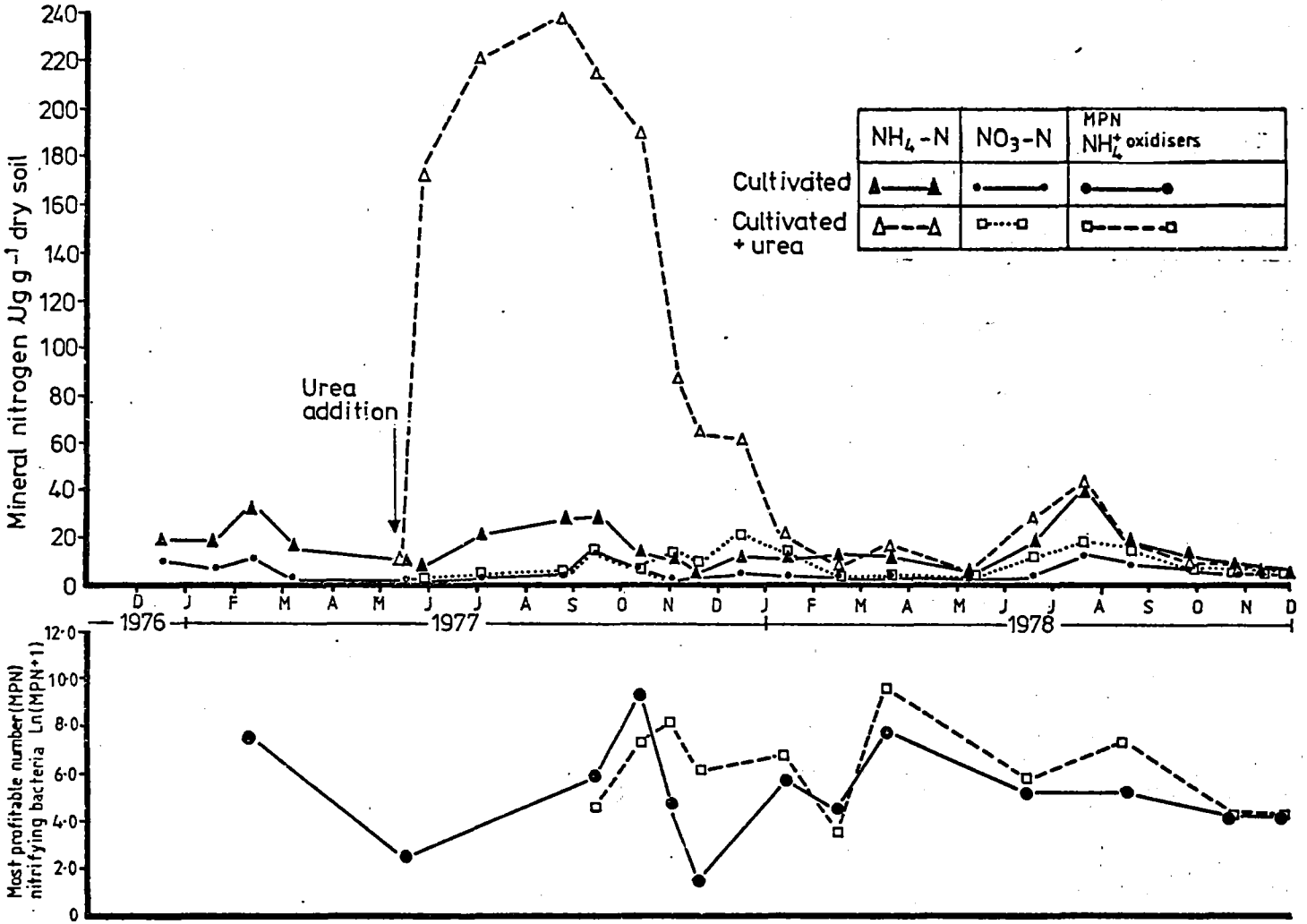

Figure 5.11 PHC Deer site. Comparison between cultivated tall tussock grassland in seasonal mineral-N levels and nitrifying bacteria numbers with and without urea application at 80g Nm^{-2}.

cultivation at the Deer plot with cultivation at the nearby Lower plot. It is interesting to note, however, that the expected surge in mineralisation and nitrification occurred at both sites in response to cultivation.

Clearly it is impossible to isolate the influences of cultivation, fertiliser and oversowing in the general study described here. The addition of superphosphate fertiliser with the clover seeds however, appears to have encouraged the rapid colonisation of bare tilled ground with a dense plant cover. It is postulated that uptake by these plants caused the substantial drop in mineral N levels with cultivation treatment over the autumn of 1977 and from November 1977 onwards and thereby may have functioned as a nitrogen-conserving mechanism.

(iv) Cultivation, superphosphate and urea (Figure 5.11)
The winter-applied urea caused an immediate massive accumulation of NH_4-N at the first sampling on 28/5/77, 10 days after application. NH_4-N levels remained much higher than at the cultivated control until January 1978, eight months after application. Grass growth at this site was vigorous from spring 1977 and plants probably absorbed up much of the NH_4-N present in the soil.

Nitrifier mpns remained near the high levels sustained at the cultivated control treatment for the duration of sampling. It is interesting that nitrifier mpns at the urea treatment, with abundant NH_4-N substrate, did not rise much higher than levels at the cultivated control treatment. This suggests nitrifier numbers may well have been at the maximum level for the treatment soil and that the limiting factor to further population increase was something other than NH_4-N substrate availability.

Surprisingly NO_3-N levels under the urea treatment did not show a marked increase compared to the cultivated control until the 3 November sampling after which NO_3-N levels briefly surged then returned to similar levels to the cultivated control by Mid-February 1978.

Since abundant nitrifying bacteria were present prior to this NO_3-N increase in November, and abundant NH_4-N substrate was available, it is concluded that either NO_3-N production was inhibited between May and November or that NO_3-N was removed from surface soil layers in the urea plot soon after it was produced during the winter period.

Because the adjacent cultivated control treatment showed abundant NO_3-N production through the same five month winter period it seems reasonable to favour the latter option. Vegetation cover was sparse on the urea treatment until early December 1977 so it seems unlikely that the NO_3-N was lost to plant uptake. A more probable explanation is that the NO_3-N was leached from the system. Soil moisture content over this period was considerably higher under cultivation treatment than at the adjacent intact tussock grassland and comprised 40% of soil weight.

5.4 DISCUSSION.

The experiments described in this chapter were conducted over a short time period in a limited area at only four sites and therefore the results obtained cannot be extrapolated with confidence to tall tussock grasslands elsewhere in New Zealand.

At Paddle Hill Creek, it has clearly been shown that major changes in soil nitrogen transformations can occur with drastic disturbance of natural grasslands through fire and cultivation. These results provide partial confirmation for the proposal of O'Connor (1974) that degradation from tall tussock to short tussock grasslands and bare ground encourages nitrogen loss from the system and that:-

> *"... the dominant pathways (for that loss) have probably been volatilisation and other gaseous or particulate loss in burning from the above ground nitrogen pools, followed by increased mineralisation, nitrification and leaching of nitrate from the soil pool ..."*

5.4.1 Burning.

The effects of spring burning on soil nitrogen transformations at the Lower and Upper Paddle Hill Creek sites appeared to be mainly short term. Burning caused a surge in nitrogen mineralisation at both sites matched by a smaller increase in nitrifying bacteria and soil NO_3-N levels. The increase in NH_4-N and NO_3-N levels lasted five months at the Lower site but was sustained for 11 months at the Upper site where tussock regrowth and colonisation by opportunist adventive plants was poor. There were indications towards the end of sampling that burning might have reduced both NH_4-N and NO_3-N levels at both sites.

Burning obviously causes a loss of nitrogen from this system through volatilisation. In addition, the brief surge in nitrate levels at both sites is likely to have increased the potential for leaching loss of this soluble ion although, in the absence of any lysimeter sampling, it is impossible to say whether such losses actually occurred.

Results for this experiment are in general agreement with increases in nitrifying bacteria recorded after burning in Kansas prairie (O'Connor, 1974) and changes in soil nitrogen levels after burning of Missouri prairie (Kucera and Ehrenreich, 1962) savanna (Christensen, 1977) and forest systems throughout the world (Likens *et al.*, 1977; Phillips, 1981).

5.4.2 Cultivation.

Cultivation of tall tussock had a more dramatic and sustained effect on soil nitrogen transformations at PHC than did burning. This effect was particularly pronounced at the two sites supporting a dense tall tussock cover, a deep litter layer and soils of high organic matter content. By contrast, the Mid site showed only a brief surge in nitrogen transformations possibly because it had already undergone significant depletion of its nitrogen pool as described in Chapter 4

Cultivation caused significant reductions in the soil moisture content of all soils at Paddle Hill Creek following the pattern described by Power (1981). Ross and Bridger (1978) and Ross *et al.* (1978) have shown that drying of tussock grassland soil can markedly increase nitrogen mineralisation.

Following cultivation there was no immediate mineral N increase but after five to six weeks there were rapid increases in NH_4-N at all sites. These increases were accompanied by increases in NO_3-N levels at those sites where significant populations of nitrifying bacteria had been present before cultivation. At the Upper site, where a major NH_4-N increase was not accompanied by an increase in NO_3-N, the very small initial nitrifier population took five months to show an increase in numbers compared to the intact control population. The dramatic increase in soil mineral N levels shown in this series of cultivation experiments has also been shown to occur after cultivation of natural grasslands in Canada (Doughty *et al.*, 1954) and elsewhere (Russell, 1961; Keeney and Bremner, 1964; Power, 1981). The results for Paddle Hill Creek cultivation contrast with those of O'Connor *et al.* 1962 who reported

a negligible mineralisation effect after cultivation of unimproved grassland and concluded that:-

> *"... an acid, low fertility, temperate zone grassland soil may differ in its behaviour very markedly from the pattern recorded from high fertility leys.."*

These contrasting results for N.Z. tussock grassland soils are not necessarily in conflict. At Paddle Hill Creek, the surge in mineralisation at the Mid site was only brief compared to the higher fertility Lower and Upper sites. This Mid site has already been pushed part way along the N losing transition described by O'Connor (1966, 1974). It is possible that the Craigieburn soil studied by O'Connot *et al.* (1962) was even further along this nitrogen-losing transition and was incapable of responding to the mineralisation-promoting effects of drying, temperature increase and substrate increase caused by cultivation unless these were enhanced with lime and phosphate fertiliser. Their conclusion that the cultivation of natural tussock grasslands with high acidity and low fertility is unwarranted because this will not initiate a surge of mineralisation and nitrification to encourage grass and clover growth may well apply to the Craigieburn soil. Certainly it seems unlikely to apply to any of the soils studies at Paddle Hill Creek, although clearly this remains to be tested more fully.

The Paddle Hill Creek studies show that cultivation can significantly promote soil nitrogen transformations. The resultant rapid increase in soil NO_3-N levels points to the possibility of nitrogen loss from the generally well-watered soils found at this locality unless cultivation is followed by rapid plant establishment and growth to reduce the high levels of mineral N present in the soil. Even with such plant establishment, a major reduction in total soil nitrogen is probably inevitable after cultivation of natural grassland. Keeney and Bremner (1964) showed that after cultivation, a range of U.S. grassland soils lost an average of 36.2% of their total nitrogen. A similar dramatic reduction has been demonstrated in soils in the well known Broadbalk experiment at Rothamstad (Newbould, 1981).

The pathways by which such losses occur include nitrate leaching, ammonia volatilisation (Woodmansee, 1978) denitrification (Woodmansee, 1979) and increased loss from the system caused by removal of crop residue and animal biomass (Power, 1981).

5.4.3 Cultivation and fertiliser

While the cultivation and fertiliser experiment at the Deer site is not directly comparable with results from the other sites, it serves as an interesting contrast to the results of O'Connor *et al.* (1962). Phosphate fertiliser added after cultivation appears to have made little difference (compared to the Lower site) to a system where nitrogen mineralisation and nitrification were already vigorous. It did, however, stimulate the growth of clover and grasses. Uptake by these plants was probably responsible for the dramatic reduction in soil mineral N levels at the site three months after fertiliser application.

This highlights the importance of establishing a plant cover as soon as possible after cultivation in this type of high country soil rather than leaving a long fallow period when leaching losses can occur (Khanna, 1981). Even with the establishment of a plant cover, through the winter months there are likely to be dramatic increases in the levels of soil mineral nitrogen, induced by improved moisture regimes, freeze-thaw effects and reduced plant uptake. These are likely to result in a marked increase in the leaching of nitrate from the cultivated tall tussock grasslands in a similar manner to that described for other natural grasslands cultivated for the first time. (Stevenson, 1965).

The grass-clover plant cover established after cultivation was unable to absorb a major winter input of nitrogen in a simulated animal urination. However, although urea addition caused an enormous increase in soil NH_4-N levels, little increase in NO_3-N levels occurred until late spring. This suggested that either nitrification was inhibited through the cold wet winter months or that as soon as NO_3-N was produced it was lost from the soil by plant uptake or leaching.

The urea application at a cultivated site introduces the concept of spatial distribution of soil nitrogen transformations already discussed in Chapter 4 . Clearly at localised spots within natural or cultivated sites, nitrogen transformations are likely to be proceeding at different rates because of spatial variation in the location of urine and dung patches, carcasses, localised soil disturbance, soil physical and climate properties etc. Any modelling of nitrogen transformations of any grassland system will need to sum all of these localised influences into an overall model of nitrogen transformations within a given area.

It is important to recognise that drastic modifications to tall tussock grasslands and their modified analogues through burning and cultivation will probably only occur in a comparatively small proportion of the total remaining area of these grasslands. There is considerable public pressure against large scale burning of tussock grasslands. Areas suitable for cultivation are fairly limited and it is far more likely that these will be altered through oversowing without cultivation. Far more significant may be the localised "drastic modifications" caused by high numbers of stock under more intensive grazing regimes. Trampling and pugging of the ground coupled with urine inputs and the grazing to extinction of vulnerable tall tussocks (i.e. *Chionochloa macra*) will simulate many of the cultivation treatments described here.

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CHAPTER 6

SEASONAL VARIATION IN SOIL MINERAL NITROGEN IN TALL TUSSOCK *(CHIONOCHLOA)* GRASSLANDS - FURTHER EFFECTS OF SIMULATED GRAZING BY DEFOLIATION AND UREA ADDITION

6.1 INTRODUCTION

The effects of grazing upon grassland soil nitrogen (N) transformations have been reviewed generally by Floate (1981), examined semi-quantatively by Woodmansee *et al.*, (1981) and discussed in relation to New Zealand tall tussock grasslands by O'Connor (1974; 1981; 1983).

Grazing influences N transformations in four main areas: the consumption of herbage, the return of nutrients in excreta, the treading of soil and vegetation, and the removal of nitrogen in animal products (Floate, 1981).

Some effects of simulated grazing by defoliation and urea application on seasonal variation in soil mineral N at a range of Canterbury and Otago tall tussock grassland sites were described in Chapter 4. There it was noted that the removal of nitrogen in animal products was likely to represent only a very small proportion of the soil/plant nitrogen pool under extensive grazing management conditions. Treading effects upon soil and vegetation have been discussed as a minor form of cultivation in Chapter 5.

In this chapter, a more intensive examination is made of the effects of defoliation and urea addition on tall tussock grasslands. The study described in Chapter 4 examined the longer term effects of repeated defoliation upon soil mineral N transformation. In that study no emphasis was given to sampling soils soon after defoliation. A soil sampling programme was not initiated until five months after defoliation of the Otago sites and until 12 months after defoliation at the Paddle Hill Creek (PHC) sites.

A further defoliation trial, with more frequent monitoring of soil mineral N following defoliation was therefore established to see whether a surge in mineralisation and nitrification immediately follows tall tussock defoliation.

A second feature noted after defoliation in the seasonal study in Chapter 4 was that defoliated sites with soil surfaces not covered with rooted plants generally lost their tussock litter cover. At low altitude sites adventive grasses and other herbs sometimes developed into a dense sward across the bare soil surface. Because it is widely recognised that soil mineral N is usually concentrated in the upper layers of the profile it was considered important to determine what changes in the vertical distribution of mineral N in the soil profile occurred after defoliation.

The addition of urea to intact and defoliated plots, simulating urination by livestock, described in Chapter 4, resulted in marked differences between defoliated and intact treatments. Urea addition caused major increases in soil NH_4-N at all defoliated plots while at some intact plots there was little or no increase in soil NH_4-N at later sampling. It was speculated that *Chionochloa* tussocks might have a capacity for luxury uptake of high concentrations of soil NH_4-N in a manner described by Chapin (1980) for wild plants and demonstrated by Houston *et al.* (1973) in some prairie grasses.

To test this hypothesis, foliar N levels were measured in leaf and sheath tissue of Otago and Canterbury tall tussocks from urea and control treatment plots. Mineral N levels were also measured at different depths in the soil profiles of the Paddle Hill Creek Upper and Lower control and defoliated sites in an attempt to trace the fate of nitrogen applied as urea.

6.2 DEFOLIATION TRIAL.

6.2.1 Site preparation and sampling.

Intact grasslands, adjacent to the PHC Upper and Lower sites, were chosen for this study. Two 5m x 5m plots separated by a 2m wide buffer strip were pegged out alongside each other.

On 8 October 1977, at each site tussocks in one of these 5m x 5m areas were clipped down to the tussock stumps in an identical manner to the defoliation described in 4.2.1.

Soil sampling and analyses, in a manner identical to that described in Chapter 4, was carried out at approximately weekly intervals from 12 October until 15 December and after this at monthly intervals until 28 September 1978.

6.2.2 Results and discussion.

Seasonal soil moisture contents for the intact and defoliated treatments at the Lower and Upper sites are presented in Figure 6.1.

Seasonal variation in mineral N levels and nitrifier numbers (NH_4^+ oxidisers only) at the defoliated and intact plots at the Upper and Lower PHC sites are presented in Figures 6.2 and 6.3.

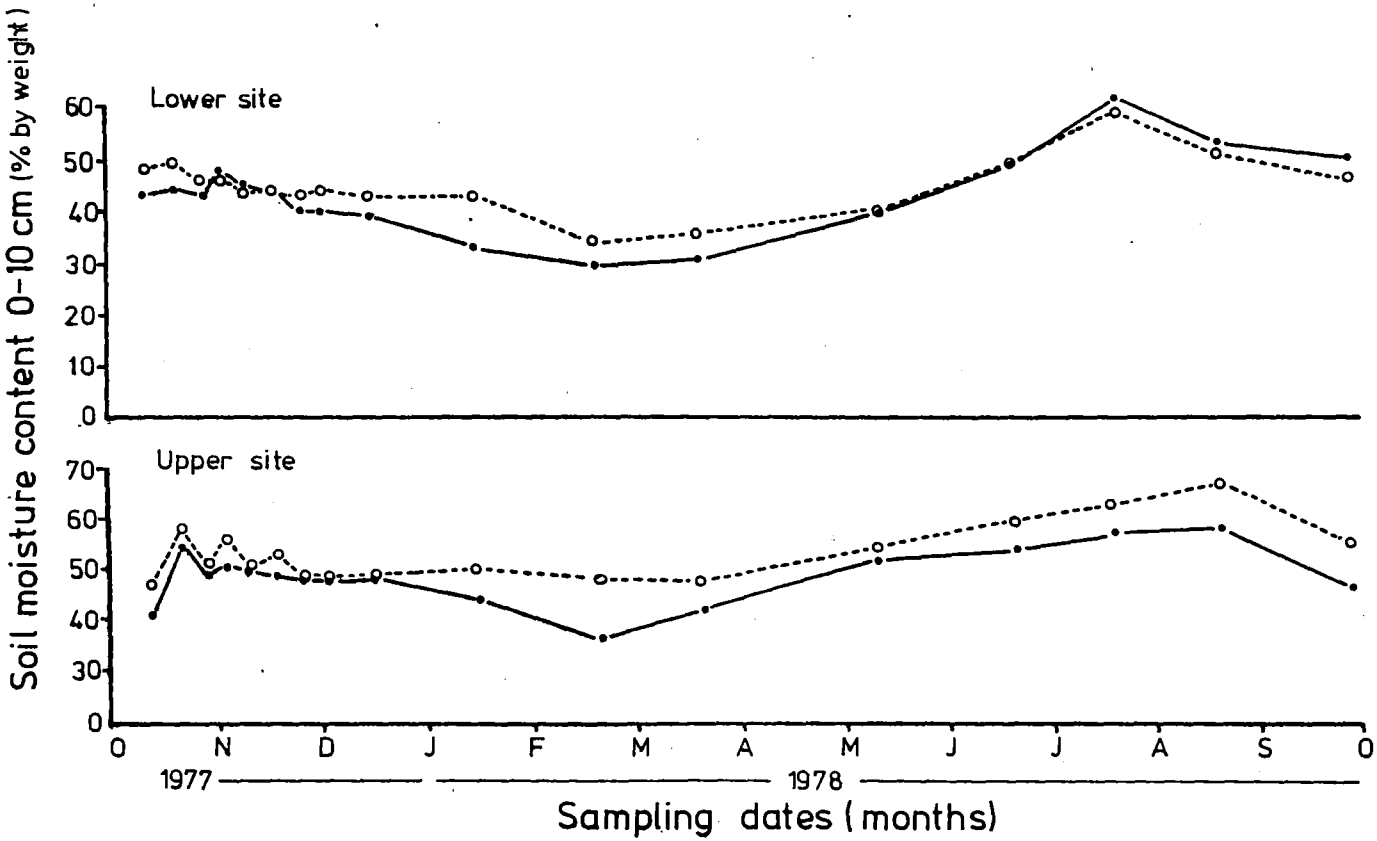

Figure 6.1 Seasonal soil moisture content - Paddle Hill Creek Defoliation Trial

•—• Intact o--o Defoliated (mean of two determinations)

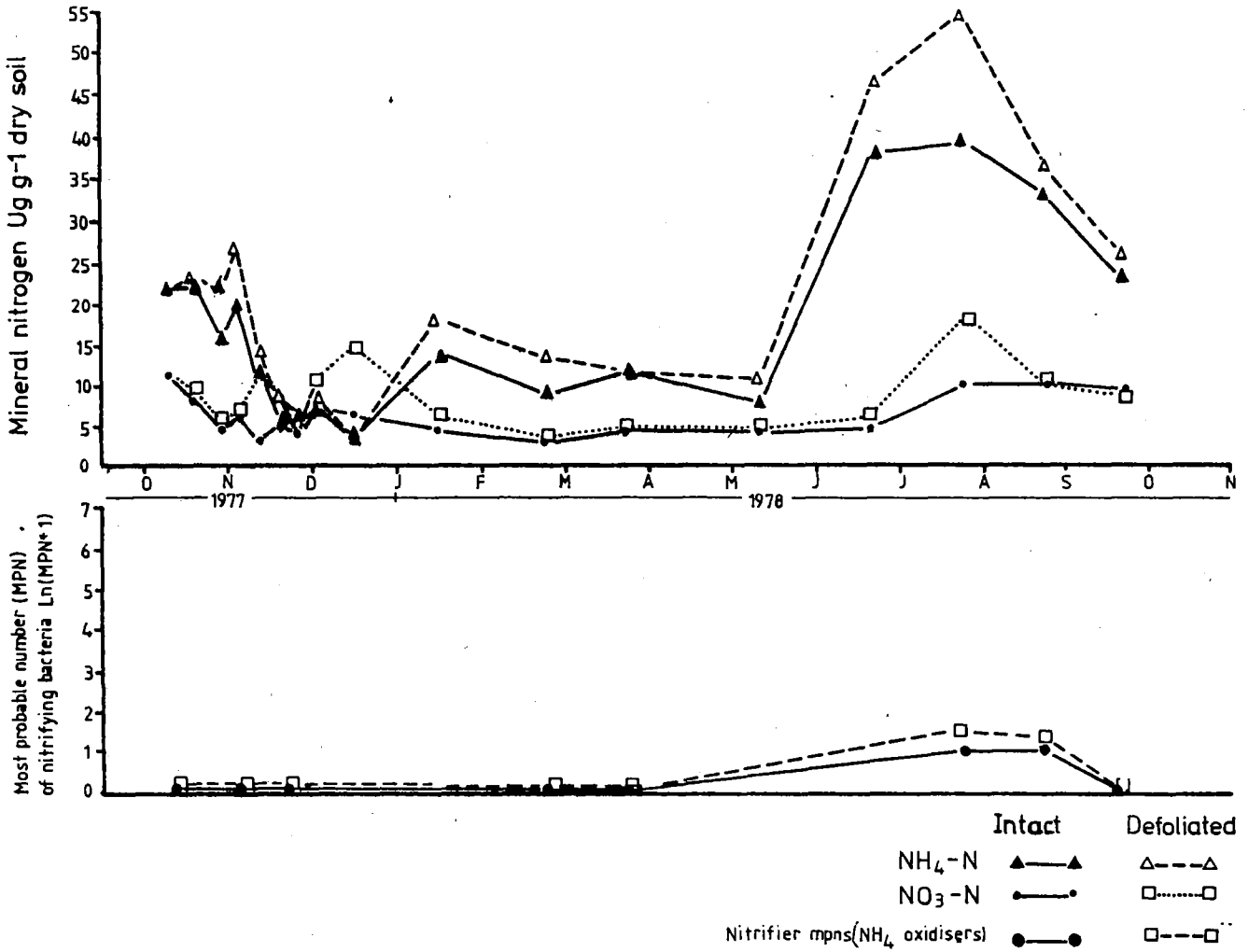

Figure 6.2 Seasonal variation in mineral nitrogen levels and nitrifying bacteria numbers. Defoliation trial. PHC Upper site.

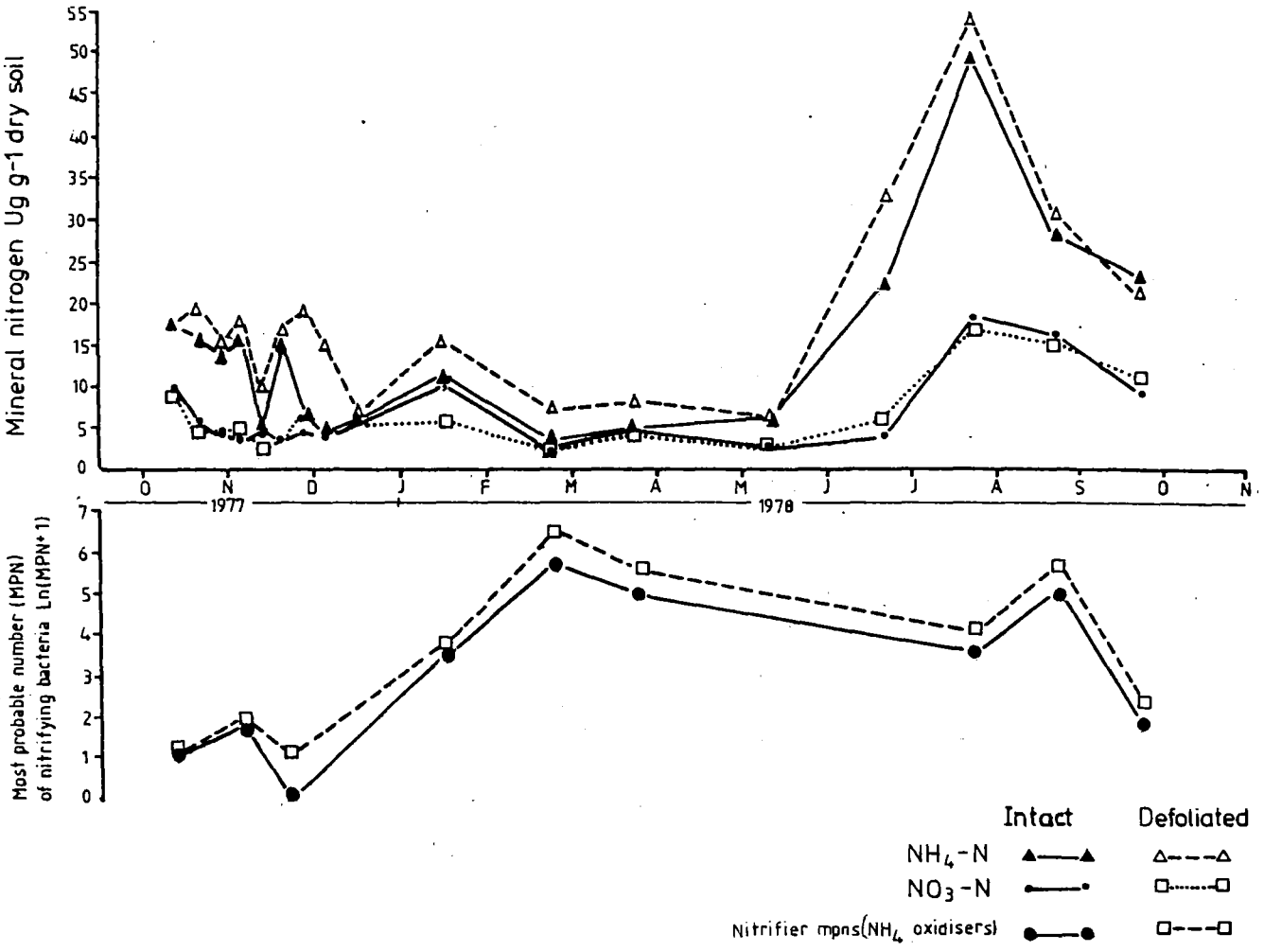

Figure 6.3 Seasonal variation in mineral nitrogen levels and nitrifying bacteria numbers. Defoliation trial. PHC Lower site.

(a) Soil moisture content.

Immediately following defoliation both sites showed slightly higher moisture content in response to defoliation. This difference became more apparent over the 1977-78 summer when the soil moisture contents of the defoliated plots at both sites were considerably higher than in the adjacent intact control plots.

While soil moisture content in the Lower defoliated plot returned to that of the intact control by May 1978 seven months after defoliation, at the Upper site this did not occur. Here defoliated plot soil moisture content remained substantially higher than at the intact plot until the end of sampling.

In the defoliation study described in Chapter 4, defoliation caused a general lowering of soil moisture levels at the Lower PHC site. This was attributed to greater evaporation from the exposed soil surface at this site. The new defoliation trial showed a comparable reduction in soil moisture content with defoliation at the Lower site nine months after defoliation took place, which is consistent with results obtained in the earlier defoliation trial where no soil sampling was undertaken until 12 months after depletion had occurred. At the Lower site defoliation possibly caused an initial increase in soil moisture content because of the reduction in transpiration losses, followed after several months by a decrease in soil moisture content compared to the intact plot resulting from an increase in transpiration losses from the sward of adventive grasses that covered the surface of the Lower defoliated plot.

This explanation would be consistent with the observed pattern of soil moisture content variation at the Upper plot. Here, recolonization of the ground after defoliation was very sparse, therefore there would have been little opportunity for transpiration losses from this site. In the new defoliation trial, soil moisture content at the Upper site increased after defoliation for at least the next 12 months compared to the intact site.

The greater fluctuations in soil moisture content induced by defoliation at the Lower plot would be likely to increase mineralisation and nitrification rates compared to the intact plot. At the Upper site, the wetter conditions induced by defoliation might be expected to limit mineralisation and

nitrification by creating a waterlogged, anaerobic soil environment unfavourable for mineralising and nitrifying bacteria.

(b) Mineral N levels and nitrifier populations.

NH_4-N levels at both the Lower and Upper sites showed small but sustained increases in response to defoliation. This difference between control and defoliation treatments continued almost until the end of sampling.

NO_3-N levels at the Lower site remained virtually the same in both the intact and defoliated plots throughout the sampling period. NO_3-N levels at the Upper site, however, differed markedly between control and defoliation treatments. NO_3-N levels with defoliation treatment were considerably higher than in the intact treatment for most of the 12 month sampling period. These differences were most marked from mid-November 1977 to mid-January 1978, and by August 1978 were no longer apparent.

The observed increase in NH_4-N levels in response to defoliation at both sites is consistent with a reduction in plant uptake of NH_4-N resulting in increased soil NH_4-N levels. An increase in NH_4-N would be expected to stimulate nitrification and hence the production of NO_3-N.

Numbers of nitrifying bacteria increased substantially in response to defoliation at the Lower site, compared to the Lower control treatment, for most of the sampling period. At the Upper site however, a similar response was only seen in samples taken during the winter months of 1978.

The increase in NO_3-N observed at the Upper site soon after defoliation was not accompanied by an increase in numbers of nitrifying bacteria. This kind of situation has been observed previously. The major survey of this site over 1977 and 1978 had shown moderate levels of NO_3-N at the Upper intact plot, particularly in winter, but very low numbers of nitrifying bacteria. The presence of NO_3-N strongly suggests that nitrification has taken place, however the incubation technique seems inadequate in revealing the actual numbers of these bacteria, at least in some soils.

A similar conclusion was reached by Ross and Bridger (1978) and Belser and Schmidt (1978) and is discussed in more detail in Section 8.2.1 of Chapter 8.

(c) Conclusions.

Detailed soil sampling soon after tussock defoliation showed that this treatment apparently altered soil moisture levels, mineral N levels and nitrifying bacteria numbers from those that characterise undisturbed tall tussock grassland at the PHC Upper and Lower sites.

These apparent changes followed rapidly after defoliation. They were characterized by an increase in soil NH_4-N levels but were not necessarily accompanied by an increase in NO_3-N levels nor by increases in the numbers of nitrifying bacteria. Mineral N levels returned close to the levels of the intact control plots 12 months after depletion but studies described in Chapter 4 show that numbers of nitrifying bacteria may remain at elevated levels compared to the intact sites for periods of up to three years after defoliation. This suggests that reduction in uptake of mineral N by defoliated tussocks may have allowed a higher proportion of the ammonium pool to enter a relatively active metabolic cycle in which nitrifying bacteria were at least periodically active. The presence of elevated NO_3-N levels and probably higher nitrifying bacteria supports this hypothesis and confirms the increased potential for N loss resulting from defoliation as suggested by O'Connor (1974).

6.3 MINERAL NITROGEN IN SOIL LAYERS AND DISTRIBUTION OF NITRIFYING BACTERIA.

6.3.1 Sampling and analysis.

Sampling was carried out at the eight Otago sites and at the PHC Upper and Lower sites (Chapter 3). The PHC mid site was not sampled because the stoney soils at this site prevented satisfactory penetration of the soil corer below 100mm. Otago sites were sampled between 24-28 April 1977 and PHC sites on 18 April 1977.

At each defoliated and intact treatment, at each site, 10 soil cores from 0-200mm depth were randomly selected from across the plot. A ruler and sharp knife were used immediately to subdivide each core into the following four soil layers:

1. 0-10mm
2. 20-30mm
3. 40-100mm
4. 100-200mm

Similar layers from each plot were then bulked and blended. Same-day

extraction (as described in Chapter 2) was carried out for mineral N determinations. Soil moisture content and nitrifier mpns of each sample were determined on return to the laboratory.

6.3.2 Results and discussion.

NH_4-N and NO_3-N content and nitrifier numbers (NH_4-oxidisers only) are presented in profile format for the Otago sites in Figures 6.4, 6.5, 6.6 and 6.7 and for the PHC sites in Figure 6.8. Mineral N levels from all sites in the 0-100mm layers were comparatively low in May 1977 (see Chapter 4).

(a) Intact plots.

At all the sites except Alta 2 the 0-10mm layer of intact plots had the highest concentration of NH_4-N and NO_3-N. At the Alta 2 site, NH_4-N and NO_3-N levels in this upper layer were lower than in any of the three lower layers. At this site very small stones and grit were widespread in upper soil layers.

At most sites the 20-30mm layer generally had the second highest level of mineral N. NH_4-N levels were generally higher in the 40-100mm layer than in the 100-200mm layer, while NO_3-N levels in both layers were similar at most sites.

The tall tussock grassland "F"-shaped mineral N profiles shown here resemble those described for Korean grasslands (Kim, 1976), German *Trisetum* meadows (Runge, 1978), Waikato, New Zealand pasture (Steele, 1982) and Canterbury, New Zealand pasture (Ludecke and Tham, 1971). They differ markedly from the "L"-shaped profiles that characterize cropland soils (Steele, 1982).

At five of the intact plots; Maungatua, PHC Upper, Tawhiti, Dunstan and Alta 1, NH_4^+ - oxidiser populations were either not detected or were very low. All the other intact plots; PHC Lower, Pisa, Alta 2 and Carrick showed highest nitrifier numbers in the 20-30mm layer, not in the 0-100mm layer where the highest NO_3-N levels were recorded. The Moonlight intact plot was unusual in that moderate numbers of nitrifying bacteria were recorded in the 100-200mm layer and very few in the upper soil layers.

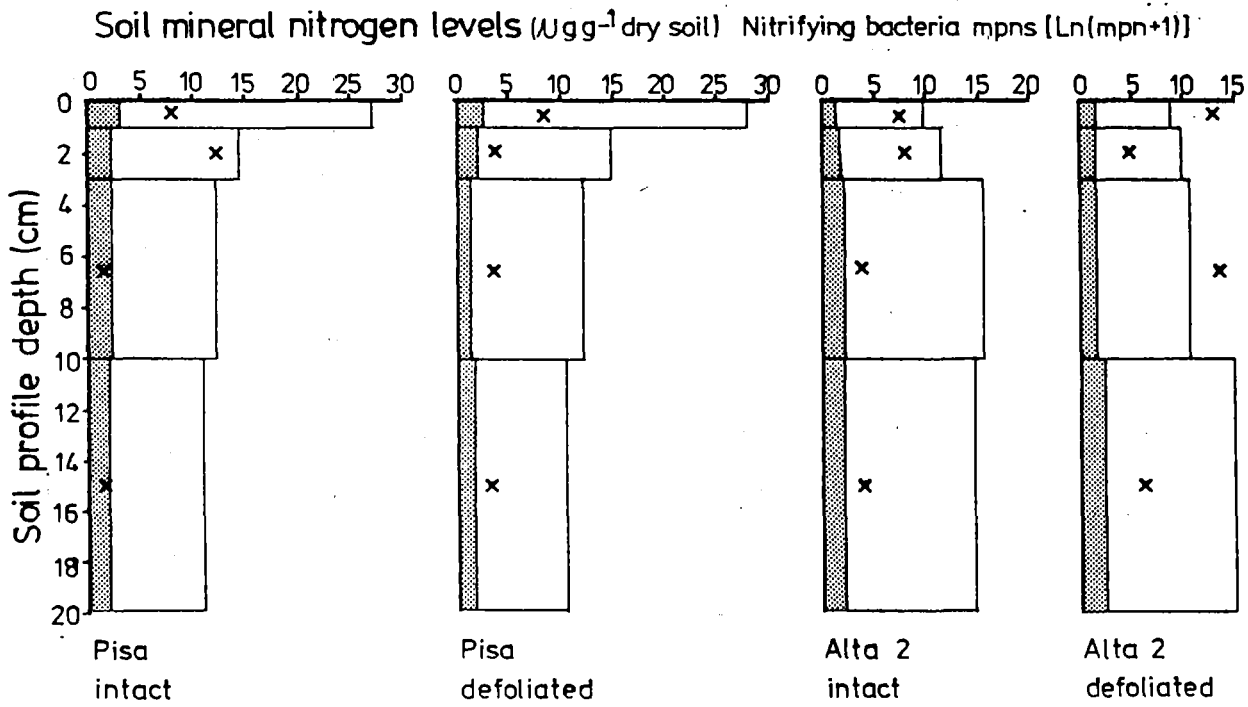

Figure 6.4 Levels of mineral nitrogen and nitrifying bacteria numbers at different depths in the soil profile on 28 April 1977

No_3-N + NH_4-N × Ln(mpn+1)

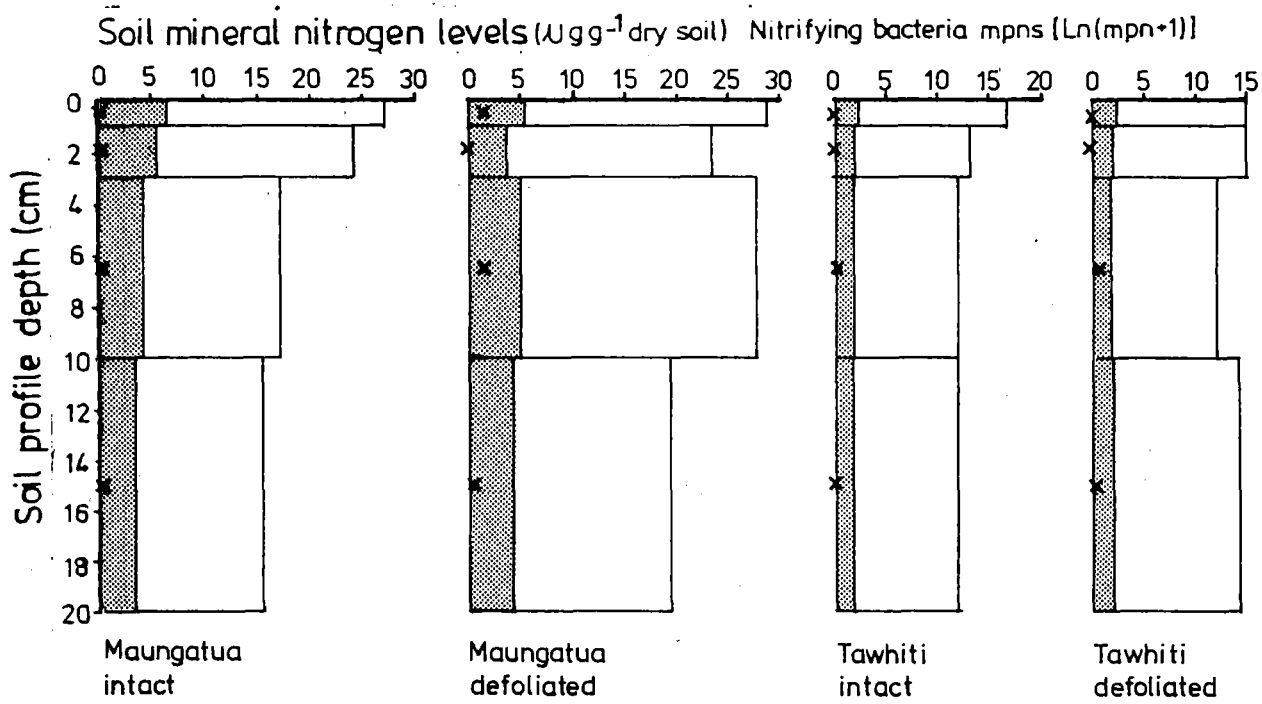

Figure 6.5 Levels of mineral nitrogen and nitrifying bacteria numbers at different depths in the soil profile on 24 April 1977

NO_3-N $+$ NH_4-N × Ln(mpn+1)

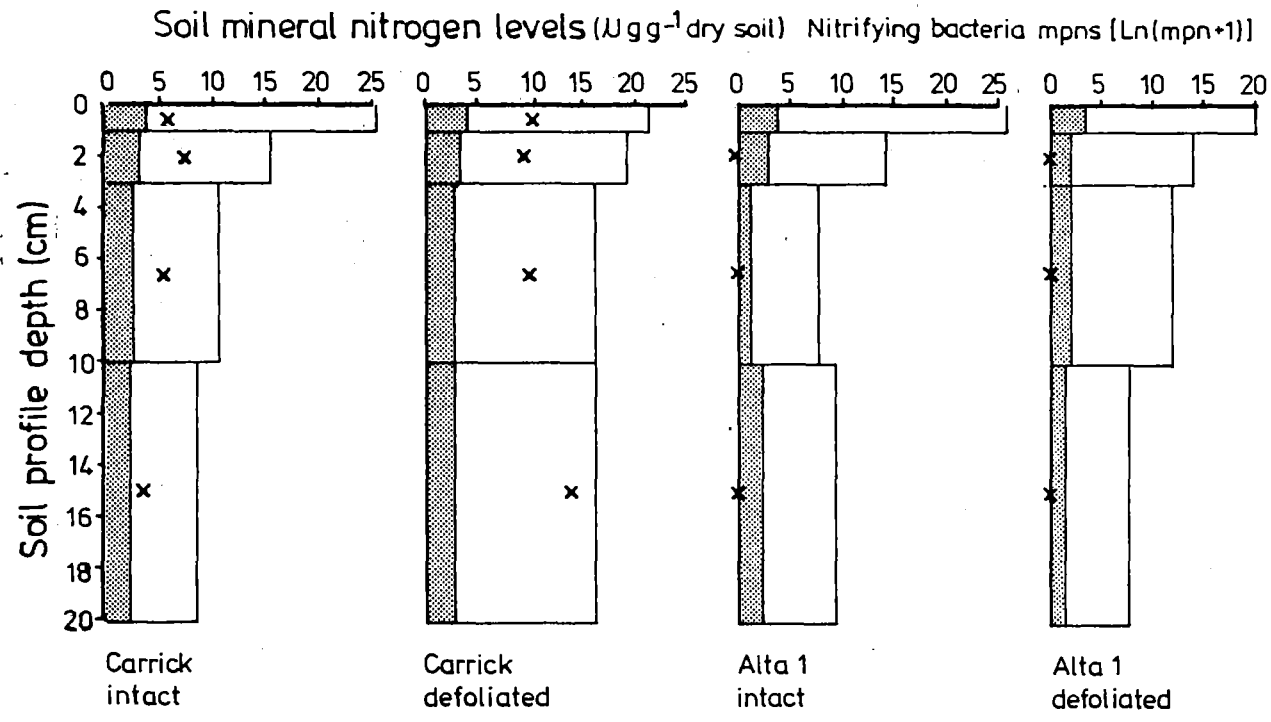

Figure 6.6 Levels of mineral nitrogen and nitrifying bacteria numbers at different depths in the soil profile on 27 April 1977

NO_3-N NH_4-N Ln(mpn+1)

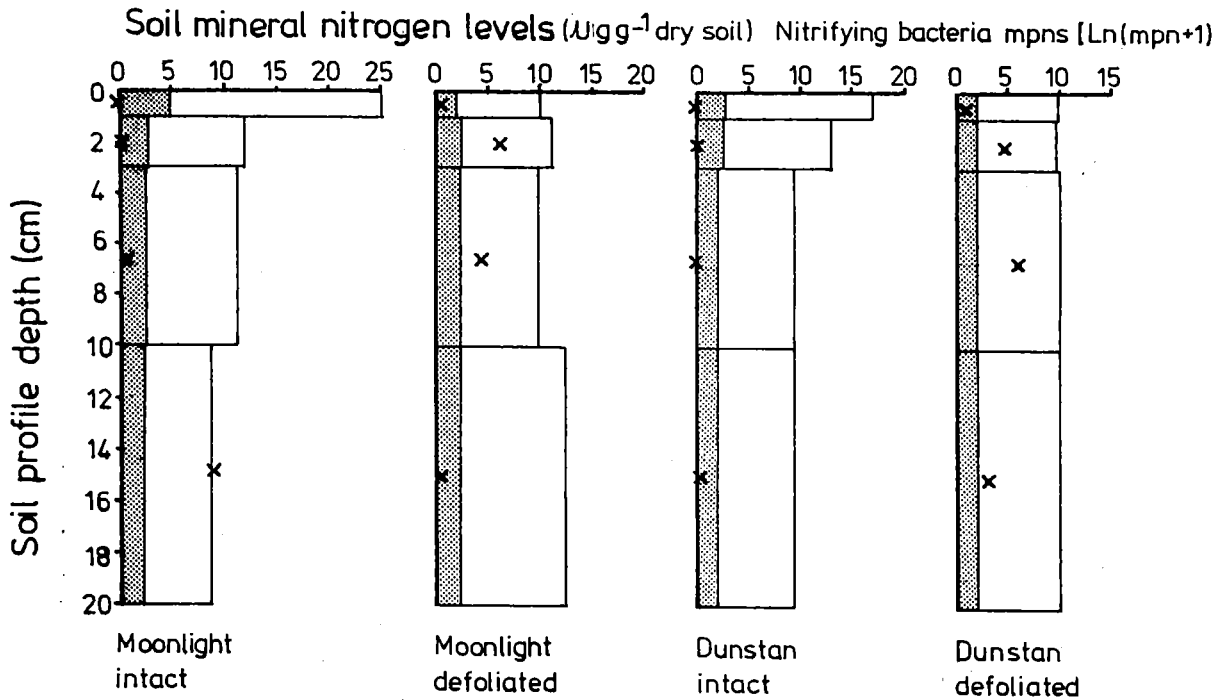

Figure 6.7 Levels of mineral nitrogen and nitrifying bacteria numbers at different depths in the soil profile on 25 April 1977

NO_3-N + NH_4-N × Ln(mpn+1)

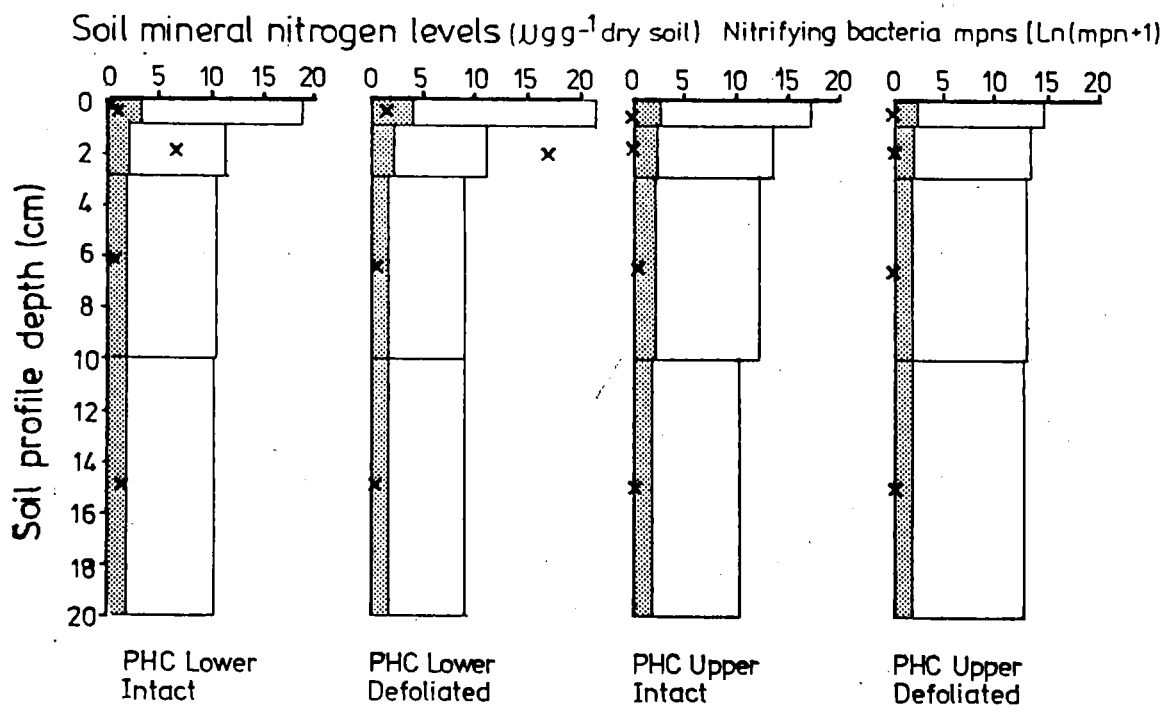

Figure 6.8 Levels of mineral nitrogen and nitrifying bacteria numbers at different depths in the soil profile on 18 April 1977

NO_3-N NH_4-N × Ln(mpn+1)

(b) Defoliated plots.

The defoliated plots showed some distinct differences from the intact plots in the concentrations of mineral N in different soil layers.

Only the PHC Lower and Pisa sites exhibited similar mineral N profiles with both defoliation and control treatments. In contrast, the "F-shaped" profiles of mineral N contents at the Carrick, Alta 1, Maungatua and PHC Upper sites were less distinctive in defoliated plots than in the comparable intact plots. NH_4-N levels in the 0-10mm layer of these defoliated plots were generally lower than in intact plots. Below this 10mm level, NH_4-N concentrations in the intact plots were slightly lower than in defoliated plots.

This apparent response to defoliation was even more pronounced at the Tawhiti and Dunstan sites. These showed similar concentrations of NH_4-N and NO_3-N in all soil layers of the defoliated plots compared to an "F-shaped" profile in their intact plots. At the Alta 2 and Moonlight sites, the mineral N profile in defoliated plots was of the "L-shape" characteristic of croplands.

At four of the sites; PHC Upper, Tawhiti, Maungatua and Alta 1, defoliated plots showed unchanged nitrifier numbers compared to their respective intact plots, with very low nitrifier numbers being recorded at these sites.

The PHC Lower site showed increased numbers of ammonium oxidisers in the 20-30mm layer of the defoliated plot compared to its intact analogue, but not in other layers. At all the other sites markedly higher ammonium-oxidiser numbers occurred in defoliated plots compared to the respective intact plots. These increased nitrifier numbers occurred in each layer down to 200mm depth.

(c) Review of defoliation effects on the distribution in the soil profile of mineral N and nitrifying bacteria.

In the introduction to this study, it was noted that defoliation at many of the tall tussock sites led to a marked reduction in the litter layer covering the soil. At the lower altitude sites other plants quickly invaded this exposed soil. However this invasion was slower at the sites above 1000m altitude.

This profile study, conducted 16 months after initial defoliation took place, suggests that defoliation resulted in a general reduction in the concentration of mineral N near the soil surface accompanied by an increase in mineral N levels deeper in the soil profile. Erosive loss of surface litter layers would account for the decline in the mineral N content of surface layers. It would not however, account for any increase in mineral N further down the profile. This could result from the reduced uptake of NH_4-N by tall tussocks damaged by defoliation. The reduced competition for soil NH_4-N from plant roots would favour microbial use of this ion by nitrifying bacteria. The increase in numbers of ammonium-oxidising bacteria in defoliated plots at many of the sites, particularly in the 40-200mm zone, could result from an increase in NH_4-N substrate.

The sites where such increases in NH_4-N oxidisers were observed were those sites which had already exhibited the presence of nitrifying bacteria even in intact condition and therefore had initial populations of bacteria capable of responding to a surge in available substrate.

Although the high altitude *Chionochloa macra* Otago sites, the two steepland sites here and the PHC Lower site showed moderate numbers of nitrifying bacteria in response to defoliation, it is difficult to offer any simple explanation for the apparent changes in NH_4-N depth profiles in response to defoliation that would take account of altitude, vegetation, climate and other variables. Clearly the individual response of different soils to defoliation deserves further study.

The overall results do, however, confirm the observations made in Chapter 4. The tall tussock grasslands most likely to suffer loss of soil nitrogen after defoliation through an increase in nitrification with the consequent potential for NO_3-N leaching (O'Connor, 1974) appear to be the high altitude Otago grasslands. Even in intact state, these grasslands have resident nitrifier populations which can quickly make use of any increase in NH_4-N substrate resulting from soil disturbance or damage to the vegetative cover.

6.4 THE EFFECTS OF UREA ADDITION ON FOLIAR NITROGEN LEVELS AND ON MINERAL NITROGEN DISTRIBUTION IN SOIL PROFILES.

6.4.1 Methods:

(a) Sampling of foliar material.

Samples of tall tussocks destined for foliar analysis were taken from the PHC Lower and Upper sites on 18 March 1977 and from the Otago sites between 24-26 April 1977. These samples were taken from plots which had been treated with urea in December 1976 (as described in Chapter 4), and from comparable plots at each site which had been left untreated.

The PHC Mid site was not sampled because the sparse tussock growth at this site would have been severely damaged by the removal of the required number of tussock shoots.

Further samples were taken from tussocks at the PHC Upper and Lower sites immediately prior to the application of more urea on 17 May 1977. Samples were also taken from these PHC sites after 10 days on 27 May 1977.

From the intact treatment at each site a bulk sample of 30 shoots (tillers) was randomly pulled from tussocks using the technique described by Williams *et al.* (1976). Only *Chionochloa macra* samples were taken from the Carrick site because *C. rigida* plants were absent from the urea treatment plot.

Tillers were stored in plastic bags at approximately $4^{o}C$ during transport to the laboratory where they were stored below $0^{o}C$ for four weeks. After thawing, each shoot was cut at the junction of the outermost live sheath with the stem and the lower portion discarded following the method described by Williams *et al.* (1976). Their subsequent dissection procedure was not followed because this failed to separate sheath material of varied age from juvenile white leaf material, thereby limiting any possible deductions on plant uptake and development. Instead the procedure described by McSweeney (1974) was followed which recognized and separated the following three distinct portions:-

- Distinctly recognizable sheaths (Sheaths)
- Mature green leaves above the sheath (Mature leaves)
- Central young leaves with undifferentiated white basal portions (Young leaves)

Dead ends on the leaf portions were cut off and discarded. All the samples were then cut into approximately 50mm lengths, dried at $80^{o}C$ in a forced draught oven and ground in a Christy and Norris hammer mill to pass through a 1mm sieve.

Total nitrogen content of the bulked plant segments from each treatment was determined using micro-kjeldahl digestion and colorimetric determination described by Metson (1972). Duplicate analysis of each sample was carried out to check on any laboratory errors and appropriate analytic controls run at the same time.

(b) Soil sampling for mineral N profiles.

Sampling was carried out at the PHC Upper and Lower sites on 17 May 1977, just prior to urea application, and again on 27 May 1977.

Bulked soil samples were taken at each site from the four treatment combinations; with and without urea, intact and defoliated, following the procedure described earlier in Section 6.3.1. Samples were analysed for both NH_4-N and NO_3-N.

6.4.2 Results and discussion.

(a) Foliar nitrogen levels.

Total N content (% dry matter) of the shoot fractions from the urea and control treatments at each site are presented in Table 6.1 for the March/ April samples, and in Table 6.4 for the PHC May samples.

Three to four months after urea application in December 1976, all shoot fractions from the urea plots had markedly higher foliar N levels than comparable portions from the adjacent control plots (Table 6.1).

Tests of statistical significance of shoot fraction effects and of urea effects were applied by analysis of variance using the ten sites as replicates. These effects are shown in Table 6.2. below.

TABLE 6.2: Effects of shoot fraction and urea treatment on foliar N content in tussock shoot fractions from ten Otago and Canterbury sites

	Sheaths	Young leaves	Mature leaves	All fractions
No Urea	$.66 \pm .22$[a] n.s.	$1.05 \pm .19$	$.92 \pm .21$	$.88 \pm .17$*
Urea	$1.05 \pm .18$	$1.34 \pm .15$	$1.26 \pm .22$	$1.22 \pm .09$
Mean	$.86 \pm .08$*	$1.20 \pm .07$	$1.09 \pm .10$	

[a] = mean $\pm$ standard error

n.s. = not significant

* = $P \leq 0.05$

TABLE 6.1: Total nitrogen content (% dry matter) of bulked tall tussock leaf fractions from intact Otago and Canterbury sites, with urea and without urea sampled in March - April 1977.

	Sheaths		Young Leaves		Mature Leaf Blades	
UREA TREATMENT	-	+	-	+	-	+
Site						
PHC Lower	.74	1.33	.94	1.67	.80	1.06
PHC Upper	.66	.96	1.07	1.27	.99	1.08
Pisa	.70	1.69	1.39	1.52	.64	1.27
Alta 2	1.19	1.33	1.27	1.83	1.38	1.57
Carrick	.67	.86	1.11	1.27	.93	1.62
Dunstan	.58	.81	.84	1.21	.96	1.12
Moonlight	.41	.93	.81	1.07	1.08	1.11
Alta 1	.58	.95	1.20	1.25	.89	1.81
Tawhiti	.52	.86	.94	1.18	.74	.80
Maungatua	.52	.80	.97	1.13	.84	1.11
MEAN	.66	1.05	1.05	1.34	.93	1.26

The greatest percentage change (59%) in foliar N levels was found in sheaths. Mean N concentration in young leaves from the Urea treatments was 28% higher than that from the control treatments while mean N concentration in mature leaf blades from the urea plots was 36% higher than that from the unamended control plots.

Four of the sites, PHC Upper, Carrick, Alta 2 and Pisa were sampled for *Chionochloa macra*. The remaining six sites supported *C. rigida*. Comparative levels of foliar N in urea and control *C. macra* and *C. rigida* shoots are presented in Table 6.3 also derived from data in Table 6.1.

TABLE 6.3: Foliar N concentrations (% dry matter) in shoot fractions of *Chionochloa rigida* and *C. macra* from urea and control treatments applied three to four months before sampling.

Species sampled	Urea treatment	Sheaths	Young Leaves	Mature Leaves	All shoot fractions
C. rigida	-	$0.58^{\pm}.17$[a]	$0.95^{\pm}.19$	$.89^{\pm}.21$	$.81^{\pm}.08$
(6 sites)	+	$0.95^{\pm}.23$	$1.25^{\pm}.11$	$1.17^{\pm}.22$	$1.12^{\pm}.10$
	Mean	$0.76^{\pm}.13$	$1.10^{\pm}.07$	$1.03^{\pm}.05$	$.96^{\pm}.08$
C. macra	-	$0.81^{\pm}.22$	$1.21^{\pm}.18$	$.99^{\pm}.16$	$1.00^{\pm}.09$
(4 sites)	+	$1.21^{\pm}.23$	$1.47^{\pm}.17$	$1.39^{\pm}.28$	$1.36^{\pm}.09$
	Mean	$1.01^{\pm}.12$	$1.34^{\pm}.09$	$1.19^{\pm}.12$	$1.18^{\pm}.06$

a = mean $^{\pm}$ standard error

Higher foliar N concentrations were found in *Chionochloa macra* than in *C. rigida* (Table 6.3). N concentrations in shoot fractions of both species were increased by urea.

Over all leaf fractions, both species showed similar increases in N concentrations as a result of urea treatment (+37%) but there is some indication that they differed in the distribution of this effect.

Chionochloa rigida tussocks showed somewhat greater proportional increase in sheath (+64%) and young leaf (+32%) nitrogen concentration at urea plots than did *C. macra* sheath (+49%) and young leaf (+21%) fractions, but in

TABLE 6.4: Total nitrogen content (% dry matter) of bulked tall tussock leaf fractions from Paddle Hill Creek before urea treatment (17/5/77) and after urea treatment (27/5/77).

		Sheaths		Young leaves		Mature leaves	
		17/5/77	27/5/77	17/5/77	27/5/77	17/5/77	27/5/77
PHC LOWER	Control	.72	.76	.95	.92	.80	.82
	+ Urea	1.20	3.34	1.62	3.21	.96	1.15
PHC UPPER	Control	.65	.63	1.05	1.01	.93	.91
	+ Urea	.92	1.21	1.25	1.27	.92	.92

mature leaves the increase in *C. macra* (+40%) was slightly greater than in *C. rigida* (+31%).

Levels of N in leaf blades recorded from the unamended control plots are consistent with those found by Connor *et al.* (1970), Williams *et al.* (1977a; 1977b).

Levels of foliar N in the PHC May samples (Table 6.4) indicated differences in N uptake between the *C. rigida* at the Lower plot and *C. macra* at the Upper plot. At both sites foliar N levels at 17 May, before the application of urea, were close to those recorded in April (Table 6.1).

Ten days after urea was applied to the sites, it appeared that substantial uptake and transfer of N had occurred into the sheath and young leaf fractions of *C. rigida* at the Lower plot and only a small increase in mature leaf N took place. By contrast, the *C. macra* tussocks at the Upper site showed slightly increased N concentrations only in sheath portions, ten days after urea application. These contrasting effects are illustrated in Figure 6.9 and the results are discussed in conjunction with the findings concerning mineral N distribution in the soil profile below.

(b) Distribution of mineral N in the soil profile.
Mineral N concentrations at different depths in the soil profile before and ten days after urea application to defoliated and intact plots are presented for the PHC Lower site (Figure 6.9) and the PHC Upper site.

Major differences between NH_4-N levels in samples collected at 17 May and 27 May were apparent at all plots apart from the Lower intact treatment where both NH_4-N and NO_3-N levels were virtually the same at both dates. Between those dates, the major increase in foliar N context of *C. rigida* at the Lower intact plot suggests that rapid hydrolysis of the applied urea to NH_4-N took place in the soil. The NH_4-N produced appears to have then been rapidly taken up by tussocks at this site and little NH_4-N remained behind in the soil.

By contrast, the Lower defoliated urea plot showed a major increase in soil mineral N levels from urea addition. A large quantity of NH_4-N was present in the 0-10mm layer (206.9µg g^{-1} soil) and an even larger concentration in the 20-30mm layer (362.6µg g^{-1} soil). Soil layers further down to 200mm

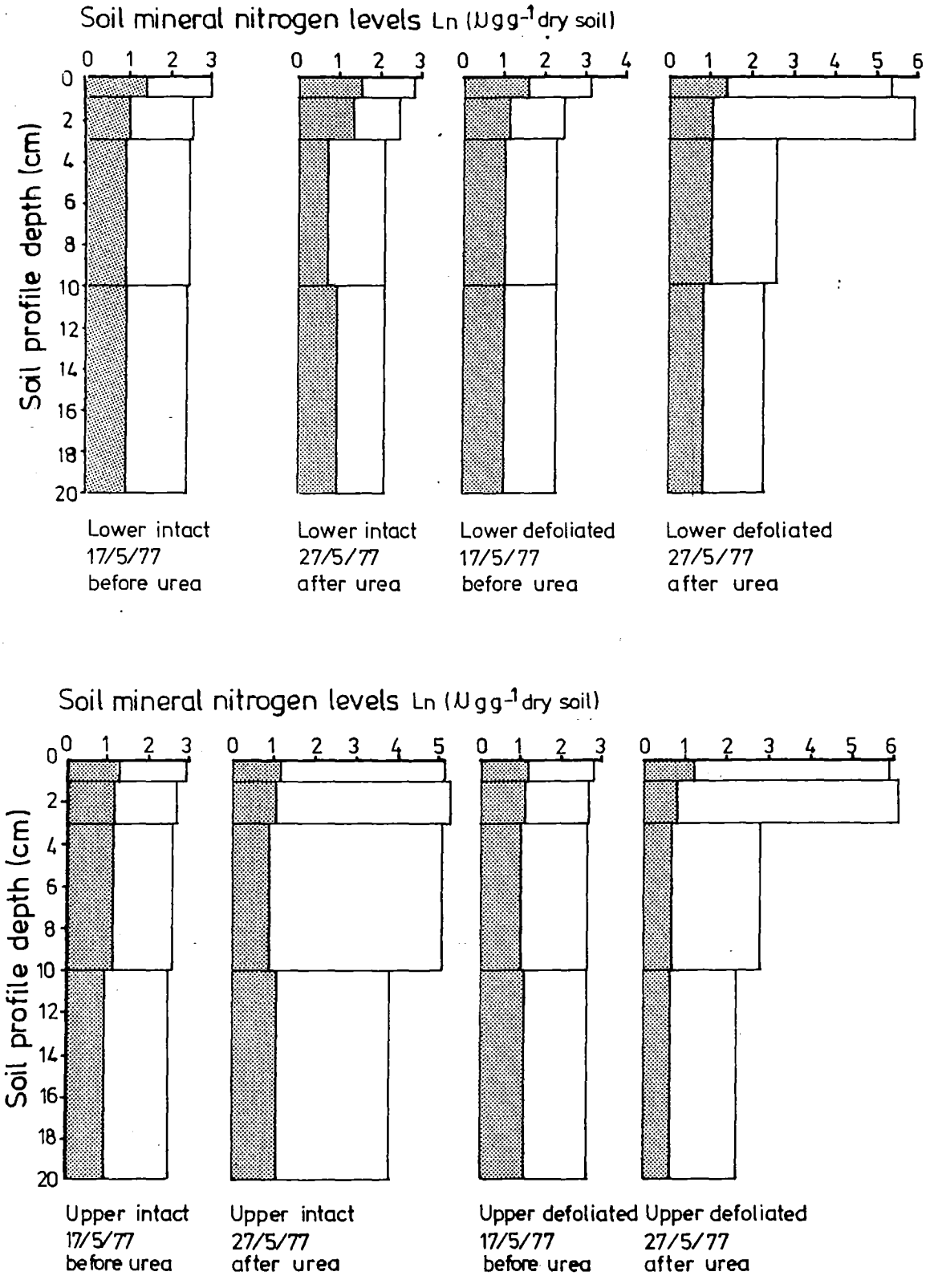

Figure 6.9 Levels of mineral nitrogen at different depths in the soil profile before (17/5/77) and after (27/5/77) urea application at 80g Nm^{-2}. PHC Lower and Upper Sites

Ln NO_3-N ▨+□ Ln NH_4-N

depth showed slightly elevated levels of NH_4-N. NO_3-N levels were unchanged compared to their levels prior to urea application.

At the Upper site both intact and defoliated plots showed a massive increase in soil NH_4-N levels ten days after urea application. The increases in NH_4-N levels in the Upper intact plot in the 0-10mm zone (169.3µg g^{-1} soil) and in the 20-30mm zone (197.04µg g^{-1}soil) were only half the size of the increases recorded in these layers at the Upper defoliated plot (350.7 and 447.6µg g^{-1} soil respectively). In contrast the two lower layers at the intact plot showed much higher NH_4-N levels than the comparable layers in the defoliated plot. One possible suggestion to account for this difference is that on the intact plot urea or NH_4-N in solution may have had more free movement through the soil profile in root cavities.

6.4.3 General discussion of the fate of applied N as urea.

This study of the levels of foliar N and of mineral N profiles in soil after the application of urea to tall tussock grassland gave some indication of the fate of applied N.

Hydrolysis of at least some urea to NH_4-N in both the PHC Upper and Lower soils appears to be rapid. This is consistent with other studies in more genial environments. Holland and During (1977) found that urea applied to a sandy soil hydrolysed in <3 days in winter and <2 days in summer.

Calculation of recovery rates of mineral N in soil at the 27 May in relation to N application rates as urea 10 days previously, indicate that only approximately 10% of added N was accounted for in soil NH_4-N measured in the Lower defoliated urea, Upper intact urea and Upper defoliated urea plots. None of the applied N was apparent as soil NH_4-N in the Lower intact plot.

It is recognized that sampling was insufficient for a detailed quantitative explanation of the subsequent partitioning of applied urea. Nevertheless, it is interesting to speculate what happened to much of the applied urea. Because the presence of urea was not tested on 27 May it is possible that some of the applied N was not immediately hydrolysed to NH_4-N. It is also possible that some was rapidly hydrolysed then volatilized as NH_3. This seems unlikely since the cool conditions that prevailed at both sites during the urea application would not have favoured volatilization and the moist soil conditions that prevailed at the PHC sites would probably have

favoured rapid hydrolysis of urea to NH_4-N.

The concentration of NH_4-N in upper soil layers does not support the proposal that some of the unaccounted for N was located deeper in the soil below the 200mm depth to which measurements were made. Leaching loss of NO_3-N formed from NH_4-N seems unlikely because little nitrification was evident in the soil. It is, however, possible that a significant proportion of the applied N may have been biologically immobilized in soil biota.

Earlier in this section it was demonstrated that considerable quantities of N were taken up during a 10 day period into foliar tissue at both the PHC Upper and particularly at the PHC Lower sites. Because analyses did not include root or rhizome tissue of the tussocks, the presence of substantial quantities of N within this tissue may have eluded detection. Roots and rhizomes are organs known to store carbohydrates and N in several temperate grasses and more especially in arctic tundra ecosystems (Sheard, 1973; Bliss *et al.*, 1973).

The inability to determine the subsequent fate of N applied to a grassland ecosystem has characterized other studies of such systems. Stillwell and Woodmansee (1981) applied urea to a shortgrass prairie and found that four days after application the urea had disappeared and the maximum amount of NH_4-N had accumulated. The distribution of this NH_4-N in the soil profile was very similar to that observed in the PHC prairie soil. In the top 30cm only 50% of the added N could be accounted for in the inorganic N fraction. Stillwell and Woodmansee suggested that volatilization of ammonia and nitrous oxide, plant uptake, immobilization and leaching are possible sinks for this nitrogen.

The uncertain destination of much of the applied N in the PHC studies highlights the opportunity for a carefully monitored quantitative study of urea application to tall tussock grassland in the manner described by Quin (1982) for intensively grazed pastures.

6.5 GENERAL CONCLUSIONS.

This study of the effects of simulated grazing on soil mineral N transformations has shown that significant changes in mineral N can be triggered by the defoliation of and urea addition to intact tall tussock grasslands.

Defoliation removes a proportion of the plant N from the system. Much of this N may then be returned as excreta. Urea applications simulating stock urination had caused a general increase in tall tussock foliar N levels when these were sampled four months later. The most pronounced increase occurred in tussock sheath tissue. Foliar N concentrations were found to be higher in *Chionochloa macra* samples than in *C. rigida* samples but the greatest proportional increase in foliar N in response to urea application was recorded in *C. rigida* samples at the Paddle Hill Creek Lower site.

A more closely monitored autumn urea application resulted in a major increase in the N content of *C. rigida* sheath and young leaf tissue sampled ten days later at the PHC Lower site. By this time no increased NH_4-N levels were recorded in soil at the intact plot, yet at the adjoining depleted plot NH_4-N levels in the soil were markedly higher in response to the urea application ten days earlier.

A higher altitude *C. macra* site (PHC Upper) showed only a slight increase in foliar N ten days after urea application yet soil NH_4-N levels in both intact and defoliated plots increased markedly from urea addition. Whether such differences between the *C. macra* site and the *C. rigida* site are attributable to specific differences in foliar concentrations or in the the ability to take up and translocate nitrogen or whether they are due to site differences in soil biological activity attributable to climate can only be speculated on until more detailed experiments are carried out.

The defoliation of tussocks simulating the heavy grazing by stock was shown to trigger changes in the vertical distribution of mineral N in the soil profile with a reduction in the concentration of mineral N in the upper soil layers being accompanied by an increase in mineral N levels deeper down the soil profile to a depth of 200mm. This was sometimes accompanied by an increase in ammonium oxidising bacteria populations.

Defoliation also caused short term changes in soil moisture content, mineral N levels and nitrifying bacteria numbers in a closely monitored study of two tall tussock grasslands. Soil moisture content was found to increase initially at both sites in response to defoliation. It also caused a rapid surge in soil NH_4-N levels at both sites and in soil NO_3-N levels at one of the sites.

These results are consistent with the hypothesis proposed by O'Connor (1974) that defoliation of tall tussock grassland and the reduction in range condition associated with intensive grazing may increase the potential for N loss from these ecosystems.

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CHAPTER 7

THE INFLUENCE OF ALTERNATE FREEZING AND THAWING ON MINERAL NITROGEN LEVELS IN SOME NEW ZEALAND GRASSLAND SOILS.

CHAPTER 7

7.1 INTRODUCTION

New Zealand's mountain grasslands experience frequent freezing and thawing of surface soil layers, particularly in the autumn and early winter when snowpack is absent. Mark (1965) has described these conditions in the tall tussock *(Chionochloa)* grasslands of Otago. Williams (1977) presented surface soil temperature data for three tall tussock grassland sites in inland Canterbury showing that freeze-thaw activity occurred for several months each year.

In a study at Twin Stream near Mt Cook in inland Canterbury, Archer (1969) showed that both aspect and vegetation cover influence the frequency and seasonal distribution of freeze-thaw (frost-alternate) activity in surface layers of the soil. Sites located at an altitude of 1240 m with a south aspect were subject to sustained snowpack and did not experience the frequency of freeze-thaw days as did a north aspect site at the same altitude. Surface temperatures beneath *Raoulia* mat vegetation were considerably lower than beneath tall tussock cover. At the *Raoulia* site freeze-thaw activity at the surface occurred through most of the year, while beneath tall tussock vegetation frost-alternate days were most marked in the late autumn period (May, June, July).

Physical effects of freeze-thaw activity on surface soil layers in high country tussock grasslands of Marlborough have been considered by Gradwell (1954; 1956). He described the development of needle ice at sites with sunny aspect where snow cover was less than 100 mm deep and which were subject to freeze-thaw regimes. This ice was observed to tear grass roots and cause major disruption to soil particles. This effect was most pronounced at open sites and diurnal ranges in temperature at 25 mm depth in unfrozen soil were approximately halved where the soil was covered or shaded by short tussock *(Festuca)* grasses.

A seasonal soil mineral N survey at Paddle Hill Creek (PHC), South Canterbury, in which monthly samples were taken from a range of tall tussock grasslands over 1977 and 1978 (see Chapter 4) suggested that repeated freezing and

thawing also causes major chemical changes in surface soil. Major surges in NH_4-N levels in early winter were attributed to physical and biological changes triggered by freeze-thaw activity.

Previous New Zealand work has not implicated freezing and thawing in any stimulation of nitrogen mineralisation in the field. Laboratory studies have, however, found that freezing could cause an increase in NH_4-N levels in tall tussock grassland soils. Ross and Bridger (1978) showed that a single freezing and thawing stimulated subsequent mineral N production appreciably in a Carrick soil and slightly in Tawhiti and Obelisk soils from the Otago region. A further study of the Carrick soil (Ross *et al.*, 1979a) suggested that this soil contained more mineralisable N in winter (25 May) than in autumn (15 March). Ross *et al.* (1979b) showed that storage of a range of Otago tall tussock grassland soils at -20°C for 24 hours caused a significant increase in NH_4-N content in all soils and a significant increase in NO_3-N levels in most soils.

Studies of grassland soils in Canada and in the United States have explored the field effects of marked downward shifts in soil temperature, freezing and freeze - thaw and have found that these generally stimulate nitrogen mineralisation (Soulides and Allison, 1961; Biederbeck and Campbell, 1973; Campbell and Biederbeck, 1982). These authors have postulated that the soil shearing involved in freeze-thaw regimes might have analagous effects to the drying-wetting regimes studied by Birch (1964) and lead to increased mineralisation of organic matter.

In this study, intact sods from a range of soils were subjected to a simulation of the alternate freeze-thaw conditions that soils might be subjected to during early winter in the South Island high country at sites free from snow pack. It was hoped that this would determine whether such treatment could stimulate nitrogen mineralisation and increase levels of soil mineral N.

7.2 SOILS AND METHODS

7.2.1. Field sampling:

Five soils were used in the study. These were chosen to represent a range of field situations from an altitude of 50 m above sea level (a.s.l.) to

1300 m a.s.l. The soils were a lowland pasture soil from Lincoln (Tai Tapu silt loam, N.Z. Soil Bureau, 1968), a degraded high country soil carrying short tussock vegetation (Craigieburn high country yellow brown earth, N.Z. Soil Bureau, 1968) in which N mineralisation and nitrification had been studied earlier by Robinson (1963), and three tall tussock grassland soils; Carrick, PHC Lower and PHC Upper soils all described in earlier soil mineral N studies (see Chapter 3).

Field sampling was carried out in mid-May 1978, a time of the year when earlier mineral N sampling had revealed moderate NH_4-N and NO_3-N levels in the tall tussock grassland soils.

At each site, a large sod complete with vegetation measuring approximately 1.5m x 1.5m x 0.5 m deep was dug carefully from the ground and lifted onto a trailer.

Great care was taken to ensure that the sods remained intact while they were transported rapidly to Lincoln. This was to prevent any mixing of the different layers of the soil and the collapse of soil structure causing a cultivation effect known to stimulate both mineralisation and nitrification (see Chapter 4). Ross and Bridger (1977) caution against extrapolating results from their laboratory freeze-thaw experiments to field situations because of the soil disturbance and absence of living plant roots in the soils used in their various soil incubation studies of nitrogen mineralisation.

It was hoped that the collection of large, intact soil sods would overcome the disturbing effects of transportation and allow careful replicated experiments with intact soil cubes.

7.2.2. Laboratory treatment:

Immediately upon return to Lincoln, vegetation was cut down to 100 mm above the soil surface. This vegetation and the upper 100 mm of soil beneath it was trimmed with a sharp knife from each sod and eighteen 40 mm x 40 mm x 100 mm deep rectangular blocks were cut from this upper soil layer. These eighteen samples of each soil provided duplicate samples for the three temperature treatments at each of the three sampling dates and overcame

the problem of obtaining sub-samples from a frozen sod. Samples were placed in 40 mm x 40 mm x 100mm deep plastic pots which had previously been washed with deionized water.

The eighteen pots for each sampled sod were randomly assigned six to each of three temperature treatments:-

1. CONTROL 5°C: Dark cold room. 80% relative humidity.
2. FROZEN - 9°C: Freezing chamber on a high setting.
3. FREEZE-THAW 5°C/-9°C: Interchanged every 12 hours between treatments 1 and 2.

All 30 potted soil cubes at each temperature treatment were randomly assigned to positions on a single plastic tray.

7.2.3 Sampling and analysis:

Prior to starting the incubation, two pots of each soil at each temperature treatment were sampled. After trimming and discarding the surface vegetation the soil in each pot was crumbled free from roots, weighed and mineral nitrogen extraction procedures and soil moisture content determination carried out using the methods described in Chapter 4.

After six days incubation, a further two pots of each soil at each temperature were sampled and analysed in similar fashion. The final sample was taken 36 days after the start of incubation. Vegetation on each pot remained green in colour at this stage.

7.3. RESULTS:

Mean NH_4-N and NO_3-N levels recorded for the duplicate soil samples at each sampling date under the different temperature treatments are presented in Tables 7.1 and 7.2. Total mineral N levels for each temperature treatment at each site are graphed against time in Figures 7.1 and 7.2.

7.3.1. Freezing and thawing:

Figures 7.1 and 7.2 reveal that a major increase in mineral N levels occurred in the PHC Upper and Lower soils and to a lesser extent in the Carrick soil in response to the alternate freezing and thawing treatment.

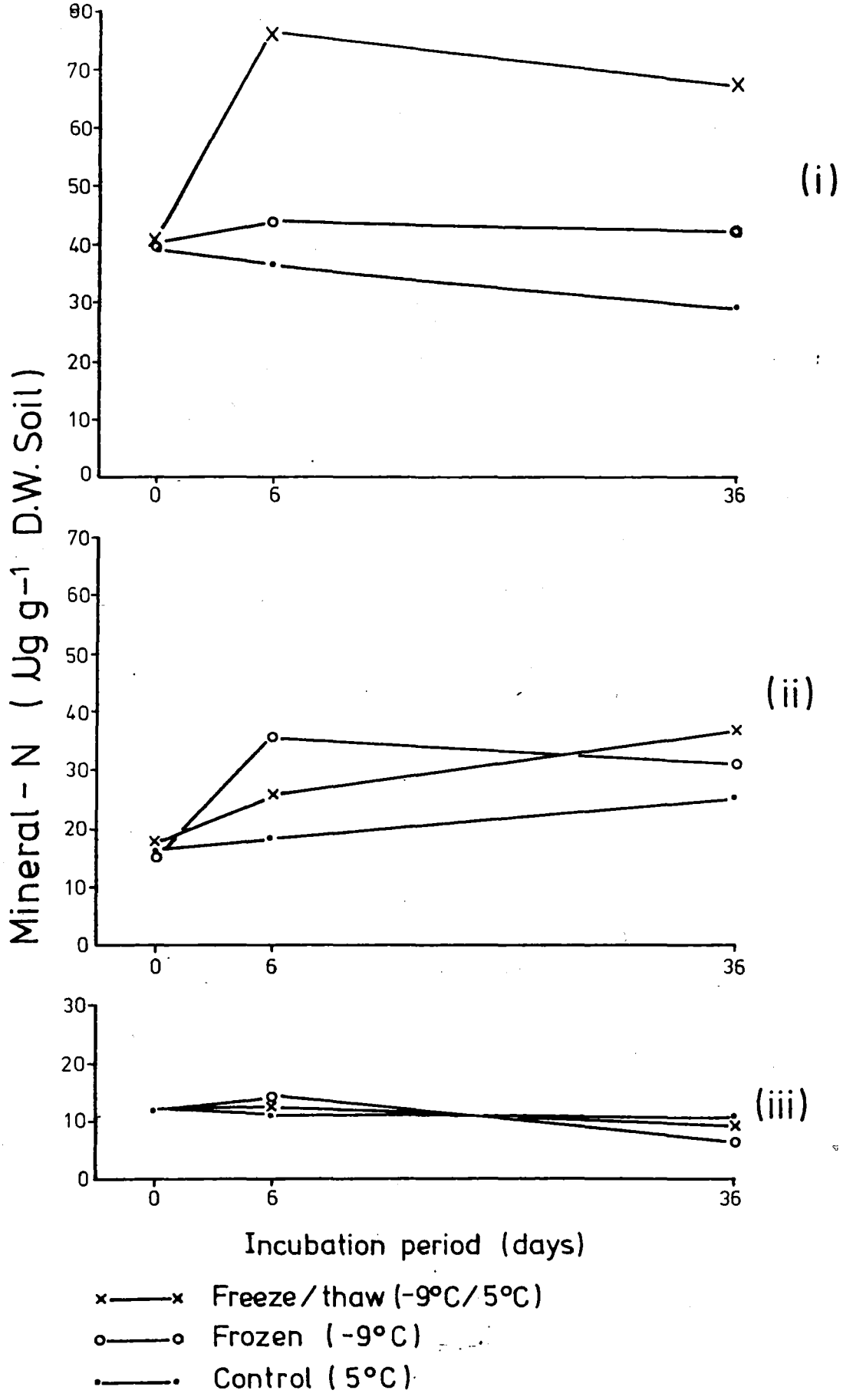

Figure 7.1 Mineral nitrogen content of a range of soil sods during 36 days incubation under three different temperature regimes: (i) Carrick (ii) Lincoln (iii) Craigieburn

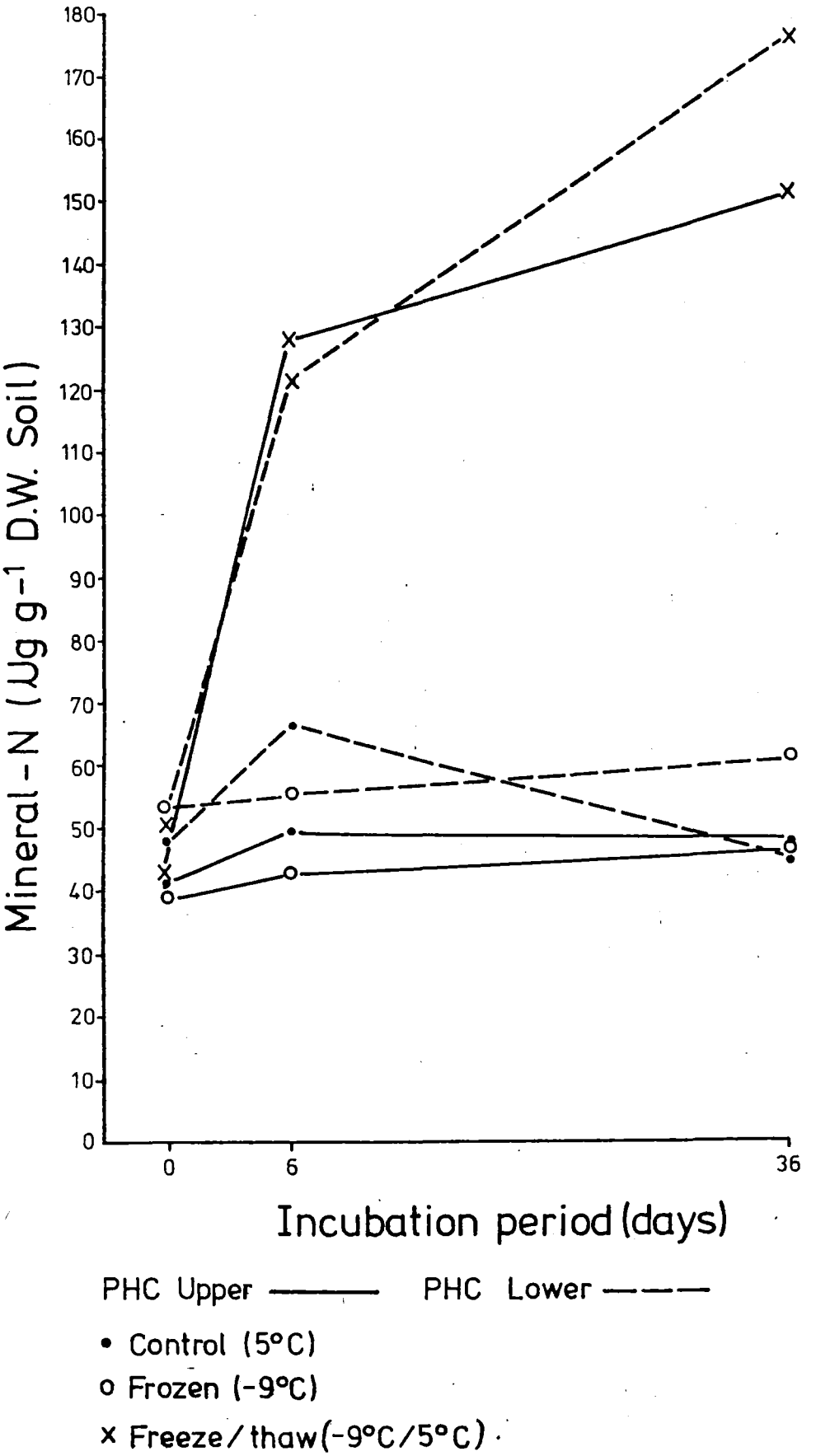

Figure 7.2 Mineral nitrogen content of Paddle Hill Creek (PHC) soil sods during 36 days incubation under three different temperature regimes.

TABLE 7.1: Influence of freezing and freeze/thaw on NH_4-N ($\mu g\ g^{-1}$ soil) content of soil sods from a range of sites incubated for different periods.

SITE	Sampling Date (Days after Start)	TREATMENTS Frozen -9°C	Freeze/thaw -9°/5°C	Control 5°C
Carrick	0	33.2	35.2	33.3
	6	38.6	79.8**	30.7
	36	37.2*	66.0**	26.1
Lincoln	0	11.2	12.3	10.8
	6	30.2**	16.1	12.1
	36	26.9*	21.5	18.6
PHC Upper	0	28.1	29.1	30.5
	6	35.3	114.3**	37.2
	36	33.8	131.0**	35.3
PHC Lower	0	40.1	37.7	35.8
	6	48.2	108.1**	52.8
	36	57.8	167.3**	40.4
Craigieburn	0	5.9	5.6	5.7
	6	7.9	5.4	4.6
	36	5.8	7.8	8.0

N.B. Results are means of 2 samples of each soil at each date. The significance of differences from control at each sampling date for each soil of frozen, and freeze/thaw treatments as determined by students t-test is given by *, **=$P<0.05$, 0.01.

TABLE 7.2: Influence of freezing and freeze/thaw on NO_3-N ($\mu g\ g^{-1}$ soil) content of soil sods from a range of sites incubated for different periods.

SITE	Sampling Date (Days after start)	TREATMENTS -9°C	-9°C/5°C	Control 5°C
Carrick	0	7.2	5.7	5.9
	6	5.2	5.9	5.8
	36	4.2	1.4	2.7
Lincoln	0	4.7	5.2	5.3
	6	5.3	10.0*	6.6
	36	3.8	15.1*	6.4
PHC Upper	0	11.5	13.5	11.0
	6	7.8	13.2	12.4
	36	12.8	12.5	12.1
PHC Lower	0	13.0	13.1	12.1
	6	7.2	12.9	13.6
	36	3.4	8.5	5.8
Craigieburn	0	6.3	6.5	6.5
	6	6.6	6.8	6.9
	36	1.1	1.9	2.4

NB Results are means of 2 samples of each soil at each date.

The significance of differences from control at each sampling for each soil and frozen, and freeze/thaw treatments as determined by students t-test is given by *, ** = $P<0.05$, 0.01.

Both the Craigieburn and the Lincoln Soils showed no significant general increase in mineral N levels in response to alternate freezing and thawing.

Reference to Table 7.1 reveals that the main component of this mineral N increase is a significant increase in NH_4-N levels under freeze/thaw treatment compared to the control (5^oC) treatment in the PHC Upper, Lower and Carrick soils. No significant increases in NH_4-N levels were recorded in the Lincoln or Craigieburn soils in response to freezing and thawing. Significant increases in NO_3-N levels in response to this treatment were recorded only in the Lincoln soil after six and 36 days incubation (Table 7.2).

The major increase in NH_4-N levels detected in freeze/thaw treatments at the three snow-tussock sites occurred within six days of the start of treatment. In the PHC Upper and Lower soils a further 30 days freeze/thaw treatment increased NH_4-N levels appreciably.

7.3.2 Freezing

Freezing caused NH_4-N levels to increase substantially in the frozen PHC Lower soil and in the frozen Carrick soil after 36 days treatment compared to control samples of both soils. A substantial increase in NH_4-N levels was also recorded in the frozen Lincoln soil after six days which was sustained in this soil sampled after 36 days.

These increases in NH_4-N were not accompanied by any significant increase in soil NO_3-N levels. In Chapter 2 an increase in NH_4-N level in response to freezing to -20^oC and storage at this temperature for a week was demonstrated in the Craigieburn soil. Ross *et al.* (1979b) showed that after storage at -20^oC for 24 hours eight Otago soils exhibited significantly higher NH_4-N contents. The major differences between both these earlier studies and the study described here are as follows: whereas the earlier studies both used crumbled and sieved soil, this experiment used intact sods in which the structural properties of the soil were retained. Second, this freezing treatment was done at -9^oC, a soil temperature much more likely to occur in field conditions than -20^oC, as used in the earlier studies.

7.4 GENERAL DISCUSSION

It is widely accepted that the increase in soil NH_4-N levels from freezing

results from disruption of organic or inorganic soil colloids (Hinman, 1970). If previously non-exchangeable inorganic NH_4-N is released it is detectable as NH_4-N. It may or may not be true mineralisation. If, however, colloids or cells are disrupted by freezing and thawing as described by Campbell and Biederbeck (1972) then the transformation of organic nitrogen to NH_4-N occurs through a flush of mineralisation.

Because the studies described here differed from the earlier studies of Ross *et al.* (1979b) both in the temperature of freezing and in the sieving and preparation of soil, it is not possible to ascribe to one factor or the other the differences in results from these two sets of studies.

Clearly freezing to a stable -9°C of intact sods had much less effect on NH_4-N in the three snow tussock soils than did 24 hour freezing to -20°C of sieved soils from Otago snow tussock grasslands (Ross *et al.*, 1979b). Perhaps the disruptive forces on cells and colloids from initial freezing can act much more effectively in loose or sieved soils than in soil retained in an intact sod.

Equally clearly, an alternate freeze-thaw regime had dramatic effects on the NH_4-N levels of snow tussock soils. Repeated freezing and thawing would be expected to cause appreciable disturbance and shearing of soil aggregates and colloids and even to cause the rupture of microbial cells. Such mechanisms may therefore explain why the phenomenon of winter flushes of soil mineral N production is most evident in situations where repeated freezing and thawing occurs than at sites where the soil remains frozen throughout the winter months.

The absence of any general increase in soil NO_3-N levels in response to freeze-thaw under laboratory conditions conforms to field evidence from Paddle Hill Creek studies. In the field studies the initial surge in mineral N levels in early winter was caused by a marked surge in NH_4-N levels. Not until at least a month later did NO_3-N levels increase during both seasons of field study. This delay in NO_3-N production was considered to result from the lag during which populations of nitrifying bacteria built up in response to the fresh abundance of NH_4-N.

In the incubation experiment, there was probably insufficient time (36 days) in the three snow tussock grassland soils for nitrifier populations to increase from their low autumn levels and produce NO_3-N in response to the high availability of NH_4-N substrate resulting from freeze-thaw treatment.

The Craigieburn short tussock grassland soil, suffering from low nitrifying bacteria populations, low NH_4-N release from freeze-thaw treatment and generally low responsiveness to treatment (Robinson, 1963) showed no increase in NO_3-N levels, or in NH_4-N levels.

The Lincoln lowland soil behaved differently from the others and showed marked increases in NO_3-N levels after 6 and 36 days freeze-thaw treatment. This soil has been shown to possess the capacity to readily nitrify any surplus NH_4-N within it. It also contains high numbers of nitrifying bacteria both under grass and in the fallow state (Hart, 1978). Since nitrifying bacteria are likely to have been already present in the Lincoln soil in moderate numbers, no lag phase in NO_3-N production occurred when increased NH_4-N levels became available because of freeze-thaw treatment. In contrast, the NH_4-N levels which were increased by freezing alone were not nitrified in the sustained freezing conditions.

Laboratory simulations of field freezing and thawing of soil have been carried out in other studies which also showed a variable response to freezing and thawing, depending on the soil conditions studied. These experiments have shown that freezing and thawing often stimulate the production of mineral N. (e.g. Jagar, 1967; Hinman, 1970; Ross and Bridger, 1978). A general conclusion which can be drawn from the laboratory studies of Ross and his fellow workers, as well as the present studies, is that whereas freezing and thawing often increases mineral N levels (particularly NH_4-N) in many soils, the magnitude of this increase is dependent on the soil type or condition of the soil involved. Ross and Bridger (1978) found a marked stimulation of mineral N production in Carrick soil from Otago in response to freezing and thawing and subsequent incubation but only a slight stimulation of mineral N production in Tawhiti and Obelisk soils from Otago. Three soils (Conroy, Tima and HariHari) showed no significant changes in mineral N production. Ross *et al.* (1979b) found that after storage of a range of Otago soils at -20^0C for 24 hours

all but one soil, the low altitude Conroy shallow sandy loam, had significantly higher NH_4-N contents compared to soils stored for the same period.

Different workers have sought explanations in soil conditions for differences in N mineralization in response to freezing and thawing treatments. Mack (1963) had found higher N mineralization in high organic matter Canora and Grenville soils than in a Trossachs low organic matter soil. Ross *et al.* (1980) sought an explanation in bio-chemical properties of four Otago soils for their different net N mineralization after freezing and thawing. No clear factors emerge from these studies to explain why in the present study, three of the soils, PHC Upper, PHC Lower and Carrick, showed rapid increases in mineral N in response to freezing and thawing, while only minor effects were shown in the lowland soil and none in the Craigieburn soil. The soil conditions determining N mineralization response to freezing/thawing warrant closer investigation.

On the basis of results from this laboratory simulation study, and from early winter field evidence from Paddle Hill Creek grasslands, it is concluded that whenever freeze-thaw conditions prevail in tall tussock grasslands they are likely to have an important influence on the seasonal transformation of soil nitrogen.

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CHAPTER 8

NITROGEN TRANSFORMATIONS IN NATURAL AND MODIFIED TALL TUSSOCK GRASSLANDS - DISCUSSION OF SOME ENVIRONMENTAL INFLUENCES AND THEIR IMPLICATIONS FOR GRASSLAND ECOLOGY AND MANAGEMENT PRACTICES.

8.1 INTRODUCTION

The studies described in earlier chapters have revealed some of the variety and magnitude of mineral N transformations that occur in different seasons in tall tussock grassland, both in natural state and in response to cultural modification.

The first stage of these studies led to recognition that major changes in forms and levels of mineral N could occur between time of soil sampling and laboratory analysis of samples for mineral nitrogen. Extraction and storage procedures were devised which could overcome this problem. The magnitude of the changes during storage in mineral N cast doubts on the field interpretation of results obtained in many earlier studies of tussock grassland soils where soil storage techniques had been used such as those by Robinson (1963), Tan (1967) and Ross and McNeilly (1975).

Regular monthly mineral N measurement of soils from Paddle Hill Creek (PHC) yielded results indicating that previous studies of mineral N in tussock grasslands which had involved only a single or a few (usually autumn) soil samples produced insufficient information to make useful general conclusions on the mineral N status and nitrification ability of tussock grassland soils. These earlier studies had concluded that tussock grassland soils contained generally low levels of mineral N and very low rates of nitrification (Ross, 1958; 1960; White, 1959; Robinson, 1963; Tan, 1967). As a consequence of this, NH_4-N and not NO_3-N was considered to be the major source of nitrogen to plants in the upland and high country tussock grasslands (Ross and McNeilly, 1975).

While selective use of results obtained in the studies described in preceeding chapters could confirm many of these earlier conclusions, the striking feature of overall results was the marked variability in mineral N levels and nitrifier populations in different seasons and at different locations. Tall tussock grasslands at PHC generally exhibited very low soil mineral N levels at certain times of the year, particularly in the late summer-autumn. There were, however, other times of the year when both NH_4-N and NO_3-N were as high as those which might be recorded in a fertile lowland horticultural soil.

In this chapter, some of the most striking conclusions from earlier chapters are reviewed and opportunities for further research identified. The influence of three environmental variables, soil moisture, soil acidity and soil temperature, is assessed. The relationship between soil mineral N and tall tussock foliar N levels is examined to indicate the extent to which periodic surges in soil mineral N might result in increased N uptake by plants. Applications of the results of these tall tussock modification studies to management of tall tussock grasslands are considered in a discussion which highlights the value of retaining areas of tall tussock grassland.

8.2 MINERAL N TRANSFORMATIONS IN RELATION TO SOME ENVIRONMENTAL VARIABLES

8.2.1 Soil acidity and nitrifiers.

Soil chemical analyses at the Otago and Canterbury sites showed surface soils to have a pH level at or below pH 5.2 and a mean level over all sites of pH4.7. This suggested that nitrification, widely recognised as a process which tends to be reduced or even inhibited by acidic conditions, was likely to be limited at all sites. It was considered likely, however, that such acid conditions would have less inhibitory effect on nitrogen mineralisation which has been shown to proceed rapidly in highly acid soils (Nyborg and Hoyt, 1978) and has been found to be less sensitive than nitrification to acidic conditions (Harmsen and Kolenbrander, 1965).

Three sites (PHC Lower, Alta 2, Pisa) showed nitrifier most probable numbers ($_{mpn}$s) exceeding 50 g^{-1} at some stage during sampling. The Carrick site showed nitrifier numbers up to 20 g^{-1} and all the other sites showed nitrifier mpns below 12 g^{-1} in all of the soil samples. Such levels were very low and comparable to the low levels found in mpn tests by Robinson (1963) in unamended Craigieburn soil [20 nitrifiers g^{-1}], by Tan (1967) in a Carrick soil [50 nitrifiers g^{-1}], and by Ross and Bridger (1978) in a Carrick soil [4 to 6 nitrifiers g^{-1}] and in an Obelisk soil [4 nitrifiers g^{-1}].

These levels are also well below those found in lowland pastures of introduced grasses and legumes. Steele *et al.* (1980) reported populations of 46,000 nitrifiers g^{-1} in a Waimate North clay loam and of 8,500 nitrifiers g^{-1} in a Wharekohe silt loam measured by the mpn technique. Using the same technique, Sarathchandra (1978) found high nitrifier populations in a range of soils varying from 52,000 nitrifiers g^{-1} in a Wharekohe silt loam to 680,000 nitrifiers g^{-1} in a Horotui sandy loam.

From the nitrifier counts of tall tussock grassland soils it might be concluded therefore, that nitrification was severely limited in these soils and that the factor probably responsible for this was soil acidity. Significantly, the soil which showed the highest numbers of nitrifiers at any sampling date (1,635 nitrifiers g^{-1}) was also the soil with the highest pH (PHC Lower site pH 5.2). The two sites which recorded the next highest levels of nitrifying bacteria were however soils where the acidity level was no higher than the mean level for all sites (Alta 2 pH 4.6, Pisa pH 4.6), so other factors besides acidity clearly are involved in limiting the measured nitrifier populations in soils.

Ross and Bridger (1978) reached a similar conclusion. They found that while numbers of nitrifiers and ammonifiers tended to increase with increasing soil pH, these populations appeared to be regulated more by other factors. They considered that the numbers of nitrifiers measured by the mpn technique gave only a rough indication of the nitrification potential of the Otago tussock grassland soils they studied. Marked differences were found in both nitrification and N mineralisation rates between different samples of the same soil under pasture and tussock vegetation but the different samples showed little difference in nitrifier mpn counts. Even more significantly, in samples taken in 1975, nitrifier mpns were correlated mainly negatively with the NO_3-N content of the soils from which they were sampled.

Accuracy of the most probable number (mpn) technique has been questioned in recent years. Belser and Schmidt (1978 and pers. comm.) criticise the technique for counting nitrifiers because it has large statistical uncertainty, requires a long incubation time and uses growth conditions that do not accurately mimic the natural environment. Nevertheless Belser (1979) admits that:

> *"For counting nitrifier populations the mpn technique has been and will continue to be the most commonly used method, not necessarily because this is the best method, but because it is the only technique available to most investigators."*

Two key problems with the mpn technique noted by Belser (1979) are of relevance to this discussion. Firstly, he considers that the mpn technique often underestimates nitrifier populations. One way in which this can occur is by allowing insufficient incubation time for full development of nitrifier counts. Another potential problem is the possibility of media selectivity i.e. acid-adapted nitrifiers from a tussock grassland soil might find difficulty developing in the neutral/alkaline medium used in laboratory incubations. Both these factors were considered in the experiments described in Chapter 4 (4.2.3). The use of both a longer incubation time and of an acidic medium were tested to determine whether these would give increased counts of nitrifiers and thereby explain the high levels of NO_3-N detected in many of the soils. However, these devices made little difference to mpn counts.

The second factor of importance in any ecological interpretation of nitrifier populations and soil NO_3-N levels is the persistence of either of these factors in the soil.

> *"the presence of a high nitrifying population does not mean that nitrification is occurring, only that it occurred sometime in the past. Low counts, on the other hand, do not rule out the possibility of active nitrification taking place since counting may not be efficient. ... nitrate (presence) only indicates that nitrification has occurred sometime in the past. After the nitrate was produced, the population could have rapidly declined."*
>
> Belser (1979)

From these discussions it appears therefore that a better indicator of the occurrence of nitrification activity in a soil is the level of the product of nitrification, NO_3-N, within the soil. Moderate to high levels of NO_3-N (compared to other natural grassland levels described in Section 4.4.1) were recorded in all of the Otago and Canterbury tussock soils over most of the two year sampling period. These levels fluctuated markedly, generally following corresponding fluctuations in NH_4-N levels described in Chapter 4. This supports the conclusion that NO_3-N was being actively produced by nitrification at different seasons in each of the soils and was not simply persisting or accumulating in the soil as a residue of an earlier nitrification as is suggested for the high NO_3-N levels recorded

by O'Connor *et al.* (1966) for the Monte Gallina soil in Southern Chile.

In conclusion, it appears that nitrification is active in the tall tussock grassland soils of Otago and Canterbury described in this study despite the high acidity of these soils. To determine exactly when this nitrification takes place will require direct measurement of nitrification by the use of the fluorescent antibody (FA) techniques or short-term activity measurements described by Belser (1979). Relatively frequent measurement of NO_3-N levels suggests, however, that two important periods of nitrification are following dry/wet alternations and after freeze-thaw activity. Further studies should also investigate the importance of heterotropic nitrification (see Section 1.4.5) compared to autotrophic nitrification in tall tussock grasslands. Such activity might provide a further explanation for the presence of NO_3-N in many of the soils despite very low autotrophic nitrifier mpns. However the response, as evidenced by mpn counts, of autotrophic nitrifiers to the addition of urea at these sites indicates clearly their ability to nitrify in acid soil conditions if the NH_4-N substrate is increased.

8.2.2 Soil moisture content and surface soil dry-wet influences.

The moisture regimes likely to prevail in tall tussock grasslands of Otago and Canterbury were discussed in Chapter 1 (1.4.2) where it was concluded that soil moisture deficits were likely to occur periodically in the surface soil layers of these grasslands.

The mineral N profile studies of Chapter 6 showed that mineral N in most intact tall tussock grasslands is concentrated in the upper 30mm soil layer. This zone contains the highest levels of soil organic matter (Harvey, 1974; Molloy and Blakemore, 1974).

Soil moisture measurements described in earlier chapters did not regularly differentiate between zones in the upper 100mm of soil and therefore did not clearly show the periods of moisture deficit in the upper soil layers which would probably be revealed in a more intensive study. Low soil moisture levels recorded in late summer-autumn suggest, however, that such deficits do occur. They would be unlikely to restrict severely the growth of tall tussock, since as Williams (1977) showed, only 68% of *Chionochloa rigida* roots and 50% of *C. macra* roots at PHC are located in the top 100mm of soil. The remainder of the roots, reaching down to about 400mm depth,

are located in a zone which Mark (1965) showed remains considerably moister than surface soil layers.

The December 1976 surge in mineral N levels is thought to be the only clear example during the study of a dry-wet effect causing a flush of mineralisation and nitrification as described by Birch (1964).

The dry-wet effect is probably much more widespread through the tussock grasslands than is suggested by these studies. Sites were deliberately chosen here on flat to rolling topography to minimise any inflows or outflows of mineral N from study sites. A large proportion of the tall tussock grasslands however, are located on steep, coarse textured and well drained soils on north and west facing slopes subject to the desiccating north-west winds, as described by Archer and Collett (1971). Furthermore, tussock grasslands at lower altitudes than those described in these studies may be subject to considerably drier conditions arising from lower precipitation and generally higher evapo-transpiration levels at such sites (Mark 1965). Under both such situations, the dry-wet effect is likely to play a more important role in nitrogen transformations than at the 12 Otago and Canterbury sites described here.

8.2.3 Soil temperature and freeze-thaw effects.

The studies described in Chapters 4 and 7 have shown the widespread winter surge of mineralisation and nitrification thought to result from freezing and thawing of surface soil layers in these tall tussock grasslands. Production of NO_3-N following the surge in NH_4-N levels appears to result from nitrification and may therefore confirm the presence of nitrifiers adapted to low temperature in tall tussock grasslands, as predicted in Chapter 1 (1.4.1).

The concentration of mineral N in intact tall tussock grasslands in the upper 30mm of soil was described in Chapter 6. This is also the soil zone most susceptible to diurnal fluctuations in temperature including freeze-thaw effects which have been widely demonstrated throughout the tall tussock grasslands (Mark, 1965; Archer, 1969; Williams, 1977). The surface soil layers will also experience the marked shifts in temperature as are shown by Biederbeck and Campbell (1973) to stimulate mineralisation and nitrification. Sub-zero air temperatures can occur at most sites above 800m altitude at any time of the year. Mark (1972) found that over a five year study period on

the top of the Old Man Range, Otago, the longest period without a frost was eight days. Freezing and thawing of surface soil layers will be particularly marked from about May to October, particularly at high altitude sites when these remain free from snow cover. Aspect is clearly also important. North and west-facing slopes are exposed to the sun in winter and therefore warm up markedly during the day and may remain free of snow cover for considerable periods through winter. They will be subject to greater diurnal temperature fluctuations including freeze-thaw effects than shady south and east-facing slopes.

It would be valuable to compare seasonal mineral N transformations on north and west-facing slopes (sunny, high evapo-transpiration) with south and east facing slopes (shady, lower evapo-transpiration) and also to identify the influence mineral N regimes may have upon features such as flowering frequency, foliar nitrogen levels and species composition of tall tussocks and other plants on sites of different aspect.

Freeze-thaw stimulation of nitrogen transformations in New Zealand mountain grasslands deserves further investigation to determine just how widespread it is throughout these natural communities. Because of New Zealand's maritime climate and consequent mild winters such an effect is likely to be more significant here than in other continental grassland ecosystems such as the prairies of North America, where snow cover is likely to be more continuous throughout the winter season.

The fate of the N mineralised during winter has not been conclusively established in this study. Rapid uptake of large quantities of mineral N by tall tussocks may occur over the winter period. The apparent capacity of *Chionochloa rigida* to do this following the application of large quantities of urea was described in Chapter 6 and is further considered in more detail in the following section.

Both NH_4-N and NO_3-N ions persisted at moderate but declining levels until late spring following the winter surge of mineral N production. NO_3-N is a highly mobile ion and is vulnerable to leaching from the tall tussock grassland soils throughout the winter-spring period when soil moisture content is high, because considerable quantities of water stored as snow are released during the spring thaw and the high country is also subject in the spring to high precipitation from north-westerly storms.

Soil lysimeter studies and chemical analyses of stream water are needed to find out how much leaching of NO_3-N occurs during the winter-spring period from high country tussock grasslands. Such a study could extend more general work already carried out only in specific catchments (e.g. Mark and Holdsworth, 1979).

8.3. *CHIONOCHLOA* FOLIAR NITROGEN AND SOIL MINERAL N LEVELS

8.3.1 Winter root development.

It has been postulated by O'Connor (1983a) and in Chapter 6.4.2 that nitrogen uptake by *Chionochloa* vegetation is likely to follow the winter N mineralisation and nitrification surge revealed in the studies described in Chapters 4 and 5.

An unpublished study in 1975 at the Tussock Grasslands and Mountain Lands Institute, Lincoln College, carried out by the author and S. Newton examined new root development in *Chionochloa*. Four species were studied, *C. macra; C. rigida; C. flavescens* and *C. rubra* at altitudes ranging from 760-1200 m. In all these species, new root development was found to occur from mid-winter onwards, while leaf elongation was not measurable until after as much as two months. Root development occurred even in frozen soil. The roots that first emerged from the tall tussock rhizome had large, white smooth tissue which regular sampling showed were capable of growing up to 300mm in a week. Smaller rootlets covered with a mantle of tiny root hairs were not evident until several weeks after the initial roots had emerged. The capacity of these winter-produced roots to absorb N from the soil is unknown and deserves further study. Woodmansee *et al.* (1981) have described how the N uptake capabilities at plant roots and micro-organisms in natural grasslands almost always exceed the mineralisation potentials of these systems, thereby resulting in very low concentrations of mineral N within natural grasslands. Intense competition for mineral N is generally considered a characteristic of natural grasslands, ensuring conservation of N within these systems.

Chionochloa grasslands, which exhibited high levels of mineralisation of N in winter but were yet unable to absorb such levels, would be therefore most unusual amongst natural grasslands. Such an attribute might indicate maladjustment of the soil-plant system, permitting the loss of nitrogen (Reiners, 1981). Were this to be the case, one explanation might be that

Chionochloa grasslands, which have developed over widespread areas only in recent centuries, have had insufficient time to adapt to the forest soils on which they are now widespread. Connor (1973) has pointed out that, for the greater part, tall tussock grasslands in the altitude range 600m-1500m are probably only 1000 years old or less. If intact tall tussock grasslands are found to be capable of absorbing and retaining winter-mineralised nitrogen, it would be a valuable attribute which should not be lightly abandoned, especially if replacement vegetation lacks such a capability.

8.3.2 Storage of N and carbohydrates.

The foliage of above ground plant tissue in *Chionochloa macra* and *C. rigida* at Paddle Hill Creek was sampled by Williams *et al.* (1977) in October and December 1971 and in March 1972. *Chionochloa rigida* tissue was also sampled in September 1972. The N content of leaf blades showed little variation throughout the year whereas sheath N content showed distinct seasonal variation in both tussock species. Similar contrasts in sheath concentration were observed over a more restricted summer and autumn sampling at Temple Basin, Arthurs Pass (Williams *et al.* 1978). At Paddle Hill Creek, highest N levels in sheath tissue were found in the October 1971 and September 1972 samples. Levels recorded in December 1971 had fallen well below those recorded two months earlier, and remained at this low level in the March 1972 samples. The sheath tissue samples included the undifferentiated leaf portions of the plant which subsequently develop into leaf blades. No seasonal sampling was made of element concentrations in the root and rhizome tissue.

Williams *et al.* (1977) suggest that element fluctuations within live tussock sheaths reflect the internal patterns of translocation of the plant. They also considered that both *C. macra* and *C. rigida* store potassium, nitrogen, phosphorus and some sulphur in sheaths over winter.

The magnitude of the translocations of N that occurred in the PHC grasslands studied by Williams *et al.* (1977), were estimated from the weights and concentrations of N in the different plant components at successive samplings. Between October and December 1971 it was calculated that 3.83 kg ha^{-1} of N were translocated from the immature and mature sheath tissue in *C. rigida* and 2.09 kg ha^{-1} N in *C. macra*. The percentage of annual shoot uptake of N (from root and rhizome tissue to green blades) these quantities represented were 21.6% for *C. rigida* and 7.2% for *C. macra*.

No clear distinction was made in that work, however, between N accumulated in sheath tissue through translocation and that which might have resulted from winter N uptake. Subsequent distribution of N to blade tissue between October and December may have occurred from both winter sheath storage and winter root uptake. Clearly labelling of N and its monitoring in uptake, storage, translocation and redistribution is necessary to clarify these issues. Likewise, because Williams *et al.* (1977) did not undertake seasonal sampling of N levels in root and rhizome tissue, the role of these organs in any winter N uptake and storage is unclear. However, studies were described in Chapter 6 which found that roots and rhizomes store carbohydrates and N in temperate grasses and in arctic tundra ecosystems (Bliss *et al.* 1973). Likewise, Sheard (1973) showed a close relationship between N and carbohydrates in organic reserve functions in temperate grasses. Hence studies of carbohydrate storage in *Chionchloa* root and rhizome portions by Payton and Brasch, (1978) might indicate the role of these organs in N storage. *Chionochloa rigida* and *C. macra* from the Old Man Range in Otago were studied by Payton and Brasch. Total non-structural carbohydrate (TNC) levels were measured at different times of the year in plant tissue including leaf (green blade and leaf sheath), "stem" (tiller bases and rhizome) and root portions. TNC built up to high levels in both leaf and "stem" tissue during the summer, reaching a peak in late autumn/winter (1 June, 1974) samples. Reserve carbohydrates were stored in both leaf and "stem" tissue while roots were found to be consistently low in non-structural carboyhydrates.

The indications from both *Chionochloa* studies summarised here are that the leaf sheath/rhizome portion of *Chionochloa* plants may have an important role as an N storage as well as a carbohydrate storage zone, particularly during the winter season.

8.3.3 Rapid uptake of N by *Chionochloa* plants.

The studies described in Chapter 6 show how rapidly N uptake can occur by *Chionochloa* from the soil. Within 10 days of the application of a large quantity of N to the soil, N levels in the sheaths, young leaves and mature leaves of *C. rigida* and in the sheaths of *C. macra* had shown marked increases. (Root and rhizome tissue was not analysed because this would have destroyed the plants).

Further evidence for the rapid N uptake ability of *Chionochloa* has come from studies of urea application to *Chionochloa pallens* grasslands in the Murchison Mountains of Fiordland [Mills, J.A.; Lee, W.G.; Lavers, R.B. (in prep.)]. Urea was applied at a rate of 20 gN m^{-2} in early December. N levels of undifferentiated basal portions of the tussock were analysed in early February, two months after application. Foliar N-levels after N treatment were more than double the levels in control plants.

It is likely that foliar N levels increased much more rapidly than was indicated by foliar analyses. By mid-December, two weeks after N application, takahe (*Notornis mantelli*), which feed primarily on the succulent bases of *Chionochloa*, were consuming three times the number of tussock tillers from the N treatment plants compared to the control plants. In view of these birds' apparent ability to select for foliage with a high N and P content (Mills and Mark, 1977) this suggests that the N content of undifferentiated *Chionochloa* leaf bases increased within two weeks of N application, a result consistent with the pattern described in Chapter 6.

It should be noted that increased foliar concentration of nitrogen in *Chionochloa* following application of N fertilisers may not necessarily result in rapid increases in growth. O'Connor (1963) reported results from defoliation experiments, on what was later identified as *C. macra* on the Craigieburn Mountains, in which no clear difference in leaf elongation could be discerned as a result of application of 22 gN m^{-2}, even though several-fold increases were measured in resident *Poa colensoi* and in planted *Dactylis glomerata* on the same sites. No opportunities were then available for nitrogen analyses of tissues. Current field research to follow up the solution-culture experiments of Chapin *et al.* (1982) involve several levels of applied N as well as of applied P(G. Evans pers. comm.). Although responses to N were soon visible in accompanying fescue and poa tussock in these experiments, the first obvious effects in *Chionochloa* tussocks were an increase in flowering, especially on N treated plots.

The ecological advantages of a rapid N uptake ability and its within plant conservation are clear. Evidence has been presented throughout this study that N mineralisation rates vary markedly in response to environmental factors and seasonal influences. An adaptation which enabled *Chionochloa* plants to absorb rapidly large quantities of N from the soil would mean

that they could make maximum use of surges in NH_4-N and NO_3-N production. These could result from wet/dry periods, fluctuations in soil temperature, freeze/thaw induced mineralisation, mineralisation caused by soil disturbance or fire, or resulting from the addition of N from the deposition of an animal carcase, or excrement to the soil.

This N uptake capacity could also be significant for the conservation of N within the soil-plant system. Without rapid N uptake NH_4-N, surplus to plant uptake requirements, would be otherwise available for nitrification to the mobile NO_3-N form which may then be leached or dentrified and thereby lost from the system.

8.3.4 Integration of findings.

The discovery in this study that mineralisation of nitrogen is a significant and substantial freeze-thaw phenomenon in subalpine soils under tall tussock grasslands and the indications from this and associated studies that such mineralized nitrogen may be rapidly taken up into the plant subsystem even in winter, together allow new insights into the nutritional regimes of these tall tussock grasslands. In reviewing the mineral nutrition of wild plants, Chapin (1980a) wrote:

> *"Seasonal patterns. Nutrient concentrations in soil solution and therefore nutrient absorption by plants fluctuate considerably during the year. In non-agricultural soils there is generally a predictable spring nutrient flush and in some areas also an autumn or winter flush associated with leaching and breakdown of fresh litter, a spring increase in microbial activity, and freeze-thaw or wetting-drying cycles that lyse microbial cells. Other less predictable flushes in nutrient availability occur at other times. In infertile habitats it is likely that a large percentage of annual nutrient absorption occurs during nutrient flushes, particularly during late winter and early spring, rather than by steady-state absorption under average conditions."*

Prominent among the references cited in support of these statements are the tundra studies with which Chapin was closely familiar (Barel and Barsdate, 1978; Chapin and Bloom, 1976; Chapin, Barsdate and Barel 1978), as well as the simulation studies of Biederbeck and Campbell (1971) referred to

earlier in this work.

Because of the many analogies between tundra systems and alpine and sub-alpine systems, closer attention to this tundra research is warranted here. Chapin, Miller, Billings and Coyne (1980) demonstrate the close parallel between some features of nitrogen and phosphorus nutrient regimes in their review of tundra studies. They conclude that:

> *"because the soluble nutrient pools are small relative to the annual plant requirement, particularly for nitrogen and phosphorus, uptake by the vegetation must depend upon simultaneous nutrient release by decomposition or chemical exchange processes. Nutrient release by decomposition and nutrient absorption by the vegetation are thus apparently closely coupled."*

Chapin, Barsdate and Barel (1978) had advanced the hypothesis that phosphorus released by micro-organisms during their periodic population crashes accounted for most of the phosphorus return to the available phosphorus pool. They also noted that 40 percent of the annual transfer of phosphorus to the soil soluble P pool occurs within 10 days of snowmelt. In their review of the regulation of phosphorus cycling in tundra, these authors recognise various causes in different situations, including lysis of microbial cells during the freeze-thaw cycle, for P release into the available inorganic pool in its highly pulsed, seasonal pattern. From the fact noted above that nearly half the annual phosphorus return to the soil occurs during the snowmelt period, they concluded that there must be strong selective pressure for plant roots and mosses to be physiologically active at this time, despite prevailing low temperature. Chapin, Tieszen, Lewis, Miller and McCown (1980) reviewed the control of tundra plant allocation patterns and growth, demonstrating several features of adaptation of graminoid tundra plants to low soil temperatures. For example, in contrast to temperate graminoids investigated, *Dupontia fisheri*, a non-caespitose tundra graminoid, was capable of active rhizome growth at soil temperatures at least as low as $4^{o}C$, while elongation of primary roots in that species occurred in the first half of the growing season when root temperatures were lowest. In the sedge, *Eriophorum angustifolium*, the zone of most rapid root elongation occurred in the coldest soil, closest to the retreating permafrost. Chapin, Johnson, and McKendrick (1980) showed that in the caespitose (or tussock form) *Eriophorum vaginatum*, rhizome

weight decreased by 25% during the first two weeks of the growing season, coincident with the rapid initiation of growth of roots with snowmelt (Chapin, van Cleve and Chapin, 1979). During the first twenty days, nitrogen and phosphorus contents of rhizomes diminished. This decline was then arrested, apparently by uptake from the soil by the new roots. Weight of leaves increased only slowly during these first twenty days from their overwintering state, although nitrogen and phosphorus concentrations in leaves increased significantly, before declining during the subsequent period of maximum leaf growth rate. Chapin (1980) summarised graphically these biomass, nitrogen and phosphorus changes, along with changes in total non-structural carbohydrates, in shoots, rhizomes and roots.

The phenomena discussed here from *Chionochloa* grasslands of a substantial pulse of mineralization from freeze-thaw, vigorous late-winter new root growth, apparent concentration of nutrients in rhizomes and leaf sheaths during cool season conditions, and apparent rapid uptake of nutrients from the soil with development of new roots and ahead of noticeable shoot growth, are all generally consistent with the described pattern for tundra graminoids. The striking differentiating feature of the New Zealand mountain grassland systems here revealed is that the freeze-thaw pulse of nutrients release may occur in the heart of winter, rather than apparently at its end as in the Arctic tundra. The features of apparently rapid root growth and nutrient uptake in winter which have been suggested from the observations may constitute a remarkable adaptation to the soil mineralization regimes of an island mountain climate. As such they warrant urgent research, not only for their confirmation and quantification in *Chionochloa* but also for their investigation in other vascular plants of tussock grasslands and in the many cultivars, herbaceous and woody, which are considered for introduction to the tussock grasslands.

Winter mineralisation is at present clearly demonstrated only in those tall tussock grassland systems which have not been modified through what has been described (O'Connor, 1966, 1974, 1981, 1983a) as a nitrogen losing phase. Evidence has been presented here which confirms that the vegetation-modifying processes of severe defoliation and cultivation increase the risk of N loss from the system. Whether N depleted systems, such as are represented by the low productivity fescue tussock grasslands on Craigieburn soils (O'Connor *et al.*, 1962; Robinson, 1963), would still lose more nitrogen from freeze/thaw cycles, were their pools of labile and microbial

N to be augmented by pasture improvement, is uncertain. Clearly the winter N regimes and the influence of freeze/thaw cycles in such N enriched soils likewise warrant accelerated research as does the capacity of plant introductions to match the apparent winter and early spring nutrient-conservation properties of *Chionochloa* species.

8.4 *CHIONOCHLOA* GRASSLANDS AND LAND MANAGEMENT.

8.4.1 Conservation of *Chionochloa* grasslands.

Since European settlement, tall tussock grassland in the South Island high country has been progressively reduced in extent and condition in response to various pastoral land use practices described in Chapter 1. This deterioration in tall tussock cover was noted by many of the early naturalists as well as by more recent botanists working in these areas. Its timing and distribution have been summarised by O'Connor (1980a, 1980b, 1982, 1983b).

Over the last thirty years there has been growing awareness of the values of the remaining tall tussock grasslands and the extent to which these grasslands have been depleted, both by their reduction in area and by the modification of communities in which the tall tussock plant remains, even conspicuously.

A special review committee examined high altitude snow tussock grasslands and identified some of the important functions of these grasslands and the threats to their continued survival. (Tussock Grasslands Research Committee, 1954). Amongst their conclusions were the following:

1. Changes in the soil mantle because of accelerated erosion were considered to be preventing snow tussock regeneration.
2. Some of the snow tussock grasslands in higher and drier areas were considered to be relic stands in which regeneration under any circumstance was unlikely.
3. Pastoral use was seen to conflict directly with the retention of snow tussock for the purpose of preventing soil erosion and consequent stream bed aggradation.
4. A desperate need was seen for research work into revegetation and the restoration of plant communities and the soil mantle.

> In the interim it was considered that all possible steps should be taken to protect the remaining snow tussock communities and soils from known destructive agents such as grazing animals and fire.

As has been pointed out by O'Connor (1980a, 1982), the primary public motivation at that time behind efforts to conserve tall tussock grassland was the prevention of soil erosion, which was seen to be widespread throughout the high country and came to be generally viewed as a consequene of European pastoralism. Only in recent years has further research revealed that many apparently recent erosion features such as the blocky screes in the Canterbury Mountains probably have their true origins well before European or Polynesian settlement (Whitehouse *et al.* 1980; O'Connor, 1983b). Other erosion features may be associated more with such geologic features as faulting or crush zones rather than with the loss of vegetative cover as a causative feature.

From the 1950s onwards, identification of the risk of soil erosion and the consequent aggradation of river systems led to a policy of retiring land considered to be eroding or erosion-prone, so that by 1972 approximately 520,000 hectares of land in the South Island high country was estimated to have been retired or to be in the process of being retired (Molloy and Leamy, 1973). Many considered that the

> *"sole economic justification for retiring high country from grazing is the prospect of downstream benefit"*
> (Hamblett, 1973).

Because retired land was generally the erosion-prone, high altitude or steepland sites, a large proportion of the vegetative cover in retired land was tall tussock grassland. As well as retirement of land, a dominant concern was how to encourage an extensive vegetative mantle as a means of minimizing erosive processes.

Molloy and Leamy (1973) indicated that soil erosion was removing a large quantity of the tussock cover, litter layers and the topsoils which contained the bulk of the nutrients in the soil-plant system. Once these more fertile upper soil layers were removed from the system, only exceedingly infertile subsoils remained with not only serious soil chemical limitations for plant

growth, but also major physical limitations such as exposure to frost-heave and desiccation (Dunbar, 1970, 1974; O'Connor, 1980b).

Revegetation programmes implementing the research recommendations of the 1954 Tussock Grasslands Research Committee have shown the enormous practical difficulties and economic costs involved in attempting to permanently replace topsoil nutrients lost to erosion. (Nordmeyer, 1978; O'Connor 1980b). Clearly prevention of any further loss of topsoil and associated vegetation must be given high priority, because once such vegetation and soil are lost, restoration has proved to be so difficult and expensive.

Maintenance of water quality and water yield have also been identified as important reasons for retention of tall tussock cover. O'Connor (1958) considered that in New Zealand's pastoral history water and not wool had been the most important product of rangeland. Water production from rangeland is even more important today with the large scale development of irrigation in the lowlands and valley floors of the South Island. Most research work into water production from pastoral zones tall tussock grasslands has been in the grasslands of Otago (Mark and Rowley, 1976; Mark and Holdsworth, 1979) and these studies concluded that tussocks trap more rain and mist than bare surfaces. The downstream implications of such factors are still under investigation. In other zones such as the Waitaki (O'Connor, 1976), pastorally-held land contributes only a small proportion of total stream flow, but management of land for water yield may be locally significant.

Concern with maintenance of water yield has therefore become an important rationale for much of the retirement of high altitude tall tussock country on the block mountains of Otago where parent material and topography make terrain less vulnerable to erosion than in the outlying ranges of the Southern Alps (Ramsay, 1973).

Benefits for pastoral farming from the retention of tall tussock in grasslands have been described by O'Connor (1971). These include value for lambs' shelter, and as a conductor for melting and breaking snow thereby making sward plants growing amongst the tussocks more accessible to stock. The nutritive value of tall tussock to stock has been identified as generally low because of a high structural carbohydrate content, low

mineral content and in many cases low digestibility (Connor *et al.*, 1970; Macrae and O'Connor, 1970), although with supplementary protein and minerals, tall tussock can provide a substantial proportion of stock maintenance requirements. The primary role for tall tussocks for stock grazing is seen as an emergency food, in winter when snow blankets shorter-statured vegetation and in summer if drought affects lower altitude grazing land. In such a role it is recognized, however, that tall tussock is only suitable for occasional lax grazing and that repeated heavy grazing will kill the plants.

In recent years, it has been recognized that there is an urgent need to reserve areas of both short and tall tussock grassland for nature conservation purposes (Scott, 1979; Mark, 1979; O'Connor, 1982). Both short and tall tussock grasslands have been neglected as nature reserves apart from the much wetter areas near the Main Divide ranges. Areas included within the likes of National Parks therefore are not representative. This neglect has persisted despite the widespread use of these grasslands for scientific purposes of research and study and despite the increasing indications that without specific action to preserve them, some of the more important grassland types will no longer be available for such research purposes. O'Connor (1982) points out that in the climate of current rapid development in the high country, nature conservation must compete with other suited uses for limited natural resources. This competition is especially acute for lowland, tall tussock grasslands and for short tussock grasslands in natural condition, not just because of their increasing scarcity but because of their value for other purposes, especially pastoral development.

An important justification for the protection of tussock grasslands for nature conservation on more fertile soils is the benchmark role these can perform in comparison with the same soils subjected to agricultural or forestry development. Scientific monitoring of grasslands in natural condition and degraded condition, in conjunction with grasslands under development, can provide insights into the success of the pastoral or forestry development process and the ecological changes that accompany such development. A range of instances where such comparative monitoring is already underway have been presented by O'Connor (1982). Clearly the study described here has been an example of such research.

8.4.2 Mineral N transformations and *Chionochloa* grassland conservation.

These studies have shown that repeated defoliation, burning or cultivation of tall tussock grasslands leads to substantial changes in many features that characterize these grasslands. A major reduction in tall tussock vigour resulted from repeated defoliation and burning and was accompanied by increased vigour of subordinate plant species in the inter-tussock spaces, particularly at lower altitude sites.

A marked change in the distribution of mineral N in the soil profile resulted from defoliation treatment, while defoliation, burning and cultivation all triggered substantial changes in mineral N transformations which generally resulted in an increased potential for N loss from the grassland ecosystems, through denitrification or leaching of the mobile NO_3-N ion.

The difficulties of restoring topsoil nutrients to permanently replace those lost to erosion have been already described (Nordmeyer, 1978). They provide an important reason for not allowing further degradation of the soil N pool of tall tussock grasslands to occur. The fate of any NO_3-N leached from tall tussock grassland subject to cultural modification is also of concern particularly if such NO_3-N enriches water bodies where N supply is limiting or enriches groundwater used as a source of drinking water.

The studies described here have highlighted differences between different tall tussock grasslands at a range of sites and a variety of altitudes. Defoliation, burning and even cultivation of lower altitude tall tussock grassland seem less likely to result in a sustained depletion of the N resources of such systems because colonisation and growth of other plant species was vigorous and opportunities exist for the development there of N-gaining systems (O'Connor, 1974). By contrast, recolonisation at higher altitude defoliated sites was slow. Clearly the risk of repeated depletion of the soil N pool from such sites appears to be high. The fact that the primary pulse of mineral N release in such localities appears to be from a freeze-thaw effect on soil organic matter, including soil microbes, suggests that mineralized phosphorus and sulphur might also be at risk from such depletion.

In steeper parts of the South Island high country, conservation of tall tussock grasslands has been justified because of the expected prevention of soil erosion through slope stabilisation. On less steep or rolling landforms elsewhere in the high country (e.g. Otago block mountains) conservation of tall tussock grasslands through retirement from grazing has also proceeded, justified more by concerns to maintain water yield and to retain vegetative cover against wind erosion than by any necessity to stabilize soils against downslope erosion. Although the arguments for conservation of tall tussock grasslands to prevent soil erosion have not always been fairly presented in the past, such motives may still be justified. If chemical analyses of streams draining from defoliated and modified tall tussock grasslands confirm that the potential risk of loss of NO_3-N and accompanying ions from these systems is being realised, a further reason for the retention of tall tussock cover will therefore have been shown, namely the conservation of the N and other nutrient resources of these tall tussock grassland ecosystems.

8.4.3 Priorities for tussock grassland protection.

The comparative study described here was only possible because a range of sites and soil types could be isolated which still retained reasonably intact tall tussock cover. These intact sites could then be used as baselines against which tussock modification would be compared. In the initial stages of this study, difficulty was encountered in finding areas of intact tall tussock particularly at low altitude sites. During the six year period since these studies were initiated, further widespread destruction and degradation of the remaining tall tussock grasslands has occurred. Some review of this wasting process and of progress in reservation to counteract it is appropriate.

In south Otago and in eastern and western Southland, extensive areas of *Chionochloa rubra* grassland continue to be destroyed by heavy grazing or cultivated and transformed into grass/legume pastures. In central and north Otago, tall tussock has largely disappeared from lower altitude sites under the same influences. Some small areas of *C. rubra* have been reserved in Southland, while proposed more extensive red tussock reserves have yet to receive permanent protection (P.N. Johnson, pers. comm.). Some small remnants of *C. rigida* have also been retained such as five hectares at 50 metres altitude at Shag Point, Otago (Department of Lands and Survey,

pers. comm.) and *C. rigida* in the Nardoo catchment on the Waipori farm settlement (Mark, 1982). Difficulties arise, however, in using such small reserves in comparative studies because of the influence of edge modification (e.g. fertiliser drift) and the inadequacy of small reserves to represent the natural variety of grassland in terms of a range of slope, aspect, moisture regimes etc, features which are essential if a comprehensive understanding is to be gained of natural processes operating within these systems.

At higher altitudes in Otago, *Chionochloa macra* grasslands continue to be reduced in extent through grazing by cattle. The difficulties of locating *C. macra* grassland growing on Obelisk mountain top soils were earlier described in Chapter 3. The demise of this particular vegetation type has continued as a consequence of persistence with cattle grazing on the range summits (C. Meurk, pers. comm.). The type description for the Obelisk soil is of a soil supporting *Chionochloa macra* vegetation (Soil Bureau, 1968) yet complete elimination of this vegetation on this soil type seems highly probable. If this were to occur the difficulties of re-establishing a tussock cover would be enormous, judging from results from preliminary restablishment work (Dunbar 1970). Both in Canterbury and in Marlborough low altitude *Chionochloa* grasslands have largely been eliminated. *Chionochloa rubra* grasslands survive in some wetter, low altitude areas of the Canterbury high country but throughout both provinces there are numerous examples where the drainage and cultivation of such grasslands has occurred or is proposed (e.g. Rakaia gorge, Lake Heron basin, Lake Tekapo region, inland Marlborough). Ironically the pastoral land retirement schemes which are relieving grazing pressure on tall tussock grasslands at higher altitudes have increased this pressure on the remnants of tall tussock and short tussock (*Festuca* and *Poa* spp.) grasslands at lower altitudes, as well as on wetlands so vital for native wildlife habitat.

Such short tussock grasslands, which have generally been induced from tall tussock, are themselves worthy of retention in any system of preservation of natural and modified vegetation systems. It is valuable in any comparative studies of the transformation of a natural grassland to pasture to retain examples of intermediate transition stages and thereby clarify the components and processes of the transformation. Frequent reference has been made throughout this study to work by Robinson (1963) and O'Connor *et al.* (1962) which examined N tranformations in a Craigieburn soil supporting largely

short tussock vegetation and showed this grassland to be characterised by markedly different mineral N regimes from those shown here to be operating in intact tall tussock grassland. This study site has now been transformed and limited opportunities remain for preserving less modified short tussock grasslands.

Fortunately there is belated but encouraging interest today to conserve some examples of the tall and short tussock grasslands that characterize so much of the South Island high country. This is evidenced by public policies such as the Government High Mountain Policy (N.Z. Government , 1979), the Land Settlement Board's High Country policy (Land Settlement Board, 1980) and by a recent commitment to ensure that nature conservation opportunities are identified before irreversible decisions are made to permit land tenure changes which will encourage pastoral development (Lands Settlement Board, 1983).

Protection of a diversity of natural grassland communities can only be assured by the selection of a range of representative natural communities within each of the 80 ecological districts which have been identified within the South Island tussock grasslands and mountain lands (Simpson, 1982).

Such a network of representative reserves should ensure that future opportunities exist to conduct the type of comparative studies that have been described here to reveal not only the complexity and significance of ecological processes within natural tussock grasslands but also the direction and magnitude of changes to such processes resulting from cultural modification to these grassland systems.

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