PASTURE DYNAMICS UNDER CATTLE TREADING

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Tara Nath Pande

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ABSTRACT

Treading damage by cattle in wet winters is an important limitation for all-grass wintering systems in New Zealand. This study evaluated the impact of cattle treading in winter on pasture plants in both hill country and flat dairy pasture over three trials.

On hill country pasture, one severe treading treatment in winter resulted in losses in herbage accumulation rate of 9 kg (or 25%) DM ha^{-1} day^{-1} on tracks and 6 kg (or 26%) DM ha^{-1} day^{-1} on slopes compared to relatively untrodden treatments over a 9 month (Aug 98 to April 99) period. In repeatedly trodden treatments at heavy stocking rates, the loss in herbage accumulation rate averaged 19 kg (or 54%) DM ha^{-1} day^{-1} in tracks but found no loss on slopes compared to lightly grazed treatments over the same period. Treading seriously reduced pasture cover and changed species that contributed cover.

In flat dairy pastures, the loss of herbage accumulation rate was 29 kg (or 36%) DM ha^{-1} day^{-1} in highly damaged areas, and 5 kg (or 7%) DM ha^{-1} day^{-1} in low- to medium-damaged areas compared to untrodden areas during the 7 weeks regrowth after treading. This loss in herbage accumulation rate was associated with an initial 66% reduction in grass tiller density in high-damaged areas. Treading also reduced leaf area index. Post-treading pasture cover was only 43% in high-damaged areas compared to 80% in untrodden areas. Compared to other grass species, perennial ryegrass was least affected by treading. Losses in herbage mass and tiller density as a result of treading recovered, or tended to recover, by the end of the 7-week regrowth period.

In a second experiment on dairy pasture, treading in winter, again, greatly reduced residual herbage mass and tiller population density. Losses in both residual herbage mass and tiller density recovered by the end of the 7-week regrowth period. Differences in pasture height before treading did not effect pasture growth but, relative to the tall canopy height, the short canopy height enhanced tillering of ryegrass during the recovery period. The effect of treading on the weight of ryegrass tillers was small. An important aspect of treading was its role in increasing tiller appearance rate of ryegrass and encouraging faster growth of these newly developed tillers. Ryegrass-dominant pastures recovering from treading damage are reliant on the emergence and growth of new tillers.

Keywords: Treading, herbage accumulation rates, tiller density, tiller weight, leaf area index, grazing management, tiller appearance rate, cattle, sheep.

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CHAPTER 1

GENERAL INTRODUCTION

In New Zealand, in an all-grass wintering system, cattle are often hard grazed on pasture throughout winter and early spring (Levy, 1970). In this system, especially when the soil is wet, many authors (Edmond, 1958a; Scott, 1963; Edmond, 1974; Gradwell, 1974; Climo and Richardson, 1984; Betteridge *et al.*, 1999) have reported the effects of treading damage on both soil and pasture. This means that a greater area and range of soils are being exposed to the potential damage of soil and pasture from treading.

The deleterious effect of cattle treading during winter or early spring when the soil is wet has led to the increased use of feed pads, loafing or sacrifice paddocks, well designed and maintained drainage systems and subsoiling. Alternative to grazing could be expanded to removal of the cattle from pasture using these techniques. Climo and Richardson (1984), Horne and Hooper (1990), Harrison *et al.* (1994), and Drewry and Paton (2000a) reported that these alternatives to grazing substantially improved soil physical conditions and increased pasture growth.

Studies measuring the effects of treading on pastures have shown that pasture production is adversely affected (Gradwell, 1965; Brown and Evans, 1973; Johnson *et al.*, 1993; Ledgard *et al.*, 1996). Animal hoof pressure and/or action applied to soil and plants is the main source of damage. Destruction of a large portion of shoot and root under treading (Cluzeau *et al.*, 1992), and reduced regrowth and botanical changes of pasture species after treading (Charles, 1979) may affect pasture production subsequently.

Treading damage to pastures can be attributed to (a) soil damage such that it becomes an inferior environment for plant growth and (b) damage to plants – loss of leaf area, growing points, root tissue. On wet soils, Edmond (1963) attributed such losses directly to bruising of foliage, damage to root systems, plant displacement and burial in mud. After damage existing plant material generally contributes to regrowth processes and recovery (Bazzaz *et al.*, 1987).

Soil damage from treading tends to be long term with slow recovery. There is concern about the long-term impact of intensive treading damage by dairy cattle especially on weakly structured soils and its ability to recover after damage (Haynes, 1995). Previous research (Edmond, 1958a; Brown, 1968; Patto *et al.*, 1978; Sheath and Carlson, 1998; Singleton and Addison, 1999; Drewry and Paton, 2000b) showed that cattle treading has impact on soil properties and hence on pasture production, and considered this to be a problem for wintering systems.

Plant damage, assuming survival of some material, is dependent on species but usually short term in treading-tolerant species. Brown and Evans (1973) summarising Edmond's work, showed that a perennial ryegrass (*Lolium perenne*, here onwards named ryegrass) plant is least affected by sheep grazing (treading). Since ryegrass is known to be one of the most tolerant species to treading damage, manipulation of stocking density and/or stocking rate may be important to encourage the growth of ryegrass during wet seasons of the year. There is little or no information in the literature on the damage to pasture species under cattle treading in winter and the extent of damage that may cause losses in pasture production.

This thesis reports on a series of field experiments designed to investigate the causes of loss of pasture productivity after cattle treading in field conditions and the growth of pasture species recovering from treading damage. Thus the specific objectives were to:

(i) *Identify possible causes for the loss of pasture production under different levels of treading and grazing management.*

(ii) *Examine the impact and extent of different levels of cattle treading damage on pasture plants and soil properties.*

(iii) *Determine how damaged pasture recovers during regrowth after treading.*

(iv) *Determine how canopy height and treading intensity impact on the recovery of ryegrass.*

CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION AND OVERVIEW

New Zealand livestock farming systems have been developed to make best use of a temperate climate that is favourable to pastoral farming, and allows high stocking rates of 10-25 stock units/ha (1 stock unit is equal to 55 kg body weight) and grazing all the year round (Reid, 1992). All-grass wintering systems are an important element of low cost pastoral farming. The present trend is that cattle farming is increasing compared to sheep farming. Dairy cattle numbers have increased from 3.0 million to 4.3 million in the last twenty years, while sheep numbers dropped from 68.8 million to 45.7 million (Meat and Wool Economic Service of New Zealand, 1998/99). The land area classified as dairy farms has increased from 1.4 million hectares in 1986 to 2 million hectares in 1996 (Statistics New Zealand Agriculture, 1999). The average stocking rate has increased from 2.1 to 2.7 cows/ha over the same period (Dairy Statistics, 1999), assuming that average body weight of a dairy cow is 400 kg.

Pastoral farming systems based on year-long grazing at high stocking rates face increased risks of severe disturbance to both the soil and pasture resources (Betteridge *et al.*, 1999). One of the main causes of poor performing pasture is the excessive damage of pasture by treading, especially during wet winter and spring weather and high stocking rates (Edmond, 1963). Treading reduces herbage cover, exposes soil and affects soil physical properties. These effects may cause increased runoff and increased erosion. Treading is a significant factor in the reduction of pasture utilization and animal production on dairy farms (Blackwell, 1993), and reduces recovery rate of pasture during spring (Sheath and Carlson, 1998). Moreover, treading increases the potential for wind and water erosion (Noble, 1974), and disturbs the biological activity in soil (Cluzeau *et al.*, 1992).

Stocking rate, soil moisture content, management strategies, and pasture and soil characteristics all play a role in pasture and soil damage by treading (Edmond and Hoveland, 1972). In the past, interest in treading focussed its impact on soils and pasture production, but more recently, the effects of treading damage on the wider environment such as soil and vegetation stability, pasture biodiversity, and system management has received attention. Careful management of animal grazing is an important factor in avoiding this damage (Gradwell, 1968; Mullen *et al.*, 1974; Climo and Richardson, 1984; Matches, 1992; Betteridge *et al.*, 1999; Drewry *et al.*, 1999), and maintaining sustainable farming systems.

This review deals with the effects of treading by grazing animals on soil and pasture. The structure of the literature review is shown in Figure 2.1. Attention will be concentrated on the effects of treading on pasture production, and on those components of plant and soil dynamics which determine production responses to treading and their sensitivity to management. The recovery mechanisms of soil and pasture after treading, and management strategies to reduce treading damage will also be covered.

2.2. DEFINITION

Treading is defined in this thesis as the physical impact of the animal hoof on soil and plants. The effect of treading is measured as reduced pasture utilisation, pasture growth, decline in soil structure and change in pasture species. Treading damage is the outcome of integrated effects of combinations of animal, soil, plants, soil moisture content, and other environmental components. Sears (1947) expressed the term treading as "hoof cultivation".

Other terms used to describe the effect of animal traffic on the soil/plant complex are 'pugging' 'trampling', 'poaching' and 'puddling'. Trampling is used in some references to denote damage of pasture by hoof pressure. Pugging and poaching is used to describe events where the hoof penetrates the soft upper few centimetres of wet soil and compacts soil layers under the hoof. The term 'puddled' states the condition of the soil after pugging, when soil pores, filled with water, do not compact but rather become reoriented such that the drainage and gaseous exchange functionality of the soil are greatly impaired. In this review, the term 'treading' is used to describe both soil and pasture damage, 'trampling' is used for pasture only and 'pugging' for soil only effects of animal hoof action.

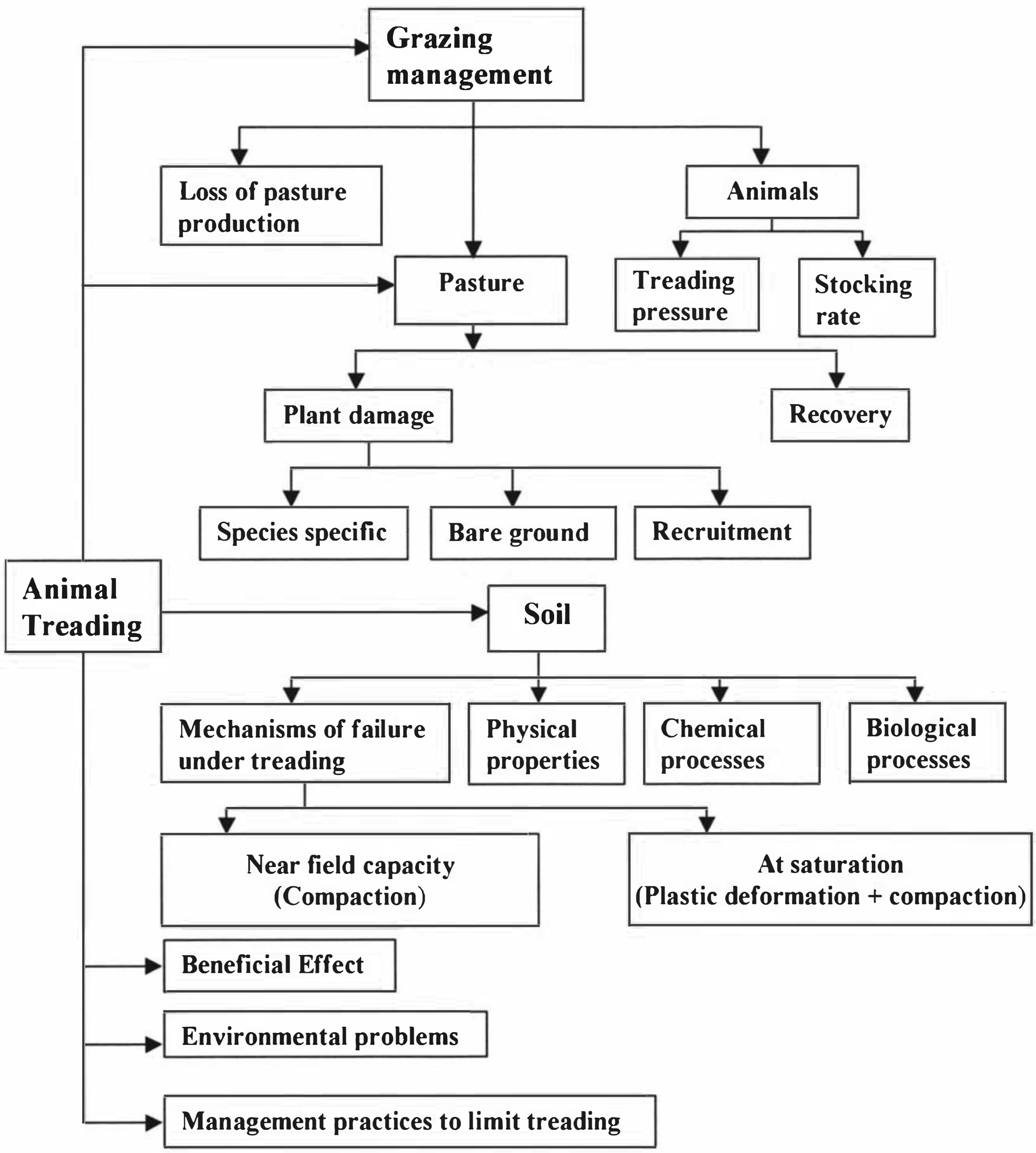

Figure 2.1 Framework for Literature review of the effect of animal treading on pastures and soils.

2.3. GRAZING MANAGEMENT

Walker (1995) described successful grazing management as the ability to accomplish three objectives: (a) control what animals graze, (b) control where they graze, and (c) monitor the impact on both the environment and the animal. Animal treading during grazing, especially on wet soils, has become an integral part of sustainable animal farming systems. The interaction of many site, soil, weather, and vegetation factors determines the severity of hoof action on the soil, with varying effects.

Longer grazing duration lead to high utilization of dry matter, but is risky in terms of treading damage. Cattle treading in frequently and closely defoliated swards (a sward is an amorphous collection of foliage which has characteristics of mass and density) might cause more damage than in more laxly grazed pasture. For example, high stocking rate, which consequently causes hard grazing in winter, is considered likely to reduce cocksfoot production through treading damage to tillers. Each tiller is a replica of parent shoot, complete with its own stem apex, leaves, nodes, internodes and adventitious roots. A grass plant may have constituent tillers which can be grown separately (Brown, 1968).

Herbage cover helps to provide protection to treading in winter and spring when the soil is wet. Sheep treading in short defoliated pasture reduces herbage production by 40-50% compared with undefoliated pastures (Brown, 1968). Mayne *et al.* (1987) found considerably more treading damage by dairy cows in pastures with heavy soils under wet conditions when grazed at 5 cm compared to 6 cm height. Defoliation to 3 cm compared to 6 cm may increase harvested DM and ryegrass tiller population density (Boswell and Crawford, 1979), but can cause a reduction in DM yield if swards are grazed during rain or on wet soils due to treading effects. On the other hand, Hunt (1979) found no effect of defoliation height on the response to both winter and summer sheep treading on the growth of *Paspalum dilatatum*, although defoliation height of 2.5 cm was superior to 5 cm in terms of seasonal distribution of yield and total yield.

Densely populated pasture with tall herbage and greater leaf area can alter the treading effect. O'Connor (1956) produced evidence indicating that grazing on tall herbage could help to minimise treading damage, as this provides a cushioning effect between hoof and plant. At the beginning of a grazing event, animals start with little damage to a wet soil as the long pasture provides some protection to the soil, but as grazing duration lengthens pasture cover diminishes resulting in more damage by hoof action. Pasture residuals (above ground plant material left after grazing/cutting) with low leaf proportions makes easier detachment of stems and displacement of plants by hoof action, especially at a period when the soil is wet and animals are kept longer in a paddock (Charles, 1979).

2.3.1. Loss of pasture production

Treading plays an important role in reducing pasture production, the effect varying with the pasture and grazing management systems. Recent research by Singleton and Addison (1999) showed that the depression in pasture productivity by cattle treading could vary between 30 and 90% and last for at least two years. During early-mid spring, cattle treading in hill pasture caused a loss of 5-10 kg DM ha^{-1} day^{-1} (Sheath & Carlson, 1998), and in dairy pasture caused a loss of 20-30% in growth rate (Horne and Hooper, 1990). Mayne *et al.* (1987) observed a reduction in net herbage accumulation up to 30% greater on severely grazed pasture than on laxly grazed pasture as a result of treading damage by cattle over a 15-week period. Charles and Valentine (1978) also observed a reduction in annual mean DM yield of 9% by cattle treading in mixtures of diploid and tetraploid ryegrass for 4 years after sowing.

Treading damage to plants and soils can disturb the grazing system and affect the allocation of quality forage production to the nutritional requirements of animals. For example, Lambert *et al.* (1983) observed a 20% greater loss of herbage mass in sheep set stocked on pastures over spring and early summer than in rotationally grazed pasture. These authors indicated that this apparent loss in herbage mass in sheep set stocked pastures is probably caused by treading and consequent pasture damage. This loss in annual pasture production can reach up to 5.2 tonnes DM year^{-1} or 38% due to sheep treading compared with pastures not damaged by sheep (Brown, 1968).

The losses in pasture production from treading occur through direct damage to plants and indirectly through compacted soil conditions or other physical/structural damage limiting subsequent growth. Many researchers (Gradwell, 1965; Brown and Evans, 1973; Edmond, 1974; Mullen *et al.*, 1974; Charles, 1979; Johnson *et al.*, 1993) have shown that direct damage to plants occurring as a consequence of hoof pressure can cause a significant reduction in pasture yield.

Herbage production of the sward (foliage) has two yield components: tiller density and tiller weight (Volenec and Nelson, 1983). Leaf area index, longevity of individual leaves, photosynthetic efficiency, and carbohydrate reserves determine tiller weight (Tavakoli, 1993). Tiller density, if too low, could limit pasture growth potential by limiting the number of growing leaves. Several researchers (Edmond, 1958a; Brougham, 1960; Carter and Sivalingam, 1977) have reported that the decline in herbage yield following treading was associated with a reduction in tiller density. In contrast, Hongo and Oinuma (1998a) observed that repeated artificial treading on *Dactylis glomerata* increased vegetative tillers by 13-53%. On the other hand, Hunt (1979) showed that sheep treading depressed yield of *Paspalum dilatatum* by reducing weight per tiller rather than through reducing tiller density.

Treading can affect the leaf area index (LAI) of the sward, which is determined by the product of leaf size, leaf number per tiller, and tiller density, assuming that the leaf area/leaf length ratio for a given genotype is constant (Thomas, 1980).

Treading can reduce pasture utilisation. Soil contaminated grass is less acceptable to grazing stock, while fungal disease which can invade damaged plants also decreases grass acceptability. Thus the utilisation of available feed of trodden pasture can be seriously diminished (Kellett, 1978). A 20-40% loss in utilisation of dairy pasture was recorded on pugged soil (Horne and Hooper, 1990), and under these conditions, the intensification of animal health problems can occur (Bowler, 1980).

Application of high rates of N fertilizer on pasture heavily damaged by treading may help to minimise the loss of pasture production. For example, Mullen *et al.* (1977) studying the effect of cattle treading and N fertilizer application on seasonal pasture production, found that dry matter yield of pasture on trodden plots was reduced by only 4.8% under high N fertilizer compared with 15.6% under low N fertilization.

2.3.2. Animals

Animal type and size, and duration of treading may affect the damage done to swards. Heavier animals such as cattle impose a greater treading pressure on the soil surface than sheep, and young or light stock (Climo, 1985). This may be one of the reason that cattle pasture always produce lower amount of herbage dry matter compared to that of sheep pasture. For example, Scott (1977) observed that while putting the same stocking rate of cattle on cattle pastures and sheep on sheep pastures grazed previously for two years by the respective animal groups, sheep pastures produced 41% more dry matter than cattle pastures during the period August 1970 to April 1971. Scott also recorded a greater proportion of bare ground in cattle pastures (30%) than sheep pastures (16%).

Similarly, Monteath *et al.* (1977) found that intensively grazed sheep pastures produced 28% more dry matter than intensively grazed cattle pastures over a 4-year experimental period, and cattle pastures progressively developed more bare ground than sheep pastures. Both these authors also found that sheep pastures changed to being more ryegrass dominant whereas cattle pastures became co-dominant with ryegrass and cocksfoot.

In contrast, other researchers working with sheep and cattle treading found different results. For example, Edmond (1970) recorded a loss in pasture yield of 29% for sheep and 24% for cattle in a six week experimental period.

2.3.2.1. *Treading pressure*

The physical effect of hoof action is the main cause of treading damage. The total hoof area of a cow or bullock is estimated at about 320 cm^2 (Frame, 1975). Static load exerted by a cow with all feet has been estimated at a range of 200 to 350 kPa (Climo, 1985; Thomas *et al.*, 1990) that of sheep being in the range of 50-80 kPa (Willatt and Pullar, 1983). As a result, the pressures imposed by cattle hooves can be significantly more damaging to soil structure and plants than those associated with sheep treading (Willatt and Pullar, 1983). Cattle can walk up to 3,000 m a day, varying with the total grazing area and the quantity and quality of the herbage on offer (Charles, 1979). The pressure on soil can be doubled when animals are moving (Bowler, 1981) and also kinetic energy is imparted to the soil when the animal is walking which may result a further increase in applied pressure while expanding the force (Willatt and Pullar, 1983). Regardless of the animal species, increasing the grazing intensity increases soil physical damage, thereby increasing soil and pasture plant disturbance.

2.3.2.2. *Stocking rate*

The decision on what stocking rate to use when grazing a wet soil is a particularly critical problem. Generally, higher stocking rates are more detrimental to subsequent herbage yields and soil physical properties than lower stocking rates (Brown, 1968; Witschi and Michalk, 1979; Greenwood *et al*., 1997). In hill pastures, raising the sheep stocking rate from 8.3 su ha^{-1} in low fertility farmlet to 14.8 su ha^{-1} in high fertility farmlets caused greater soil physical damage (MacKay *et al.*, 1999). Curll and Wilkins (1983) observed that treading increased soil compaction but had no effect on herbage growth and botanical composition on a ryegrass/clover pasture when stocked with 25 sheep ha^{-1} compared to 50 sheep ha^{-1}. While doubling the number of grazing sheep, these authors found reduced herbage growth of 10%, reduced plant root weight of 47% and a lower percentage of clover by 11% in ryegrass/clover pasture. However, with slow rotational grazing during New Zealand winters, stocking densities can reach very high levels, for example, 800-2000 sheep compared with 10-100 sheep ha^{-1} in normally grazed pasture (Greenwood and McNamara, 1992).

2.4. EFFECT OF TREADING ON PASTURE

2.4.1. Plant damage

Treading damages plant tissues. Drewry *et al.* (1999), working with sheep in Southland, New Zealand, concluded that decreased pasture production following winter grazing was more likely to have been due to direct plant damage and plant burial by hoof action than by the reduction in soil pore space or soil physical damage. Cluzeau *et al.* (1992) observed that cattle treading caused destruction of a large portion of the aerial system, stolons and roots, with removal of at least 50% vegetation cover. Abdel-Magid *et al.* (1987) found about 38% more vegetation detached by hoof action under simulated continuous grazing (trampled once daily for 32 days) than under simulated short-duration grazing (trampled only during the last 4 days of the 32-day period). Thus, treading damages growing points and photosynthetic surfaces of the plant (Brown and Evans, 1973; Clements, 1989). Hongo and Oinuma (1998a) observed higher injury rates of tissue in sheaths than in leaves of *Dactylis glomerata*, and in trodden plots than in untrodden plots. The destruction of plant tissues by treading leads to the death of the damaged plant parts (Gradwell, 1965; Grant and Marriott, 1994).

During treading, the hoof pushes the whole or part of the plant down onto or into the soil. Treading by grazing cattle under wet conditions can push 300-350 kg herbage DM ha^{-1} into the surface soil resulting in reduced growth rates of 5-10 kg ha^{-1} day^{-1} during early-mid spring (Sheath and Carlson, 1998). Similarly, Hay *et al.* (1984) found an increased burial rate of white clover stolon with increase in rainfall, because of the influence of increased treading damage. Herbage may also be wasted as it is pressed into the mud or otherwise rendered unpalatable.

Plant species influence the susceptibility of soil to treading damage (Brown and Evans, 1973). Higher producing dairy pastures may remain more open and allow more direct hoof/soil contact than short dense pasture developed under sheep grazing. Treading damage is always likely to be less on short, dense swards than on tall, open swards. Damage also varies with length of time a pasture is grazed (Guthery and Bingham, 1996), and the susceptibility of a pasture to damage may also be greater if a pasture has already been damaged in earlier grazing (Kelly, 1985).

Poor performance of plants may also occur after treading due to restriction of root growth (Brown and Evans, 1973; Singleton, 1999) and also due to changes in species composition (Lambert and Clark, 1985). Willatt and Pullar (1983) found that plant root growth was limited by increased soil compaction after treading. In the compacted zone, even the surviving plant root may not function properly. For example, Vertes *et al.* (1988) observed that roots of white clover (*Trifolium repens*) in the compacted zone of 5-15 cm depth of trodden plots were largely destroyed, but young roots that appeared at the soil surface along with a high spring rainfall helped plant recovery. Ferrero (1991) studying effects of simulated cattle treading also found that repeated compaction reduced root development, dry root and green matter production in *Phleum pratense*.

The root system of the plant is also influenced by the destruction of the surface vegetation through shearing of the tissue (leaf and stem) or uprooting of plants, thereby causing a decrease in root weight (Pook and Costin, 1971). Restriction of air and water movement caused by decreased pore space and size after treading (Scholefield and Hall, 1985), makes the grass more vulnerable to further hoof damage (Abdel-Magid *et al.*, 1987).

2.4.2. Recovery

Tillers follow a gradual build up in numbers after treading. Species with a higher growth rate use a faster recovery strategy than the species with a lower growth rate after treading (Sun, 1992). Brown and Evans (1973) suggest that swards sown with several species often rapidly simplify to ryegrass and white clover due to their relatively high tolerance of treading.

Grass tillers are short-lived. The ability of a plant to persist from year to year depends on its capacity to replace dead tillers (Jewiss, 1972). Thus, residual leaf tissue, carbohydrate reserves and meristematic activity of the surviving tillers, nutrient status, and water uptake ability of the soil can all influence regrowth in trodden pasture.

The rapid turnover of tissue taking place as new leaves are continually produced and old ones die was well documented by the 1960s (Hunt, 1965), but the significance of these processes following treading was not appreciated until much later. Rates of leaf appearance give an indication of the overall scale of tissue turnover, especially in grasses where the number of leaves per tiller may remain relatively stable for long periods (Davies, 1988). The reason is that growth becomes largely governed by the rate at which cells are produced (Körner, 1991).

Treading may cause more damage to, or destruction of the plants which are intolerant to grazing. For example, in grazing-intolerant plants, with relatively weak shoot meristematic activity after defoliation, the proportion of carbohydrate resources allocated to roots is higher than in tolerant species, and this may result in the long-term decline in the plant because the root:shoot balance is not restored (Richards, 1984).

In trodden pasture, the recovery of plants is slow, especially after heavy treading in wet soil conditions (Edmond, 1958a and 1963). Both growth rate and competitive ability of the surviving tillers for regrowth may determine recovery rate of the pasture after treading. On moderately compacted soils, pasture growth can recover completely within six months (Sheath and Carlson, 1998), but full recovery of pasture may be delayed in severely trodden pasture can take longer to recover (Singleton and Addison, 1999).

The vegetative cover of the pasture can be affected both by grazing and treading (Edmond, 1958a; Witschi and Michalk, 1979). Treading pressure has a greater affect on young compared to mature tillers (Edmond, 1966; Gradwell, 1967), and results in more rapid seedling mortality for all species in thinly rather than densely vegetated soils (Panetta and Wardle, 1992). Besides crushing vegetation by hoof pressure, shearing damage also occurs from slipping and sliding of the animal during treading (Edmond, 1966). These effects in wet soil during grazing may lead to death of pasture plants.

2.4.2.1. Species specific effects

Heavy treading of pasture in winter reduces subsequent species diversity (Edmond, 1964; Charles, 1979), because some pasture species are more sensitive to treading than others. For example, Edmond (1964) ranked 10 species according to the decrease in number of tillers or nodes, and found ryegrass the most tolerant compared to other species following heavy treading by sheep. Edmond (1966) also reported that after treading, a reduction in Yorkshire fog (*Holcus lanatus*) was accompanied by an increase in white clover.

Grubb (1977) stressed the importance of regeneration, which influences the ability of plants to take advantage of niches created within a pasture. Plant damage by treading may eventually lead to botanical changes involving replacement of sown species (Charles, 1979). Treading damage in grass-legume mixtures can create a shift in botanical composition towards grass dominance (Brown and Evans, 1973), since legumes are less resistant to treading damage than grasses (Matches, 1992). However ryegrass/clover pastures are relatively resistant to the effects of treading damage (Campbell, 1966; Brown and Evans, 1973).

White clover is sensitive to treading damage at high stocking rate. For example, Curll and Wilkins (1983) found that sheep treading decreased clover content by 86% in a pasture grazed at a high stocking rate but increased it by 65% in a pasture grazed at the lower stocking rate. The decrease in the content of white clover in a pasture grazed at high stocking rate could be due to both grazing (defoliation) and treading activity. In a pasture grazed at high stocking rate, these authors also noted that ryegrass was more encouraged by the return of excreta than was white clover. Vertes *et al*. (1988) studying the effects of treading by cattle on clover populations in pure swards showed that clover populations had a higher percentage of dead stolon and reductions in organ size and branching complexity as treading intensity increased, but attempts to determine whether individual marked stolons were buried, damaged or remained intact were unsuccessful.

Ryegrass is the most common pasture species in New Zealand. This species is relatively tolerant to low soil oxygen concentrations caused by compaction (Gradwell, 1965 and 1969). Witschi and Michalk (1979) studying the effect of sheep grazing, showed that the ryegrass content increased after soil compaction during grazing of a clover/ryegrass mixed pasture. Ryegrass was also least affected by sheep grazing or treading, maintaining a relative yield of 95% of zero grazing, whereas white clover yield dropped to 90% of that of zero grazing and Yorkshire fog dropped to 43% of zero grazing for 20 sheep ha^{-1} equivalent (Brown and Evans, 1973). This might be due to the higher tillering activity in ryegrass from November to January (summer), soon after defoliation of the apices of the main group of reproductive tillers (Korte, 1986; Da Silva *et al.*, 1993), and this activity was not influenced by stocking rate (L'Huillier, 1987). Laycock and Harniss (1974) while observing treading losses on native mountainous open range containing more than 80% forbs and the rest grasses, found that when sheep were grazed in late summer, 23 % of the herbage had been eaten and 27% trampled, but when cattle grazed in the pasture all summer, 50% of the standing herbage had been eaten and 18% trampled. Similarly, Charles and Valentine (1978) found that the overall effect of cattle treading on both diploid and tetraploid ryegrasses for four years after the year of sowing was not large, but the annual dry matter yield was reduced 9%.

Other species, for example, *Poa annua* with its special character of plasticity in leaf structure, can maintain growth and reproduction under trampling, despite a reduction in total biomass, leaf number and tiller number by trampling (Kobayashi and Hori, 1999). Keuren and Parker (1974) also reported that the yield of *Festuca arundinacea* was not affected by treading and was found to be the most satisfactory for winter pasture in terms of its ability to withstand cattle treading and close grazing, and it recovered more quickly during the following summer compared to *Dactylis glomerata* and *Poa pratensis*.

Treading not only damages the plant but also changes growth habit. *Dactylis glomerata* responds to treading stress by reducing plant height, producing more vegetative tillers, and changing growth habits from erect to prostrate (Edmond, 1974; Hongo and Oinuma, 1998a).

2.4.2.2. Bare ground

Hoof damage to pasture is the key factor in creating bare ground, which is usually a feature of grazed wet soils, but can occur on almost any soil and in any season of the year (Brown, 1968). More importantly, cattle treading can increase bare ground to more than 50% (Cluzeau *et al.*, 1992) and this increased open space with reduced vegetation cover may increase the impact of raindrops, decrease soil organic matter and soil aggregates, increase surface soil crusting, and decrease water infiltration rates (Blackburn, 1983). In hill pastures the areas of soil that were already bare before treading were more prone to treading damage than areas with vegetation cover (Betteridge *et al.*, 1999).

2.4.2.3. Recruitment

Physical disturbances of pastures by animal treading may open sites for seed germination. Barrett and Silander (1992) found higher seed germination rates on disturbed sites than undisturbed sites. Sevilla *et al.* (1996) also found greater seedling emergence in heavily grazed sites, and enhanced survival of newly recruited seedling during the spring growing season on these heavily grazed microsites.

The exposure of bare ground by cattle activity enables good soil-seed contact and helps in establishing sown grass species, and alters the pattern of secondary succession on disturbed microsites (Williams and Ashton, 1987). Also, numbers and types of weed species can increase in bare ground. Baars *et al.* (1982) and Beskow *et al.* (1994) observed that in field situations, treading damage has the disadvantage of increasing weed seed germination. Treading created open spaces are important features for plant growth and colonization. Establishment of legumes was better in the spring, and grasses in autumn after over-sowing in these exposed areas (Sithamparanathan *et al.*, 1986). However, poor seedling survival and low final establishment occurred in severely compacted areas (Hume and Chapman, 1993).

Soil factors that limit seedling recruitment and subsequent vegetative growth after treading damage are moisture, compaction and porosity (Curll, 1982). After treading, reduced soil porosity and soil particle size may affect seed-soil contact and water availability to the seed. Bakker (1985) observed that by exposing soil and creating hollows, treading provides niches for germination and establishment of seedlings, as do bare areas left by old dung pats. These open spaces or gaps can be colonized by clonal spread from edge plants and by seedling establishment, and species differ in their 'gap colonizing ability' (Bullock *et al.*, 1994). In addition, Hume and Chapman (1993) observed that treading is useful in opening up a dense turf mat on hill country pumice soil, thereby improving pasture composition. However, treading disturbance can lead to gaps in a community where grasses recruited from seed become a major component of the plant population, and is often a major source of change in the diversity, including weed content, of species in the pasture (Burke and Grime, 1996).

Awan and Kemp (1994) observed that seedling survival of *Trifolium repens*, *Trifolium subterraneum* and *Lotus pedunculatus* was better under hard grazing with treading than hard grazing with no treading after being oversown into a ryegrass dominated pasture. Beskow *et al.* (1994) working in hill country pasture showed that ragwort germination increased in beef cattle grazed plots and in trodden plots compared to ungrazed plots, although many of the seedlings died over the subsequent summer as result of competition for space and water.

2.5. EFFECTS OF TREADING ON SOIL

Increasing the stocking intensity and therefore the treading intensity increases the damage to pasture, the degree of soil compaction and soil disturbance (Edmond, 1962). Evidence from several studies (Gradwell, 1965; Brown and Evans, 1973; Johnson *et al.*, 1993; Sheath and Carlson, 1998) has indicated that a decrease in pasture yield is associated with the change in soil physical condition caused by treading. However, grazing only when the soil is dry minimizes the effect of soil physical properties (Edmond, 1962; Witschi and Michalk, 1979).

The susceptibility of soil to damage from grazing of stock varies with soil moisture content at the time of treading (Gradwell, 1968; Mullen *et al.*, 1974; Climo and Richardson, 1984; Henderson *et al.*, 1988; Mulholland and Fullen, 1991; Proffitt *et al.*, 1995a; Betteridge *et al.*, 1999), soil texture (van Haveren, 1983), organic matter content in the soil (Soane, 1990) and grazing intensity (Warren *et al.*, 1986c). According to these authors, treading damage by grazing animals has the following impacts compacts the soil, increases soil bulk density, reduces infiltration, reduces soil macroporosity and aeration, penetrates and disrupts the soil surface, vertical displacement of soil on steep slopes, animal trails are developed and increases erosion.

Treading damage may increase after irrigation due to increased soil water content, which can reduce herbage yield. Witschi and Michalk (1979), working with sheep, found a greater loss in herbage yield potential when pastures were stocked immediately after irrigation and recorded a loss of 20% by treading alone compared with 58% loss by treading and grazing together. In a long term study, Kelly (1985) observed a 6% loss in pasture growth in the first year, 9% in the second, and 12% in the third year due to cattle treading in flood irrigated pastures in Victoria.

Soil types differ in susceptibility to treading damage and, in many cases, natural regenerative processes restore soil structure to a satisfactory state. Weakly structured soils are prone to treading damage (Burke *et al.*, 1964). Singleton and Addison (1999) reported that because of the high soil strength (ability of soil to resist a force without shearing or flowing if wet) provided by organic matter, soils derived from volcanic clay were relatively resistant to treading damage. These authors observed that Pallic soils, which have naturally compact subsoils, remain wet for a long time after rainfall and are slow to drain. As a result, treading damage on Pallic soils is relatively common, particularly where mob-stocking over winter is practiced. Similarly, Climo and Richardson (1984) studying the effect of stock treading on three soils with different physical characteristics, observed that the Tokomaru silt loam suffered most, the Manawatu silt loam was intermediate, and the Ramiha silt loam was the least susceptible to treading damage. These authors showed that the Ramiha silt loam had strongly developed structure and free drainage characteristics, the Manawatu silt loam was intermediate and the Tokomaru silt loam was weak in these characteristics.

Soil physical damage due to treading differ in good and poor soil structure profiles (Figure 2.2). Increased bulk density and surface roughness, and decreased aggregate stability, soil penetrability and herbage production were found due to treading by grazing bullocks over three years in poorly drained clay loam and loam soil in Ireland (Mullen *et al.*, 1974). Treading of fine textured soils may greatly affect forage yields due to compaction, even when at field capacity, as well as when saturated (Tanner and Mamaril, 1959). This damage may be totally due to poor drainage resulting from poor soil structure profiles. Lower porosity and slower air permeability are the characteristics of these soils. Treading further increases the risk of soil physical damage on these soils. Scholefield and Hall (1985 and 1986) concluded that the major damage from cattle hoofs on sandy and clay rich soils resulted from a progressive loss of soil strength because of repeated treading. Additionally, Singleton and Addison (1999) showed a progressive decline in pore function, pore size and aggregate size of soils even under "normal" intensive dairying management in the Waikato and Northland.

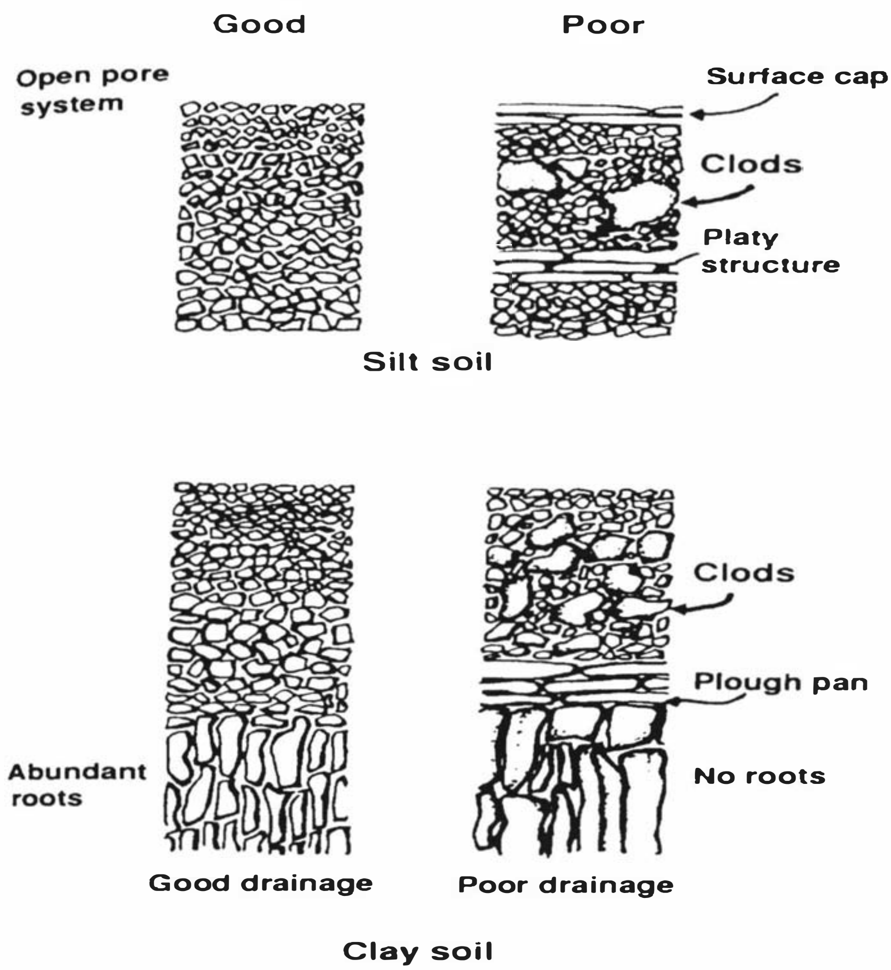

Figure 2.2 Good and poor soil structure profiles. Redrawn from McLaren and Cameron (1996).

For steep hill pastures of mixed topography, the areas most readily damaged are the track/camp and easy-contoured zones compared to inter-track zones (Sheath and Carlson, 1998). In easy-contoured zones, soil bulk density and total porosity are not useful indicators, whereas, a decrease in soil macroporosity caused by puddling is probably a more useful indicator of treading damage (Nguyen *et al.*, 1998).

2.5.1. Mechanisms of soil failure under treading

The way a soil reacts to application of hoof pressure depends on the texture of the soil, how wet it is, how compact it is, the depth of compaction below the surface and also on the shape of the contact area (Haynes, 1995). Soil structure and water content interact strongly to influence the reaction of a soil to treading pressures.

According to Horne and Singleton (1997), there are lower and upper plastic limit of soil conditions to result treading damage. When soil moisture content is around field capacity, the soil is more likely to be compacted by treading, and at this stage, puddling is less of a problem. When soil is very wet (close to saturation), animal hooves penetrate the soil surface and produce a "puddling effect" which involves the remoulding of the surface soil, often with the loss of large soil pores. When soil is very wet and reaches its plastic limit (the gravimetric moisture content at which a soil changes from being 'friable' into being 'plastic' and represents the minimum amount of water at which puddling will occur), instead of compacting, it becomes deformed and flows around a hoof (Singleton, 1999). Saturated soil cannot compact as water is essentially incompressible.

2.5.1.1. Compaction (near field capacity)

Compaction occurs when the soil does not have sufficient 'strength' to support the weight of animals. Compaction often occurs when the soil is plastic, or near field capacity. Gradwell (1968) observed that surface compaction of a sandy loam caused by treading in winter remained evident in mid-summer, six months later, but had almost disappeared by the following winter. By contrast, wet, clay soils with poor drainage are much more susceptible to compaction by treading (Edmond, 1970; Warren *et al.*, 1986b).

Apart from moisture content, soil organic matter content is an important factor influencing soil compactibility. Haynes (1995) noted that an increase in organic matter may both reduce compactibility by increasing the stability and strength of aggregates and, therefore, their resistance to deformation, and increase the elasticity of the soil (i.e. the ability of the soil fabric to "rebound" back to its original state after initial compaction).

Compaction is not always visible at the surface, but can occur to a depth of 2 to 15 cm depending upon treading intensity and animal type (Kelly, 1985; Greenwood and McNamara, 1992). For example, on wet soils, compaction by sheep treading is limited to the top 6 cm of the soil (Edmond, 1958b) and to the surface 10 cm by cattle treading (O'Connor, 1956). Furthermore, treading on moist soils can destroy existing soil aggregates and may lead to the creation of a flat, comparatively impermeable surface layer composed of dense, unstable clods (Warren *et al.*, 1986a; Proffitt *et al.*, 1993).

Compacted soil can result in water saturation of the surface soil (ponding), thus making the soil more susceptible to further treading damage (Gradwell, 1968; van Haveren, 1983; Willatt and Pullar, 1983; Climo and Richardson, 1984; Proffitt *et al.*, 1993). Further, compared to less compacted top soil, a compacted top soil resulting from animal treading develops a hard surface on drying (Gradwell, 1966), which has been reported as a significant process in the physical deterioration of agricultural soils (Gradwell, 1960; Gifford and Hawkins, 1978). Edmond (1963) also showed that soils compacted while wet subsequently developed a hard surface.

As water content increases, the pre-consolidation pressure for subsoils decreases (Salire *et al.*, 1994), and this can lead to the vertical deformation of the soil (Scholefield, 1985).

2.5.1.2. Plastic deformation (near saturation)

As soils become wetter they lose strength and deform when pressure is applied. The top 50 mm layer of the soil may be turned into a slurry and flow as a liquid around a hoof mark, with compaction occurring beneath the slurry (Singleton, 1999). A complex interaction of the compacting force, soil water content, texture, and porosity determines the extent of plastic deformation. Severe pugging damage can occur on wet clay soils during wet weather (Johnson *et al.*, 1993).

Betteridge *et al.* (1999), studying the effect of cattle grazing in hill pasture when the soil water content was above the plastic limit, observed that soils were severely deformed but that soil compaction was not apparent. Drewry *et al.* (1999) also observed that high water content of the soil at the time of grazing resulted in less compaction as all soil pores were water-filled and resisted compression by cattle.

When the soil is pugged early in the winter, excess water tends to remain for longer on the surface, especially on the deep hoof prints (Figure 2.3). As a result, the soil remains softer and wetter and the hooves of grazing animals do more damage at subsequent grazing (Nguyen *et al.*, 1998).

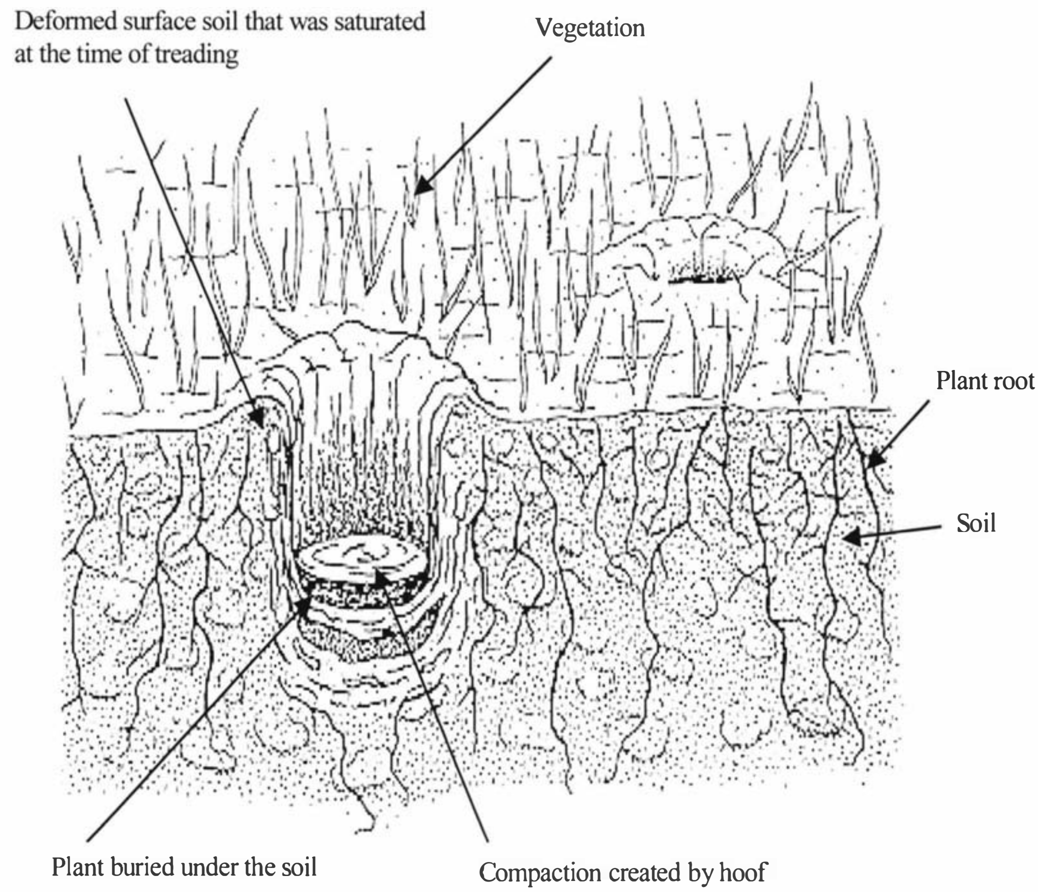

Figure 2.3 Effect of treading on compaction of the soil. Redrawn from Batey (1988), date downloaded).

Note: Available at http//www.maf.govt.nz/MAFnet/publications/soilcomp/soilco11.htm#E11E10

2.5.2. Effects of treading on soil physical properties

Soil compaction is usually measured by soil bulk density. Several authors (Edmond, 1964; Gradwell, 1968; Mullen *et al.*, 1974; Carter and Sivalingam, 1977; Willatt and Pullar, 1983; Kelly, 1985; Greenwood *et al.*, 1997) have observed an increase in bulk density resulting from increased treading intensity. On moist soils, the bulk density of the surface layer increases under compaction until the bearing capacity equals the hoof pressure of the cattle (Wind and Schothorst, 1964). Conversely, Curll and Wilkins (1983) observed that sheep treading at high stocking rate reduced soil bulk density and increased pore space where excreta was returned.

Macropores conduct most of the water through a soil during wet conditions. The major effect of treading is the reduction of macropores, thereby reducing infiltration and percolation, increasing runoff and encouraging erosion. Authors (Peel and Matkin, 1984; Greenwood and McNamara, 1992; Nguyen *et al.*, 1998) have observed that reduction in soil macropore space by treading led to considerable damage on badly drained fields. Climo and Richardson (1984) argued that loss of soil macroporosity was correlated with treading damage, but that soil bulk density and total porosity were unaffected, showing that these latter measures were not useful indicators of treading damage. Recent studies of Nie *et al.* (2001) in south west Victoria, Australia, showed that heavy pugging of dairy pastures reduced soil macroporsity at 0-50 mm depth. In addition, Drewry and Paton (2000b) found 70% greater macroporosity in ungrazed pasture compared with cattle-grazed pasture within four months of grazing exclusion in Southland, New Zealand.

The reduction in the proportion of soil pores >60 μm (Gradwell, 1968) and >30 μm (Singleton and Addison, 1999) by treading reduces air permeability. When the air forced from the soil by hoof action, water will be rapidly expelled from soil micropores

(Schofield, 1986). Under increased mechanical restraint imposed by soil compaction, treading adversely effects soil structural properties leading to reduced air permeability and restricted water movement in soil (Soane *et al.* 1981; Scholefield and Hall, 1985; Drewry *et al.*, 2000). This condition reduces the "suitability for plant growth" of a range of soils, because of reduced soil oxygen status and increased resistance to root growth (Jayasundara, 1998). Thus, under the hoof mark, soil with decreased pore space can be more vulnerable to further hoof damage (Mulholland and Fullen, 1991), which may subsequently effect plant growth.

Treading causes a decrease in hydraulic conductivity. For example, Greenwood *et al.* (1997) showed that untrodden soils had a higher unsaturated hydraulic conductivity at 5 and 15 mm compared to that of sheep-trodden soils. Lisa *et al.* (1997) and Singleton and Addison (1999) reported correlations between increased bulk density and decreased hydraulic conductivity of soil in heavy trodden areas. In addition, Drewry *et al.* (2000) showed that limiting grazing in dairy pastures increased air permeability by over two orders of magnitude 18 months after trial commencement, and saturated hydraulic conductivity by 200% to the 10-cm soil depth. Willatt and Pullar (1983) suggested that reduced water transmission through the soil profile might be primarily due to reduced pore volume as a result of increased surface soil compaction. These authors also showed a reduction in hydraulic conductivity as sheep stocking rate increased. It is suggested by the above authors that reduced water transmission through the soil profile was primarily due to reduced pore volume as a result of increased surface soil compaction.

Surface compaction reduces infiltration and results in surface ponding. In their review, Gifford and Hawkins (1978) showed considerable evidence of reduction in infiltration caused by treading. Warren *et al.* (1986c) reported that this reduction of infiltration rate was mainly due to destruction of soil aggregates and creation of a flat, comparatively impermeable surface layer. Reduced infiltration rates by treading reduce soil water storage potential (Gifford and Hawkins, 1978; Kelly, 1985; Proffitt *et al.*, 1993; Nguyen *et al.*, 1998).

Treading also increases soil strength (Mulholland and Fullen, 1991; Lisa *et al.*, 1997) and this increased soil strength in the grazed pasture causes hard-setting soils which restrict water movement (Mullins *et al.*, 1992). Hardsetting restricts plant emergence and crop growth, and can also restrict the timing of tillage and sowing operations through poor soil workability (Proffitt *et al.*, 1995a). In addition, authors (Naeth *et al.* 1990; Singleton and Addison, 1999) found increased aggregate size or clumps on the soil surface following treading. However, repeated treading in the presence of free water causes a progressive loss of soil strength (Scholefield and Hall, 1985).

Recovery of soil physical conditions after treading is rather slow and compacted conditions may persist for six or more months (Nguyen *et al.*, 1998; Drewry *et al.*, 1999). Singleton and Addison (1999) observed that the physical condition of intensively trodden soil was not fully recovered for at least 18 months. Davies and Armstrong, (1986) observed that hoof indentations were still evident 3 years after a pugging event. Thus, changes in soil physical properties can eventually reduce herbage production, particularly on heavier soils, as a consequence of reduced soil pore space and infiltration, and increased surface ponding and impeded drainage.

The more important natural regenerative processes include wetting and drying cycles, which cause shrinkage and swelling and cracking of the soil, growth and death of roots causing root channels and the burrowing action of the large earthworm population (Cluzeau *et al.*, 1992).

2.5.3. Effect of treading on chemical processes

Sharpley and Syers (1979) reported a reduction in the volume of drainage discharge due to destruction of drainage channels in the soil profile, but a 50% increase in the amount of dissolved inorganic phosphorous and a 100% increase in the amount of particulate-P transported in tile drainage due to cattle treading effects, four weeks after grazing. In addition, treading causes nitrate and sulphate loss due to their reduction under anaerobic conditions (Gradwell, 1967). Furthermore, Curll and Wilkins (1983) reported that sheep treading reduced the nitrogen concentration in the soil at high stocking rate, but not at the low stocking rates. This reduction in nitrogen concentration might be due to increased nitrate leaching or surface runoff.

2.5.4. Effect of treading on biological processes

Cluzeau *et al.* (1992) observed a reduction of 70-90% in earthworm populations after treading, which is mainly due to compaction and impeded drainage (Singleton, 1999). K. Betteridge (personal communication) found 50% fewer worms in heavily trodden pastures in winter compared to 24 hrs. before treading. Earthworms remain near the soil surface (0-100 mm) during the rainy or wet season and are vulnerable to trampling (Lisa *et al.*, 1997).

2.6. BENEFICIAL EFFECTS

In certain situations, low levels of trampling may be acceptable and even desirable in order to maintain the character of the environment. Burden and Randerson (1972) reported that extensive trampling damages broad-leaved herbaceous species more than the grasses, and encouraged grass content of the developing pasture. Thus, species of botanical interest which contribute quality pasture may develop in light or medium trodden areas.

Treading pasture by dairy cows in late July and early August may kill up to 69% pre-pupal and pupal populations of grass grub, and a treading event in October may result in a 93% reduction in pest density, a similar effect to that of rolling applied in early August (Atkinson and Slay, 1994). These authors also noted that this effect might be from both direct physical damage to grass grub larvae and a reduction in oxygen availability in the compacted soils resulting from treading.

Treading, by baring soil and creating hollows, provides niches for the germination and establishment of seedlings (Bakker, 1985). Prolonged periods of cattle grazing opens up swards (Chapman *et al.*, 1985), and burial of oversown seed in these trodden pastures has long been recommended as a practice to help seedling establishment (Sewell, 1950). Initial establishment and subsequent growth of sown species was strongly influenced by treading which created disturbance and fertility gradients (Burke and Grime, 1996). Moreover, Baars *et al.* (1982) observed that sheep treading of pelleted seed after sowing in mid June, mid July, and late September improved the establishment of *Medicago sativa* in soils derived from Taupo ash eruptions of uncultivated pumice hill country.

2.7. ENVIRONMENTAL EFFECTS

Treading effects are not restricted solely to on-farm activities. There are other parameters besides a decrease in the physical condition of a soil and in plant number that are related to treading damage, which will effect the environment. Treading increases surface ponding (Singleton, 1999), and severe water stress after treading damage makes plant material more brittle (Abdel-Magid *et al.*, 1987).

Animal treading causes more topsoil and contaminant runoff to waterways. Foster *et al.* (1990) observed an increase in erosion rates from grassland to river channels due to treading effect when grazed in high stocking densities. In heavily grazed grasslands, runoff volumes can increase up to twelve times than that on ungrazed grassland (Heathwaite *et al.*, 1990). The potential for water erosion can increase more from pastures grazed by heavy cattle when soil is wet (Noble, 1974; Betteridge *et al.*, 1999).

Hill country pastures are relatively more vulnerable than flat dairy or sheep pastures to treading accelerated erosion. Betteridge *et al.* (1999) observed that in hill pasture, cattle walked predominantly on tracks and these mostly developed into watercourses with minimal pasture cover. In contrast, on slopes between tracks, they often skid downhill as they move between adjacent tracks resulting in disturbance of surface soil which enhances movement of soil particles with rain water. Short-term (2-3 days) winter grazing periods can generate nutrient and soil runoff from the steep inter-track slope if grazing intensity is high, causing above 60% soil damage (Nguyen *et al.*, 1998). These authors also observed that up to 80% soil damage produced little effect on the suspended solid content of runoff from easy contoured plots, while above 40% soil damage produced a considerable increase in suspended solid runoff from the steep inter-tracked plots.

Animal treading increases movement of nutrients together with soil particles from the grassland. Lambert and Clark (1985) reported greater loss of nitrogen and phosphorus nutrient from catchments in hill pasture under rotational cattle grazing than under rotational sheep grazing due to greater soil erosion. Greater movement of nutrients into waterways from surface runoff after treading may also cause contamination (Smith *et al.*, 1993). In rainfall simulation studies, Russell *et al.* (2001) showed that pugging, which was greater on soils with very short pasture compared to 50 mm long pasture, reduced sediment loss most probably because hoof indentations acted as traps for moving sediments. Conversely, short untrodden pastures generated more sediment than long untrodden pastures since the long pasture reduced the erosive force of the rain drops.

Treading by intensive stocking of dairy pastures during winter causes modest reduction on the abundance of the meso- and macrofauna (Barker and Addison, 1995) and an increase in faecal coliforms in local aquifers (Nguyen *et al.*, 1998; Singleton, 1999).

2.8. MANAGEMENT PRACTICES TO LIMIT TREADING DAMAGE

Since most treading damage occurs when the soil is wet to very wet, avoidance of damage involves removing stock from paddocks at such times. A system of on-off grazing with limited grazing time or which concentrates stock on sacrifice areas in wet weather to reduce pugging damage is used extensively in New Zealand (Blackwell, 1993). Sheath and Boom (1997) suggested that grazing rotations with shorter duration in each paddock and reduction in stocking rate can facilitate efficient use of herbage and reduction of combined effect of treading damage, especially in wet condition.

Farm areas such as feed pads, loafing barns or sacrifice paddocks or paddocks of crop are used for holding cattle to reduce treading damage to the remaining farm areas while the soil is susceptible (Climo and Richardson, 1984). Also, removal of lactating cows from pasture, after a period of grazing (on-off grazing) that is sufficient to meet their daily feed requirements, will limit the extent of damage to soils and pasture, allowing the farm to sustain higher pasture growth rates (Blackwell, 1993). Allowing animals to graze in taller pasture could be the other option as it provides a cushioning effect between hoof and soil and reduces treading damage (O'Connor, 1956; Russell *et al.*, 2001).

Pugging damage can be minimised by providing adequate drainage to susceptible paddocks, which increases soil strength. Careful engineering of tracks and bridges in hill slopes may avoid nutrient and sediment runoff into streams. Climo and Richardson (1984) researching sheep treading found that the drained areas on Tokomaru soil had only 10 unsuitable grazing days during the year, while undrained areas remained unsuitable for grazing for 82 days. These authors also concluded that drainage is critical to reduce treading damage on poorly drained soils, and that care must be taken to give soil time to dry out after heavy rain. Quick recovery of soils in wet weather conditions is obtained by making an efficient subsurface drainage system so that they remain wet for the shortest possible time following heavy rain (Tarbotton *et al.*, 1997). Tyson *et al.* (1992) observed that spring herbage DM yield increased 11% on drained plots compared to undrained plots.

To reduce damage in winter and encourage rapid recovery of pasture during spring, authors (Sheath and Boom, 1997; Betteridge *et al*., 1999; Singleton and Addison, 1999; Russell *et al.*, 2001; Ledgard *et al.*, 1996) have suggested good management guidelines. To encourage spring pasture recovery, Sheath and Carlson (1998) have also suggested excluding cattle from grazing plots that had been severely damaged during winter or from less-improved wet paddocks which are susceptible to treading.

Subsoiling, the mechanical loosening of soil to 20-30 cm, is commonly used to improve the soil physiscal condition and alleviate the adverse effects of soil compaction caused by treading. This is a useful method to improve soil physical conditions for ameliorating compacted soil supporting permanent pasture on dairy farms (Burgess *et al.*, 2000). Greenwood and Cameron (1990) reported that subsoiling increased macroporosity volumes by up to 30% of total soil volume in Pallic soils (Yellow-grey earth soil) in Southland of New Zealand and increased air permeability and hydraulic conductivity by 2-4 orders of magnitude. Drewry and Paton (2000a) showed that subsoiling of Waikiwi silt loam (Brown Soil) in Southland of New Zealand to 25-30 cm increased macroporosity by up to 39% of the soil volume, and increased saturated hydraulic conductivity and air permeability by up to two orders of magnitude. Drewry and Paton also observed reduced ryegrass-white clover pasture production by 9% following subsoiling in the second year indicating that this reduced pasture production may have been related to a decreased water-holding capacity of the soil, and increased permeability of the soil.

2.9. SUMMARY AND CONCLUSIONS

This literature review has covered the progress over the last few decades in understanding the impact of animal treading on pasture plants and soil. The experiments reviewed demonstrate the importance of animal treading in damaging soil and pasture plants, especially in wet weather, and on wet soils, and its consequent effect on pasture production and soil physical properties.

A number of authors showed that treading damage, especially by grazing cattle, has both negative and positive impacts on plants, soil and environment. It impacts negatively by (1) direct damage to pasture plants, thus causing losses of leaf, tillers and pasture cover (2) reducing leaf area and other shoot parts (3) removing active apical meristems (4) restricting root growth of the plants (5) increasing soil surface roughness, bare ground, bulk density, aggregate size and soil strength (6) reducing soil porosity, infiltration rate, soil water content and earthworm population (7) increasing negative environmental effects like erosion, nitrate, phosphate and sulphate loss, surface ponding, and an increase in faecal coliforms in local aquifers. Conversely, treading benefits by (1) increasing many species of botanical interest such as ryegrass and white clover (2) opening up swards and burial of over-sown seeds, which helps seed germination and seedling establishment (3) reducing prepupal and pupal populations of grass grub.

Effects of treading on damage and death of pasture plants were reviewed, together with effects on variation among pasture species and on recovery and recruitment of the plants after damage to cover the bare ground. Effects of treading on mechanisms of failure under treading, soil physical properties, soil chemical and biological processes, and environment and management practices to limit treading were also reviewed.

The literature lacks detailed information on the effects of cattle treading damage and recovery of damaged soil and pasture after treading. The literature also lacks information on the dynamics of pasture species regrowth after treading. The significance and magnitude of tissue turnover mechanisms of the existing tillers and newly emerged daughter tillers of the principal pasture species after cattle treading have not been reported so far. Provision of answers to these questions is an important pre-requisite for optimising animal production through appropriate pasture management strategies, and further research is therefore necessary to integrate these principles into grazing systems.

CHAPTER 3

THE IMPACT OF CATTLE TREADING ON HILL PASTURE

3.1. INTRODUCTION

Hill country pastures of the North Island of New Zealand is the major grassland being used for grazing animals and support for about one third of country's animal production (Statistics New Zealand Agriculture, 1999). This region is highly variable in physical features and in pasture production. Farming systems of this region involve mixed sheep and cattle grazing with cattle comprising 20-40% of farmed sheep stock unit equivalents on individual farms (Ulyatt and Betteridge, 1991), and average stocking rate is increasing (Dairy Statistics, 1999). Sustainable animal farming in hill country is dependent upon the maintenance of high yielding quality pasture.

The effects of treading vary with soil moisture content, pasture species present and pasture/grazing management. The negative effect of treading on both soil and pasture can increase when cattle are grazed on wet soil (Curll and Wilkins, 1983). Pasture accumulation rate can decrease with increased stocking rate when heavy weight cattle graze on moist to wet soils (Sheath and Boom, 1997; Betteridge *et al.*, 1999). Annual pasture growth is greatest where ryegrass dominates, particularly in winter and early spring (Neely and Parminter, 1993). Thus, pasture/grazing management can be manipulated to increase ryegrass content in a hill farming system to optimise pasture production.

Farming of hill country, because of its variable topography, affects both pasture species and pasture productivity. Contour classes (tracks and slopes) of grazed hill land pastures affects herbage accumulation rate (Radcliffe *et al.*, 1968; Gillingham and During, 1973;

Suckling, 1975), and differences in accumulation rate between these contour classes can be considered a reflection of grazing pressure differences. In hill paddocks, (Sheath and Carlson, 1998) found that cattle treading damaged the soil surface more on low slopes than on high slopes. Pande *et al.* (2000) observed that a single cattle treading event in winter reduced the spring pasture accumulation rate more on tracks than on slopes. Treading by intensively stocked cattle in low slopes often creates an open canopy with more bare ground and a lower plant density. This may have implications on pasture accumulation rate and botanical composition.

Regrowth of species after treading damage may vary according to their tolerance to treading, slope class and the management imposed. Lambert *et al.* (1986b) observed that tiller densities of ryegrass and high fertility responsive grasses were higher on low slopes, whereas that of low fertility responsive grasses were higher on high slopes. Pasture species in low slope hill pastures could have faster growth as soils are more fertile (Lambert *et al.*, 1983), but conversely, low slope pastures may be heavily grazed and, when wet, more heavily damaged by treading.

The information available regarding the impact of repeated cattle treading on hill pasture at different soil moisture levels is limited. Along with losses in pasture production and soil damage by animal treading, the significance of the pasture species in production and ability to maintain cover across slope classes is a key factor in their sustainable use in pastoral agriculture. Similarly, information is unavailable on changes in species association resulting from species filling open spaces created by treading. The aim of this experiment was to study the direct physical effects of cattle treading on pasture accumulation rate; species composition and canopy cover under different stocking rates, and soil water states at treading time. Changes in species association due to bare ground becoming recolonised following treading damage is also the focus of this study.

3.2. MATERIALS AND METHODS

3.2.1. Site and pasture

The experimental site was 2 ha of steep, dissected hill country (Plate 3.1), 20 km NE of Palmerston North, New Zealand at *Ballantrae*, a hill country research area of AgResearch Grasslands. The soil was a moderately steep Taihape steepland soil developed from siltstone (J. D. Cowie, unpublished soil survey report *In*: Betteridge *et al.*, 1999). This soil is classified as a Pallic Soil/Ultic Soil or Allophanic Soil (Typic Dystrochrept) (McLaren and Cameron, 1996). Presumably local variation in parent material leads to these different soils at different microsites i.e. they are not all found at the same site. The site has a south-easterly aspect and ranged in slope between 10° and 38°. The site is described as summer-moist country with a 1200 mm mean annual rainfall and a mean soil temperature at 10-cm depth ranging from 6°C in August to 13°C in December. Botanical composition of pastures was complex. Major contributors to the canopy cover during the trial period (see 3.2.5.2. canopy cover for measurement detail) were ryegrass (*Lolium perenne*), 25%; browntop (*Agrostis capillaris*), 18%; Yorkshire fog (*Holcus lanatus*), 14%; white clover (*Trifolium repens*), the resident perennial legume about 10%; poa (*Poa spp.*), 9%; dicotyledons (flat weeds), 8%; crested dogstail (*Cynosorus cristatus*), 7%; sweet vernal (*Anthoxanthum odoratum*), 4%; cocksfoot (*Dactylus glomerata*), 3% and the rest 2%.

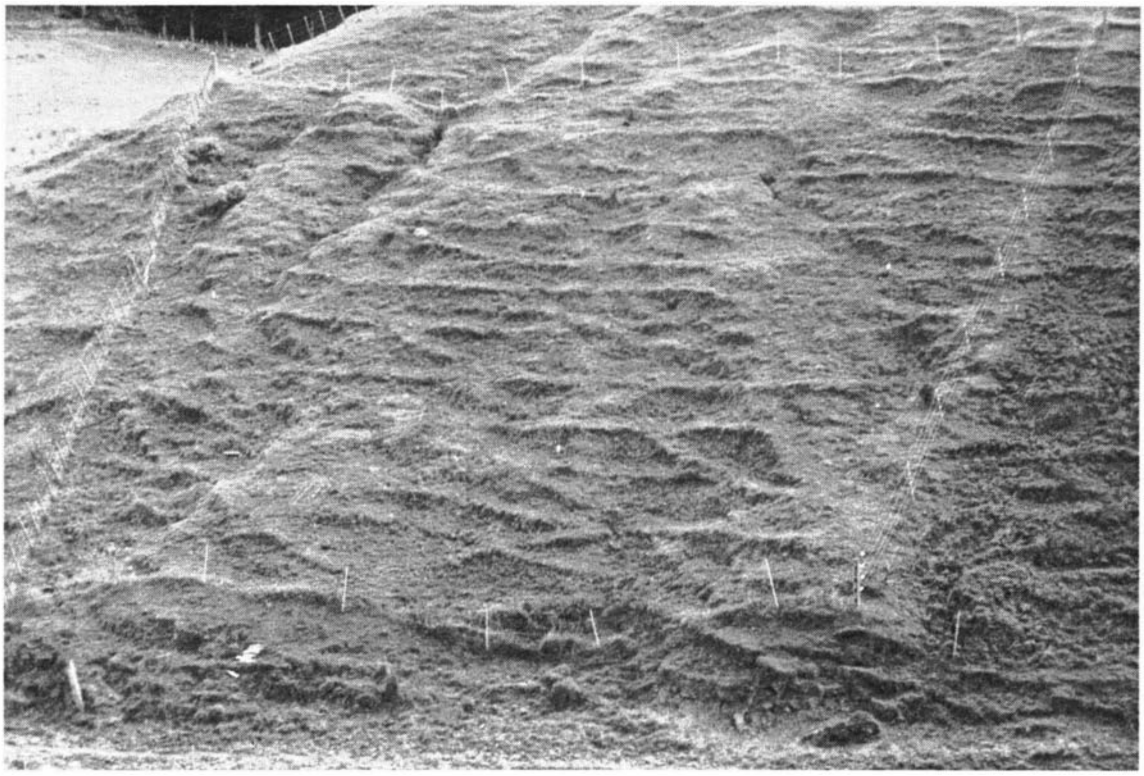

Plate 3.1 A view of a plot at the *Ballantrae* study site.

3.2.2. Trial history

This study was conducted in the hill pasture to understand the pasture, soil, and animal relationship in a grazed sedimentary hill-land environment. The pastures had a history of sheep and cattle grazing that extended back approximately 80 years to when the land was originally cleared from bush. This experiment was performed on the same pasture as a trial started in 1993 that looked at the effect of single and double treading by sheep and cattle on wet soils (Betteridge *et al.*, 1999). The experiment was initially structured to include 3 stocking rates x 3 soil moisture thresholds in a factorial design with 2 replicates. The design was modified for this study with treatments allocated as described below. A detailed description of this trial and the associated paddock histories can be found in Betteridge *et al.* (1999).

3.2.3. Design and treatments

Mature beef cows (average body wt. 530 kg) were stocked at a range from 50 to 300 head ha^{-1} for 24 hr to generate treading treatments. The range of stocking rates were chosen to simulate low to extreme damage that can happen in commercial practice. These treatments were used throughout the trial when the soil water content (vSWC) was within one of three ranges. 'Wet' treading occurred without a vSWC limitation. 'Moist' treading only took place when vSWC was below the plastic limit of 42% vSWC and 'Dry' treading occurred only when vSWC was lower than the lower critical limit of 22% (Table 3.1). Determination of vSWC was based on Time Domain Reflectrometry (TDR, Parchomchuki *et al.*, 1997) readings at 15 cm depth being below the treatment's threshold value. Five reading were taken from track and five from sloping land. If cattle grazing was not permitted treatment plots were grazed by sheep at a stocking rate of 10.5 sheep stock units (SSU) ha^{-1} to utilize pasture dry matter. In these pastures, soils were expected to deform under the hoof when vSWC was above the plastic limit, whilst soils within 22-42% vSWC range were expected to compact under the pressure of a cattle hoof, but not deform. Soil in the dry treatment was not expected to be damaged when trodden by cattle. These three vSWC regimes were used as criteria for allowing the cattle grazing within respective treatments at the time when it was determined that the wet treatment plots contained sufficient herbage for grazing.

Each treatment plot was approximately 400 m^2 (ca. 20 m x 20 m) in size and treatments were replicated twice using a randomised block design. The experiment was structured as a split-plot design of 'contour classes' comprising low slope (hereafter named 'tracks') and high slope (hereafter named 'slopes') whose relative proportion is 1:4, respectively (Betteridge *et al.*, 1999), representing the typical hill situation at Ballantrae. The track sub-plots had a slope of 0-12° and slope subplots had a slope of >12°. To facilitate some of the measurements, the slope subplots were further grouped into classes of 13-25° (medium slope), and >25° (steep areas) as described by Lambert *et al.* (1983).

The trial started in July, 1998 and continued to July, 1999. On wet plots (treatment E, Table 3.1) there were 6 cattle grazings during the trial period. Three of them occurred when vSWC was >42%.

Table 3.1 Mean stocking density of dry cows and soil water content (vSWC) factor used to apply treatments from August 1998 to March 1999.

		Stocking density (head ha^{-1} 24 hr^{-1})					
Treat. Code[1]	vSWC	19Aug98	13Oct98	17Nov98	15Dec98	27Jan99	9Mar99
A	Dry	0	0	0	0	0	50
B	Moist	0	0	150	0	150	150
C	Moist	0	0	300	0	300	300
D	Moist	300	0	150	0	150	150
E	Wet	300	300	300	300	300	300

[1]Hereafter the treatments are coded as:
A = Dry low (cattle were grazed only once at low stocking density when soil moisture was dry)
B = Moist medium (Cattle were grazed at medium stocking density when soil moisture was medium and dry)
C = Moist high (Cattle were grazed at high stocking density when soil moisture was medium and dry)
D = a single severe treatment event in August when soil was wet, but subsequently managed as a moist treatment with medium stocking density
E = a single severe treatment event in August when soil was wet, but subsequently managed as repeated grazing with high stocking density

The rationale for the design of the experiment was that treading damage to pasture or soil was unlikely to occur in treatment A as soils were cattle-grazed only when dry, and then only with a low stocking intensity. Treatment D was designed to impose a single severe treading damage event in August when the soil was wet (Plate 3.2), but was managed as a moist-medium treatment thereafter. During the previous four years this treatment had been managed as dry-high and had had an annual dry matter (DM) yield similar to dry-low. By contrast, treatment E allowed repeated severe treading damage regardless of vSWC and with a high stocking density. Treatments B and C were grazed when the soil was moist and dry but with 150 and 300 cattle ha^{-1} respectively. Treatment B had been managed during the previous four years as wet-medium and had grown less DM than the moist and dry treatments (K. Betteridge, personal communication). This management change was made to see whether a more lenient management would result in a recovery of yield potential as measured in treatment A. Treatments A, C and E had been unchanged for four years.

Throughout the trial period, mobs of sheep were used after cattle grazing to more uniformly utilize pasture in all experimental plots. Numbers of sheep were varied from 60-80 at a time. For sheep, access to the pasture plots was given under electric fences and by opening main gates. Sheep were grazed when cattle were not used (e.g. in moist and dry treatments during spring). Even when cattle were used, sheep were used to eat off surplus pasture left by cattle. After completing grazing in an experimental area (1-3 days), sheep were removed.

Plate 3.2 Soil and pasture damage resulting from cattle treading on wet soil.

3.2.4. Measurement dates

Data were collected between July 1998 and May 1999. Measurement and sampling dates allowed 3-6 weeks regrowth following grazing, with regrowth interval being shortest in spring when pastures were growing fastest. Pasture cover and species distribution measurements were made in July, September, October, November, and December, 1998 and in January, March, April, and May, 1999. Pastures were harvested prior to the grazing/treading events in: August, October, November and December, 1998 and January, February, March, April and May, 1999 for the estimation of herbage mass and accumulation rate. Tiller cores were taken for tiller density estimation only once, in May 1999.

3.2.5. Measurements

3.2.5.1. Soil moisture

Volumetric soil water content (vSWC) was measured using a Time Domain Reflectrometry (Parchomchuki *et al*, 1997) on 10 cm depth. Prior to each grazing, vSWC was determined. Ten vSWC measurements were taken from each slope class in each plot in July and December, 1998, and in July 1999.

3.2.5.2. Soil bulk density, infiltration rate, air-filled porosity and total porosity

Because of time limitation and for logistics reasons, soil bulk density, infiltration rate, air-filled porosity and total porosity were determined only in treatments A and D, in September and November 1998, and in February, March, and May 1999. Bulk density and total porosity were measured, following the methods of Gradwell and Birrell (1979) on 100 mm diameter by 80 mm deep intact cores taken randomly from 5 slope and 5 track sites from each of the treatment plots. Air-filled porosity was determined by deducting the volumetric water content from the total porosity.

The steady state infiltration rate was determined *in situ* using double-ring flooding infiltrometers (Hills, 1970). Water was poured through plastic buckets into both rings. After saturation, measurements of falling head were taken until steady-state conditions were achieved. Two measurements were taken from each of trodden and untrodden plots and mean of these values was used for analysis.

3.2.5.3. Canopy cover

Cover was defined as the proportion of the ground surface occupied by the aerial parts of individual species under consideration as determined by the perpendicular projection of a 'pin' towards the ground (Greig-Smith, 1957). In this study, cover was categorised by species and expressed as a percentage of the total number of pin projections.

The cover was measured by using a purpose built contometer (Betteridge *et al.*, 1999) with 40 pins, set 5 cm apart (Plate 3.3). Instead of using 40 pins at a time, as described by Betteridge *et al.*, only one pin was manually placed in each of the 40 pin holes (in the sequence 1 to 40, starting always from the same fixed site) to act as a point-analyser to estimate cover. Only the first-hit touch of the pin on a plant or on bare ground was recorded. In each plot, five permanent transects were located by pairs of pipes concreted into the hillside into which the frame was placed. This enabled pin measurements to be made at precisely the same positions on each reading occasion. Each of the five transects was sited to traverse both track and sloping contours and normal to the tracks, which typically run horizontally around the contour. The repeated pin hit measurements enabled collection of quantitative data describing bare ground or canopy cover contributed by known species.

The frequency of a repeated hit on the same cover class at each given point within treatments was compared between treatments from July to September, and from September to October.

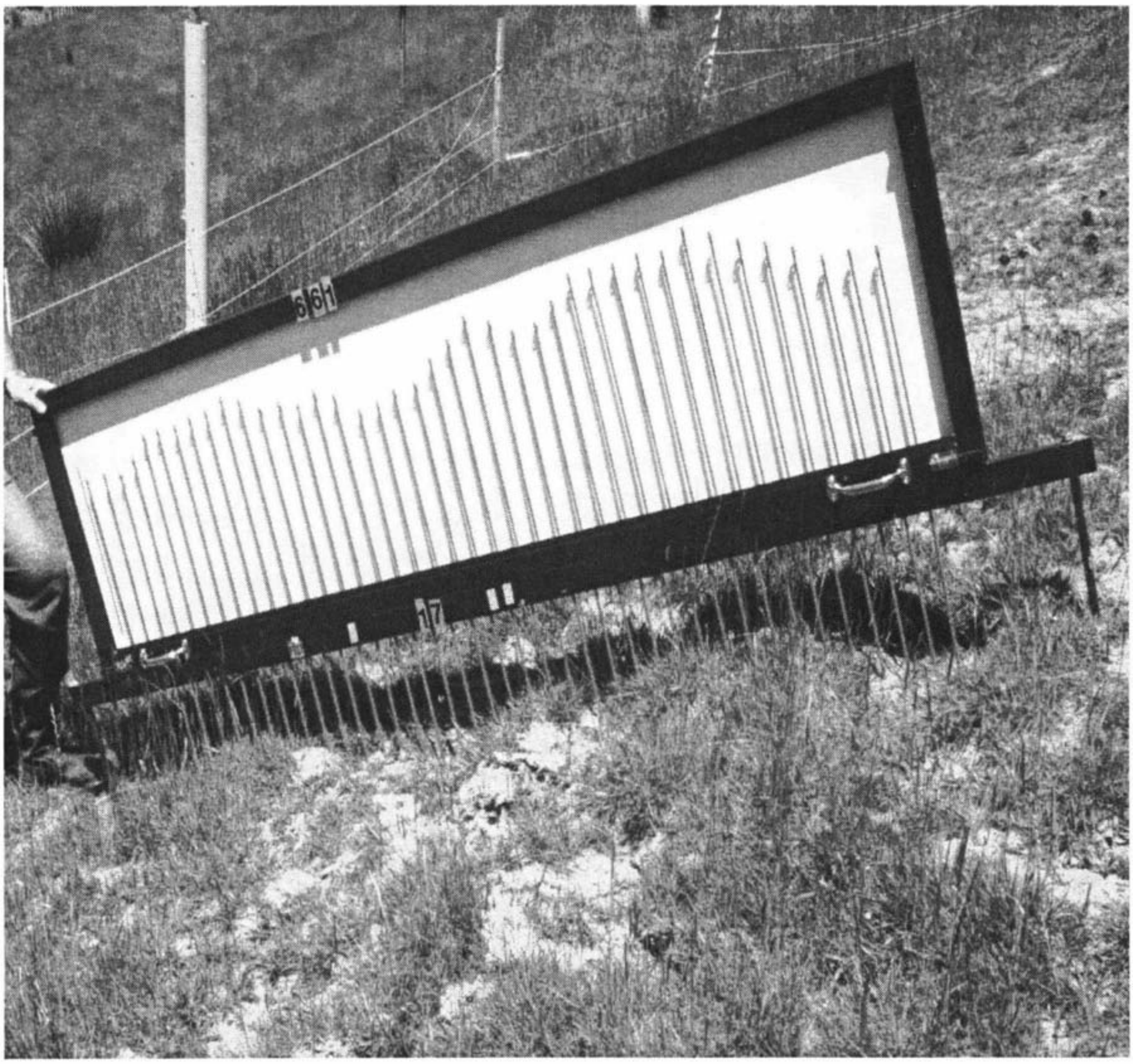

Plate 3.3 Contometer used to measure pasture cover (First-hit). In this study, instead of 40 pins, only one pin was used. It was manually placed through each of 40 pin-holes, and lowered pin to hit first a plant or bare ground.

Pin-hits were recorded in 6 categories

(i) Ryegrass

(ii) High fertility responsive (HFR) grasses: Yorkshire fog; Poa; cocksfoot,

(iii) Low fertility tolerant (LFT) grasses: browntop; crested dogstail; sweet vernal; chewing fescue (*Festuca rubra*),

(iv) Legumes: white clover; lotus (*Lotus corniculatus*),

(v) Others: flat weeds [catsear (*Hypochaeris radicata*); ribgrass (*Plantago lanceolata*); hawkbit (*Leontodon taraxacoides* [vill] Merat); moss; dead matter and other minor unidentified species,

(vi) Bare ground

The pin, sharpened to minimise error (Goodall, 1952a), was lowered until it made the first-hit and the contacted species, or bare ground was recorded.

3.2.5.4. Herbage accumulation

To estimate pasture accumulation rate, seven harvests were carried out on sites pre-trimmed to 5 mm height, from four 0.5 m^2 quadrats per plot. Cages were placed over the pre-trimmed pasture to locate these sites. At each harvest, the two quadrats from tracks and the two quadrats from slopes within each plot were cut to the pre-trimmed height. A 100g sample was oven dried at 80°C for 24 hrs and weighed to determine the dry matter content. Accumulated herbage mass from each cut was divided by the number of days of regrowth to get herbage accumulation rate. No adjustment was made to the herbage accumulation rate estimate to account for the 3-7 day period encompassing cattle and subsequent sheep grazing when necessary, during which growth was not measured.

3.2.5.5. *Botanical composition*

A sub-sample from the cut herbage of harvest 1 (spring), harvest 4 (summer) and harvest 6 (autumn) was taken and botanically separated into component species. The proportion of each species class was determined using the classes listed above in section 3.2.5.3. Contour classes were determined with visual estimation while taking first-hit-pin measurements.

3.2.5.6. *Tiller density*

At the end of the trial, in May 1999, the tiller density of the ryegrass, HFR and LFT grasses, and flat weeds from all treatments was recorded from thirty 50 mm diameter turf plugs (Mitchell and Glenday, 1958). Ten turf plugs were taken from each of the three slope classes within each plot. Turf plugs were taken to the laboratory, all grass tillers, growing points of legumes, and plant numbers of flat weeds above ground were counted.

3.2.6. Statistical analysis

Data were analysed by Analysis of Variance (ANOVA) with repeated measures, with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, 1990). A split-plot design over time was used to analyse effects of treading on herbage accumulation rate and botanical composition, and tiller density across slope classes of the hill pasture. Where necessary logarithmic ($\log_{10}$) transformations were applied to standardise the variances of the data. In such cases, actual means and their standard errors are presented in the tables or figures. Tukey's lettering to denote significant differences between means in the table is based on analysis of transformed data.

The analysis of pasture accumulation rate as a function of pasture cover was carried out using simple linear regression analysis of the Statistical Analysis System. The accumulation rates derived from the harvests (Cuts 1-7, Table 3.9) and pasture covers of the same period were regressed to test relationship between them.

For the change in association of species cover, first-pin-hit frequency data were analysed by using the GENMOD procedure of the SAS system. The frequency of shift in species cover across the fixed points in the paddocks was compared between treatments from July to September, and from September to October, 1998. The results have been presented in transition tables (Appendix 3.2 and 3.3). To read these appendices, details are given in Appendix 3.1. The structure of the SAS output is shown in Appendix 3.6. As there is no simple means of differentiating which treatment differs from which, a simple repeated measures ANOVA of $\log_{10}$ transformed stability quotient data was performed. The stability quotient represents the proportion of a species class at each given first-hit position that remained unchanged between months (Appendices 3.2 and 3.3).

3.3. RESULTS

3.3.1. Soil water content (vSWC)

There was no difference in vSWC between treatments and between slope and tracks in July and December 1998 (Table 3.2). There was a higher vSWC in treatments C, D and E than in A in July 1999 and there was also an interaction of treatment and contour class where vSWC in tracks of D and E was higher than in A, B and C, and higher in slopes of C than in the tracks of C.

Table 3.2 Mean volumetric soil water content (vSWC) from five treatment regimes and contour classes within the treatments.

Treatments[1]	Soil water content (%)					
	July, 98		Dec, 98		July, 99	
	Track	Slope	Track	Slope	Track	Slope
A	52	48	22	26	53	54
B	49	52	24	25	54	56
C	53	48	26	23	56	60
D	52	50	27	26	60	58
E	50	53	29	24	63	57
Mean (slope)	51	50	26	25	57	57
sem						
Treat.	0.6		1.5		1.5	
Contour class	0.4		0.9		0.9	
Significance						
Treat.	ns		ns		**	
Contour class	ns		ns		ns	
Treat*Contour	ns		ns		*	

[1]Refer to Table 3.1 for treatment code definitions
sem = Standard error of the least square means
*, ** and ns denote P < 0.05 and P < 0.01 significant levels and not significant, respectively

3.3.2. Soil dry bulk density and infiltration rate

Soil bulk density was greater in treatment D (which was wet-trodden in August) compared to treatment A in September, 1998, but there were no significant differences in other months (Table 3.3). There were no significant differences in soil bulk density between tracks and slopes, and no interaction of treatment and contour class. Except in tracks of treatment D, there was trend for infiltration rate to be faster in March, 1999 than at other times (Table 3.4).

Table 3.3 Mean bulk density (g cm^{-3}) from treatment A and D in September and November 1998, and February, March and May 1999.

Treatments[1]	Contour	Bulk density (g cm^{-3}) Sep 98	Nov 98	Feb 99	Mar 99	May 99
A	Slope	0.84	0.89	0.92	0.97	0.88
	Track	0.80	0.84	0.88	0.96	0.81
D	Slope	0.87	0.91	0.95	0.98	0.90
	Track	0.93	1.01	0.95	1.06	0.91
sem		0.011	0.041	0.008	0.021	0.015
Significance						
Treat.		*	ns	ns	ns	ns
Contour class		ns	ns	ns	ns	ns
Treat*Contour		ns	ns	ns	ns	ns

[1]Refer to Table 3.1 for treatment code definitions
sem = Standard error of the least square means
* and ns denote P < 0.05 significant level and not significant, respectively

Table 3.4 Mean infiltration rates (mm h^{-1}) from treatments A and D in September and November 1998, and February, March and May 1999.

Treatments[1]	Contour	Infiltration rate (mm h^{-1}) Sep 98	Nov 98	Feb 99	Mar 99	May 99
A	Slope	102	118	213	351	200
	Track	104	97	276	233	141
D	Slope	110	109	177	254	174
	Track	74	97	175	98	143
sem		4.6	13.1	44.1	53.6	26.5
Significance						
Treat.		ns	ns	ns	ns	ns
Contour class		ns	ns	ns	ns	ns
Treat*Contour		ns	ns	ns	ns	ns

[1]Refer to Table 3.1 for treatment code definitions
sem = Standard error of the least square means
ns denote not significant

3.3.4. Air-filled porosity and total porosity

Air-filled porosity was greater in treatment A compared to treatment D in September 1998, but there were no significant differences between treatments in other months (Table 3.5). There was greater air-filled porosity in slopes compared to tracks in February, 1999, but there were no differences between treatments in other months. There was no interaction of treatment and slope class. Total porosity was greater in treatment A compared to treatment D in September, but there was no significant difference in other months (Table 3.6). Whereas air-filled porosity was highest in February and March, there was no temporal pattern for total porosity.

Table 3.5 Mean air-filled porosity (%) in treatments A and D in September and November 1998, and February, March and May 1999.

Treatments[1]	Contour	Air filled porosity (%)				
		Sep 98	Nov 98	Feb 99	Mar 99	May 99
A	Slope	11.2	24.0	29.4	38.3	16.4
	Track	9.5	27.4	24.6	31.2	13.7
D	Slope	8.8	25.5	31.0	36.7	15.8
	Track	6.3	20.0	22.4	28.1	14.9
sem		0.45	2.02	0.53	1.74	0.73
Significance						
Treat.		*	ns	ns	ns	ns
Contour class		ns	ns	*	ns	ns
Treat*Contour		ns	ns	ns	ns	ns

[1]Refer to Table 3.1 for treatment code definitions
sem = Standard error of the least square means
*and ns denote P < 0.05 significant level and not significant, respectively

Table 3.6 Total porosity (%) from treatment A and D in September and November 1998, and February, March and May 1999.

Treatments[1]		Total porosity (%)				
		Sep 98	Nov 98	Feb 99	Mar 99	May 99
A	Slope	67.2	65.1	64.0	62.1	65.6
	Track	68.6	67.0	65.5	62.6	68.2
D	Slope	65.8	64.3	63.0	61.4	64.8
	Track	63.6	60.3	62.8	58.6	64.2
sem		0.44	1.63	0.32	0.80	0.59
Significance						
Treat.		*	ns	ns	ns	ns
Contour class		ns	ns	ns	ns	ns
Treat*Contour		ns	ns	ns	ns	ns

[1]Refer to Table 3.1 for treatment code definitions
sem = Standard error of the least square means
* and ns denote P < 0.05 significant level and not significant, respectively

3.3.5. Herbage accumulation rates on tracks and slopes

Herbage accumulation rates on tracks from Cut 1 were reduced by 44% to 22 kg, 33% to 26 kg, and 64% to 14 kg DM ha^{-1} day^{-1} in treatments B, D and E respectively compared to A (39 kg DM ha^{-1} day^{-1}, Table 3.7), but these differences were not significant due to a high variations between sampled sites and the low number of replications. Herbage accumulation rates on tracks from Cut 2 tended to be lower in treatment E than in A. Marked differences for herbage accumulation rate between treatments on tracks were measured in summer (Cut 4, Table 3.7). During this time, herbage accumulation rates on tracks were reduced to 31 kg (or 40%), 28 kg (or 46%) and 21 kg (or 60%) DM ha^{-1} day^{-1} in treatments B, D and E respectively compared to that of 52 kg DM ha^{-1} day^{-1} in A. There were no significant differences in herbage accumulation rates on tracks between treatments from Cuts 3, 5, 6 and 7. Herbage accumulation rates on tracks between treatments C and A from 'All Cuts' were similar in spite of the higher stocking density used. There was an interaction between time and treatment ($P < 0.05$) for the herbage accumulation rate on tracks where treatments A, B, C and E grew more slowly in cuts 5 and 6 than in other cuts. The averaged herbage accumulation rates on tracks across all seven harvests tended to be lower in repeatedly-trodden treatment E compared to treatments A and C.

There were no significant differences in herbage accumulation rates on slopes between treatments (Table 3.8). For the first 7-week period (Cut 1), the decrease in herbage accumulation rates on slopes was 7 kg (or 39%) and 1 kg (or 6%) DM ha^{-1} day^{-1} in treatments D and E respectively compared to A. During the next 4-week period (Cut 2), the differences in herbage accumulation rates on slopes between treatments were very small.

There were no significant differences in contour-adjusted herbage accumulation between treatments at any cut (Cut 1 to cut 7, Table 3.9). Contour adjustment resulted from weighting slope data by 4 and track data by 1 based on the approximate ratio of ratio of 4:1 for slopes and tracks (Betteridge *et al.*, 1999). During the first 7-week period (Cut 1), following a severe treading in August, the reduction in herbage accumulation in treatment E was 24% relative to A, 11% relative to B but very similar to C. For the same period, the reduction in herbage accumulation in treatment D, again after the single severe treading of this treatment in August, was 35% relative to A, 25% relative to B, 18% relative to C and 15% relative to E. Total herbage accumulation across all 7 cuts in treatment D was reduced to 25% relative to A, 8% relative to B, 19% relative to C and 15% relative to E. In treatment E, total herbage accumulation was only 11% lower than in A and 5% lower than in C, but 8% higher than in B.

Table 3.7 Mean herbage accumulation rate on tracks from five management regimes over seven regrowth periods.

Treatments[1]	Mean (kg DM ha^{-1} day^{-1}) for each regrowth period							Trt. mean
	[2]Cut1	[3]Cut2	[4]Cut3	[5]Cut4	[6]Cut5	[7]Cut6	[8]Cut7	of 7 cuts
A	39	52	33	52[a]	16	11	27	33
B	22	42	26	31[bc]	17	22	23	26
C	37	55	35	41[ab]	12	17	23	31
D	26	40	29	28[c]	21	17	22	26
E	14	16	21	21[c]	10	10	13	15
Mean	28	41	29	34	15	15	31	28
sem	8.8	8.2	3.5	3.7	3.6	4.9	3.7	3.6
Significance								
Treat. within cut	ns	P = 0.09	ns	*	ns	ns	ns	P = 0.12

[1]Refer to Table 3.1 for treatment code definitions
[2](24 Aug-12 Oct, 1998), [3](16 Oct-16 Nov, 1998), [4](20 Nov-14 Dec, 1998), [5](21 Dec, 1998-26 Jan, 1999),
[6](1 Feb-8 Mar, 1999), [7](15 Mar-19 Apr, 1999), [8](26 Apr-25 May, 1999)
sem = Standard error of the least square means
* and ns denote P < 0.05 significant level and not significant, respectively

Table 3.8 Mean herbage accumulation rate on slopes from five management regimes over seven regrowth periods.

Treatments[1]	Mean (kg DM ha^{-1} day^{-1})							Trt. mean
	[2]Cut1	Cut2	Cut3	Cut4	Cut5	Cut6	Cut7	of 7 cut
A	18	32	31	24	13	27	10	22
B	18	22	22	25	7	19	11	18
C	12	29	34	24	14	17	14	21
D	11	26	29	22	6	19	5	17
E	17	46	41	25	16	8	13	24
Mean	15	31	31	24	11	18	11	20
sem	1.7	8.1	9.6	4.0	3.2	7.70	1.9	2.4
Significance								
Treat. within cut	ns	ns	ns	ns	ns	ns	ns	ns

[1]Refer to Table 3.1 for treatment code definitions; [2]See table 3.7 for cut period details
sem = Standard error of the least square means
ns denote not significant

Table 3.9 Total contour adjusted herbage accumulation (track and slope weighting 1:4) from five management regimes over seven regrowth periods.

Treatments[1]	Mean (kg DM ha^{-1})							
	[2]Cut1	Cut2	Cut3	Cut4	Cut5	Cut6	Cut7	Total
A	1069	1116	753	1055	465	839	667	5965
B	921	798	541	934	325	699	669	4888
C	837	1069	823	995	466	595	762	5547
D	690	886	691	840	317	638	416	4477
E	816	1234	890	876	513	287	677	5293
Mean	860	1020	740	940	420	610	650	5250
sem	141.0	233.5	178.0	102.8	86.9	149.4	88.2	428.9
Significance								
Treat. within cut	ns	ns	ns	ns	ns	P = 0.16	P = 0.14	ns

[1]Refer to Table 3.1 for treatment code definitions
[2]See table 3.7 for cut period details
sem = Standard error of the least square means, ns denote not significant

3.3.6. Botanical composition

For the botanical separation, HFR and LFT grasses were combined and named 'Other grasses'.

There were no treatment effects on botanical composition (Figure 3.1). The content of ryegrass remained greater on tracks compared to slopes, whereas the content of Other grasses remained greater on slopes compared to tracks in spring, summer and autumn ($P < 0.001$; Figure 3.2). The legume content was greater on slopes than on tracks in spring and summer (9 and 5%, 10 and 6% respectively, $P < 0.05$), but was similar in autumn (Figure 3.2). The content of Other components (flat weeds and dead plants) was greater in slopes compared to tracks in spring and summer (10 and 3%, and 26 and 15% respectively, $P < 0.001$), and in autumn (19 and 9%, $P < 0.05$).

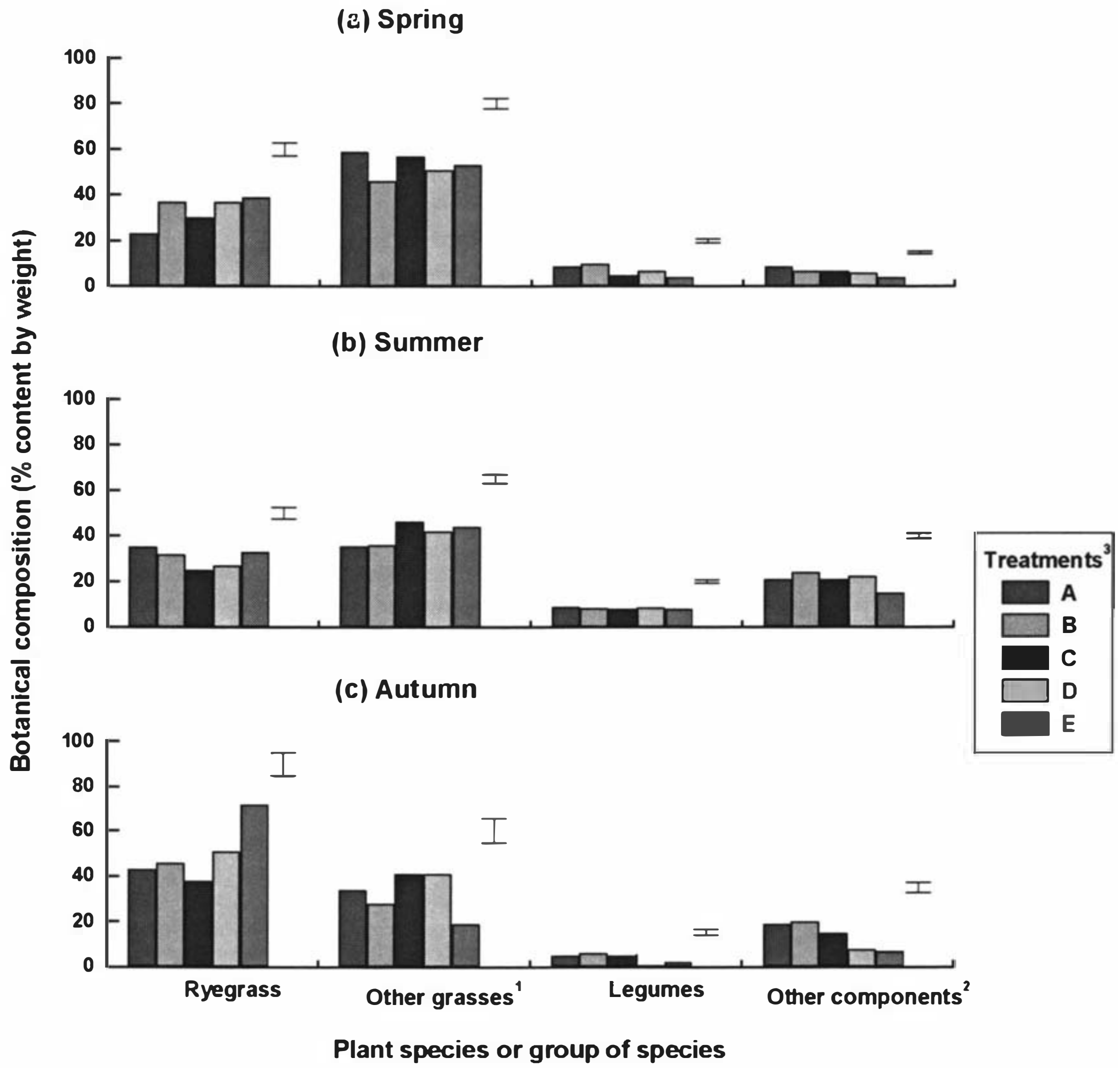

Figure 3.1 Mean botanical composition (% by weight) of the swards from tracks and slopes in (a) spring, (b) summer and (c) autumn from different management regimes. Data have not been adjusted for the 1:4 ratio of tracks: slopes when calculating the mean values.

Vertical bars show standard error of the least square means (sem)
[1]Data of HFR and LFT grasses are pooled, [2]Data of the flat weeds and dead plants were pooled.
[3]Refer to Table 3.1 for treatment code definitions

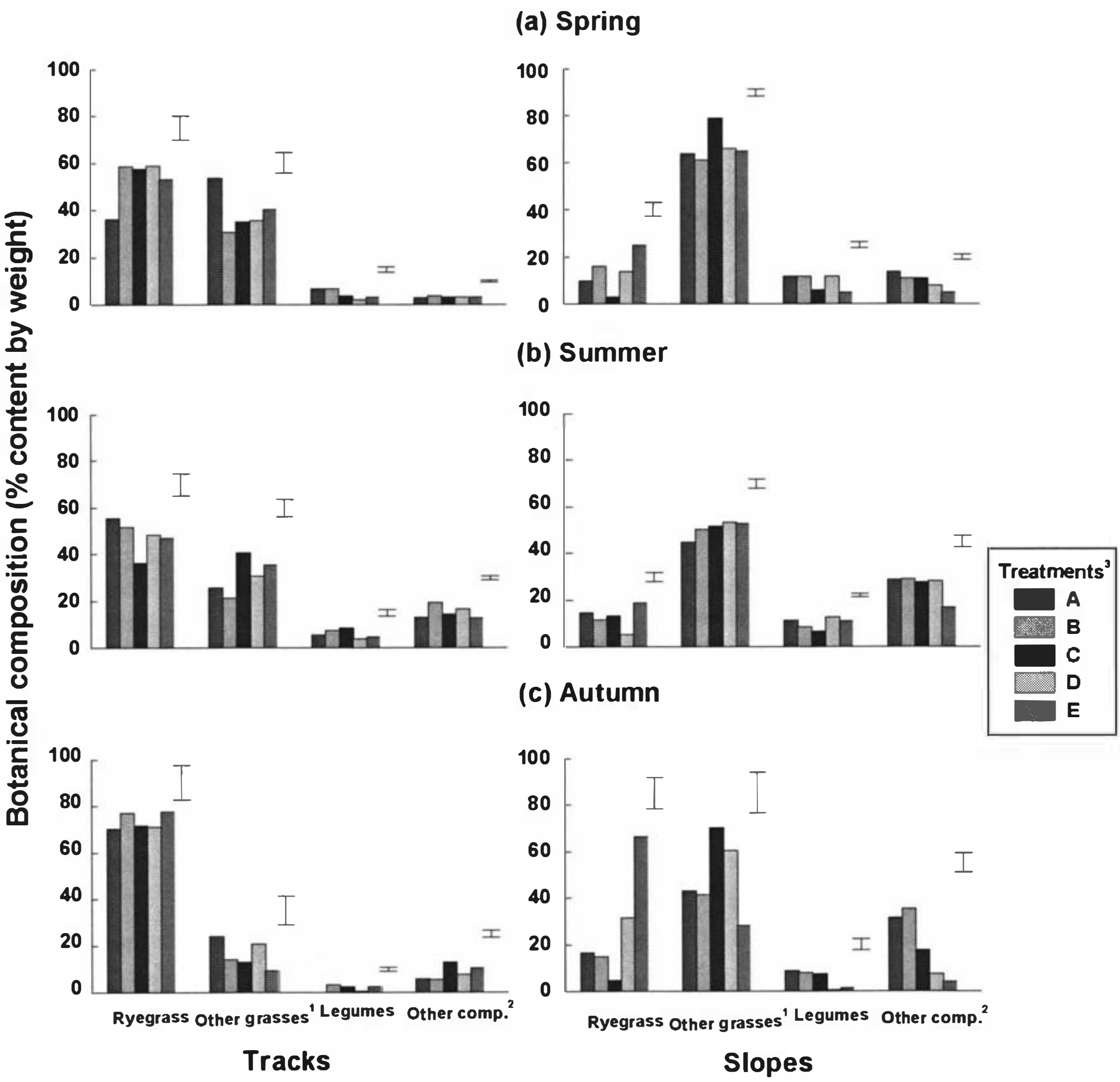

Figure 3.2 Botanical composition of cut swards in (a) spring, (b) summer and (c) autumn from tracks and slopes of different management regimes.

Vertical bars show standard error of the least square means (sem)
[1]Data of HFR and LFT grasses were pooled, [2]Data of the flat weeds and dead plants were pooled.
[3]Refer to Table 3.1 for treatment code definitions

3.3.7. Bare ground and pasture species cover

Treatment D, trodden severely once only in August, 1998 and treatment E, trodden repeatedly at a high stocking rate since 1994 showed a much higher percentage of bare ground in September (Figure 3.3a) compared to treatments A, B and C which were not cattle-trodden at that time. Treatment E had significantly more bare ground (30-50%) in all months except January, 1999 (Figure 3.3a). The percentage bare ground was least in treatment A (5-10%) throughout the trial, being significantly so in December, 1998, March, April and May, 1999 ($P < 0.05$). From December, 1988, treatments B, C and D had similar percentages of bare ground. The main effect of time, and the interaction of treatment and time was also highly significant ($P < 0.001$).

In April 1999, ryegrass cover was greater in treatment B compared to the treatments C and E (Figure 3.3b) and there was an interaction between time and treatment ($P < 0.05$) where ryegrass content in C increased and in A decreased between April and May. For all other months, ryegrass cover was similar between treatments.

Cover of HFR grasses was significantly lower in severely-trodden treatments D and E in September compared to untrodden treatment A (Figure 3.3c), but there were no differences in other months. There was also no interaction between treatment and time.

There were no significant differences in cover of LFT grasses between treatments and no effects of time or interaction between treatment and time (Figure 3.3d). In March 1999, legume cover was greater in B compared to treatments C, A and E (Figure 3.3e).

Other components (Figure 3.3f) comprised less than 10% of canopy cover except in March 1999 when Other components in treatments A and C contributed more than B, D, and E which, in turn, contributed more than A ($P < 0.01$). There was an interaction between time and treatment.

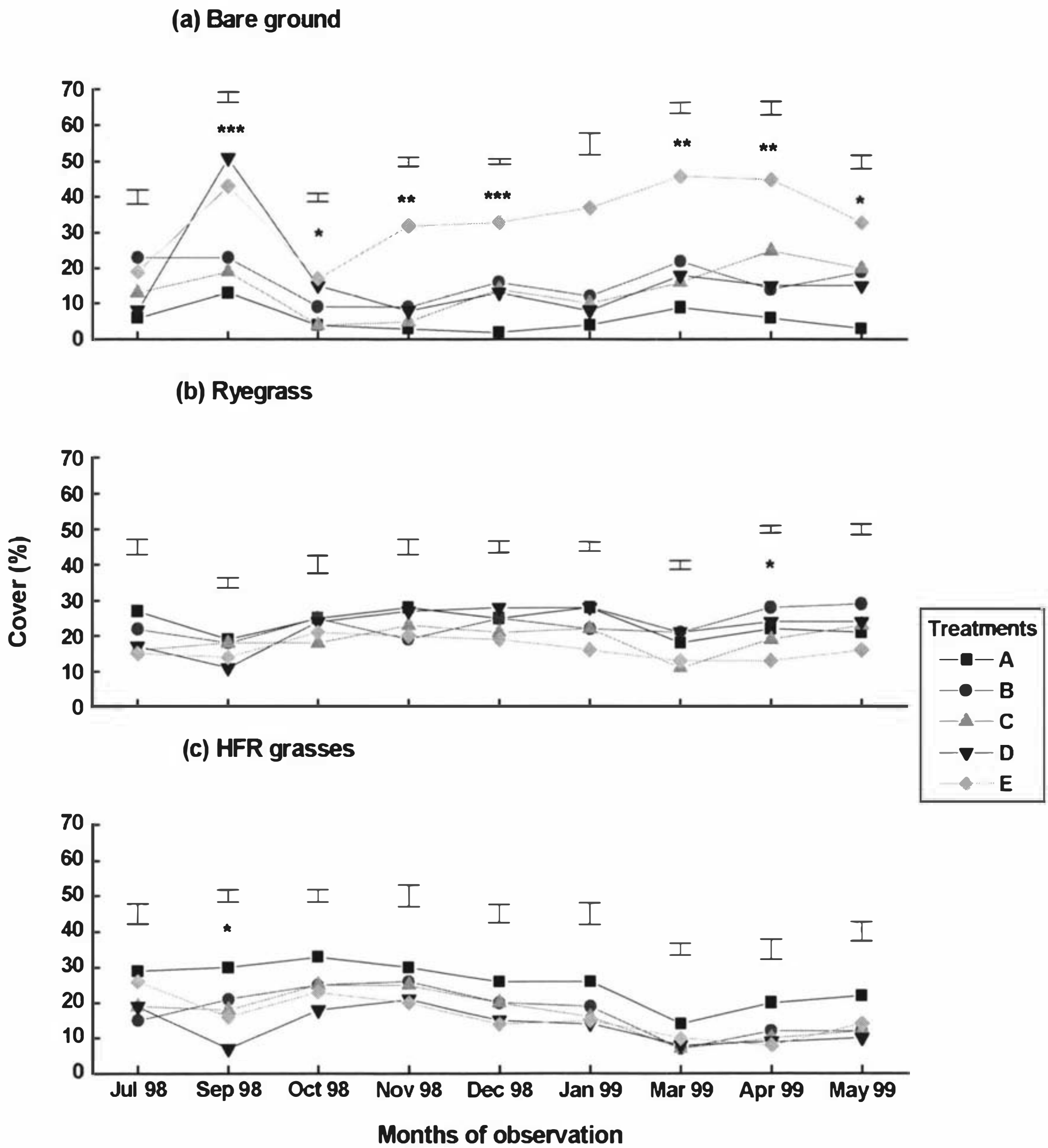

Figure 3.3 Percentage (a) Bare ground, (b) Ryegrass, (c) HFR grasses, (d) LFT grasses, (e) Legume and (f) Other components based on 200 first-hit scores across two replications under five treading treatment regimes.

Vertical bars show standard error of the least square means (sem)
*, **, *** denote P < 0.05, P < 0.01, P < 0.001 significant level, respectively.

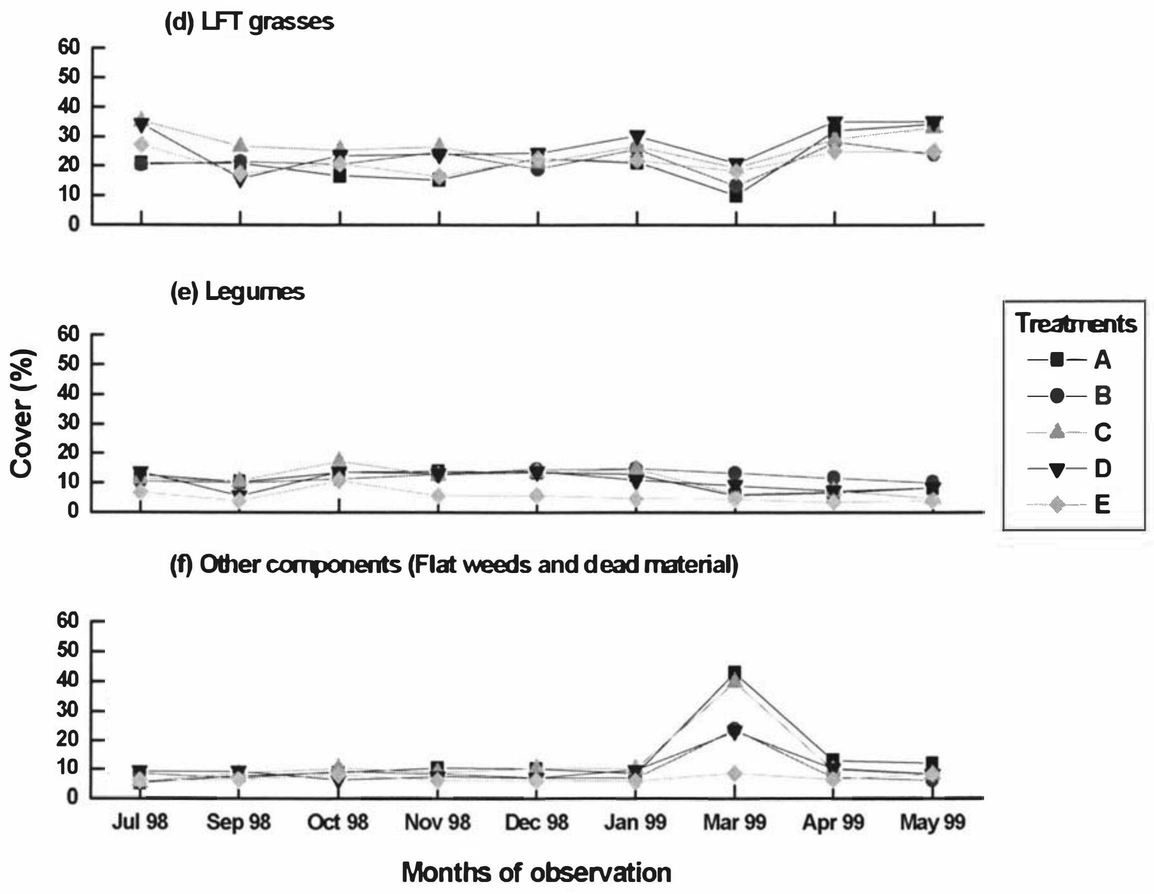

Figure 3.3 Continued.

In looking at the stability of a species, species group or bare ground at individual points in the plot it was found that hits on bare ground that were stable were lower in treatments B and C than in treatment E between July and September, and were lower in treatments A and C than in treatment E in September to October (Appendix 3.4). The smaller stability quotients of bare ground for September-October than for July-September reflect the faster growth rate of pasture in Spring than in winter. There were no differences in stability of ryegrass, HFR grasses, LFT grasses, legumes and Other components (broadleaf weeds and dead material). Further, the overall stability of the species (Appendix 3.5) for the July-September measurement in treatment D tended to be less stable than in the other treatments, whereas, for September–October, the overall stability of the species was significantly lower in treatment D compared to other treatments. By contrasts, treatment E, compared to other treatments, was most stable in September-October.

3.3.8. Tiller population density

There were no significant effects of the treatments or treatment by contour class interactions on tiller density of individual species or group of species on tracks, medium slopes and steep areas when measured at the end of trial period (Table 3.10). Tiller density of ryegrass and HFR grasses was highest on tracks and declined with increasing slope whereas the converse was found with Other components. LFT grasses were three times more abundant on medium slopes than on tracks. Legume growing point density was not affected by contour class. Tiller density of LFT grasses was higher on medium slope and steep areas relative to tracks. The density of 'other components' was greater in steep areas compared to medium slope and tracks, but there were no significant differences between tracks and medium slope. Total tiller density was lower on tracks relative to the medium slopes ($P < 0.05$), but was similar between tracks and the steep areas.

Table 3.10 Tiller density of ryegrass, HFR and LFT grasses, legumes, other components and total plants (No. m^{-2}) of tracks, medium-slope and high-slope areas in treatments A, B+C+D[1] and E, measured in May 1999, after the trial finished.

Treading Treatments	Contour classes	Mean tiller density (No. m^{-2})					
		Ryegrass	HFR grasses	LFT grasses	Legumes[2]	Other components[3]	Total
A	Tracks	2830	4480	2190	1250	50	10800
	Medium-slope	1270	4310	10440	1330	260	17600
	High-slope	180	460	13780	840	1040	16300
B+C+D	Tracks	7080	2540	5730	1250	100	16700
	Medium-slope	1730	1120	20480	1810	310	25450
	High-slope	230	540	16760	1500	1040	20070
E	Tracks	3390	3440	8300	2060	230	17420
	Medium-slope	1330	2170	21010	2600	410	27510
	High-slope	180	510	11180	940	990	13810
Mean of all treatments	Tracks	4430	3490	5410	1520	130	14980
	Medium-slope	1440	2530	17310	1910	320	23520
	High-slope	200	502	13910	1100	1030	16730
sem		924	596	2061	300	151	1976
Significance							
Trt		ns	ns	ns	ns	ns	ns
Contour		*	*	*	ns	**	*
Trt*Contour		ns	ns	ns	ns	ns	ns

[1]Data from treatments B, C and D were similar, so were pooled, [2]Legume growing point numbers, [3]Flat weeds and Dead material

sem = standard error of the least square means

*, ** and ns denote $P < 0.05$, $P < 0.01$ significant level and not significant, respectively

3.4 DISCUSSION

3.4.1. Soil conditions

With a mean 51% vSWC in all treatments in July, and 68% total porosity and 10% air-filled porosity (58% being water filled) in untrodden treatment A in September, it is clear that at the time of the severe cattle treading in treatments D and E in August, the soils were substantially wetter than the plastic limit (42%; Betteridge *et al.*, 1999) and that deformation rather than compaction was to be expected. However, the increased bulk density (Table 3.3), and lower air-filled porosity (Table 3.5) and total porosity (Table 3.6) in treatment D after the single severe treading, compared to untrodden treatment A, suggests that some treading damage, by way of compaction, had occurred.

Soils at a vSWC above the plastic limit contain water in their macropores, to the extent that at saturation all macropores are full. In this state the cattle hoof can not compact the soil as water is, essentially, incompressible. Conversely, below the plastic limit macropores and many micropores will be air-filled. Thus, the cattle hoof will more easily compact the soil. Typically, soils at Ballantrae are in a plastic state from autumn through early winter and again in late-spring through early summer. During these periods soil physical damage is likely to be common, particularly at heavier stocking intensities. During late winter, and often into spring, soils are often above the plastic limit and would thus deform under the action of cattle treading. This results in pugged soils in which water often ponds as the soil pore network has been disrupted and surface permeability has often been severely impaired. The increased vSWC in medium and heavily trodden soils (treatments D and E, Table 3.2), relative to lightly-trodden treatments at the end of the trial (second winter July, 1999) suggest that this may have resulted from carryover effects of an impeded drainage network from the spring 1998 treading damage. This contrasts with Willatt and Pullar (1983) who found that stock treading reduced soil water holding capacity, due to reduced porosity (Climo and Richardson, 1984). How ever, these soils may still have reduced water holding capacity, but it is staying there longer due to poorer damage.

Compared to treatment A, a small increase in bulk density, a small decrease in air-filled pore space and total pore space in the surface layer of treatment D soils (September measurement) after the single severe treading in August and disappearance of these differences in the following measurements (Table 3.3, 3.5 and 3.6) suggest that treading-damaged soil physical structure of these hill pastures may recover fairly quickly. Similar infiltration rates between treatment A and D (Table 3.4) also indicated that deleterious effects of treading on these soils were low. However, due to the high variability about the means of these parameters, no firm conclusion can be drawn about the treading impacts on soil physical condition.

Compacted soil with reduced air-filled space (less than 7% in the surface layer of tracks in treatment D (September) may have attributed to both the death and shrinking of plant roots. In a study of cereal growth, Carter (1988) reported that macroporosity of 8-10% would maintain adequate pore conductivity for optimum cereal production. In the grazed pastures, reduced pore volume is likely to have occurred through the processes of soil compaction and remoulding by hooves (Mullins and Fraser 1980; Proffitt *et al.*, 1995a). Gradwell (1965) has shown a decline in soil oxygen content when surface drainage is impeded. A reduction in gaseous exchange between roots and air would, therefore be expected. Water and nutrient uptake by plants can be limited in damaged soil and losses of soil nitrate by denitrification can occur (Russell, 1973). Russell also reported slower pasture growth as a result.

The likelihood of greater reduction in drainage pore volume through compaction and remoulding may explain why the topsoil in trodden treatments was wetter than in untrodden treatments when measured at the end of the trial period (Table 3.2). The consistently wetter topsoil in cattle-grazed treatments than in ungrazed treatments for the July and October measurement of this trial, has been reported in similar work by Proffitt *et al.* (1995a).

The increase in air-filled porosity in slopes compared to tracks in February, but not in later months, suggests a slower seasonal recovery rate of more compacted tracks compared to slopes.

3.4.2. Treatment effects on herbage accumulation

The purpose of this experiment was to come as close as experimentally possible to estimating the effect of a single 24 hr severe-treading by cattle in winter and repeated 24 hr severe-treading throughout the experimental period, on the changing productivity and cover of a hill pasture. In the present experiment, the adverse effect of heavy treading upon pasture production was greater on track than on slope zones. The major part of this effect took place in winter and early spring on the single severely-trodden treatment (D) and also in summer on the repeatedly-trodden treatment (E). The greater damage on tracks occurred where hooves tended to denude, deform, but subsequently compact and level off the soil surface as the soil dried out.

As expected, greatest herbage yield losses were recorded on tracks (Table 3.7) of the repeatedly trodden treatment (E) and these losses at the first cut, though not significant, reached 64% relative to production in treatment A, which produced 39 kg DM ha^{-1} day^{-1} in the first 7-week regrowth period after treading. Herbage losses of 12 kg DM ha^{-1} day^{-1} on tracks and 6 kg DM ha^{-1} day^{-1} on slopes from the single severe treading treatment D in the first 7-week regrowth period, compared with the relatively untrodden treatment A, were similar to the losses of 5-10 kg ha^{-1} day^{-1} previously reported by

Sheath and Carlson (1998) in a similar situation. The damage of both soil and pasture by treading would have reduced subsequent herbage growth. Bircham and Hodgson (1984) observed that any delay in initiation of the spring pasture growth flush could inhibit yield seriously.

The results from this experiment agreed with the investigations of Edmond (1963 and 1970) that treading damage usually produces a significant and progressive reduction in pasture yield as the stock intensity increases, especially on wet soil. The effect of a given intensity of treading on pasture growth is influenced by soil moisture content at the time of treading, and its subsequent effect on pasture production is also of importance. Root shearing by hoof action, and plant pulling while grazing (Thom *et al.*, 1986) may have affected the pasture cover too, but these were not observed in this study. Further, the only minor and transient effects on bulk density, air-filled porosity and total porosity can not adequately explain the prolonged slower pasture growth on tracks of treatment D and E. However, little is known about the impact treading has on above-ground parts when the soil is firm enough to resist hoof penetration.

Relative to 39 kg DM ha^{-1} day^{-1} on tracks in 'low stocked dry' (treatment A) from Cut 1, a reduction in herbage accumulation rate of 17 kg DM ha^{-1} day^{-1} in treatment B resulted at a time when soils of this treatment were not trodden. This non-significant difference in herbage accumulation rate between these treatments also followed in Cuts 2 and 3. Lower herbage accumulation rate on tracks in treatment B relative to treatment A was probably due to the carryover effect of treading by grazing cattle from the previous four years under the medium stocked wet management regime. During the period leading to Cut 4 (Dec-Jan), as a result of cattle grazing in November, the reduction in herbage accumulation rate on tracks reached 21% in 'high stocked moist' (treatment C), 40% in treatment B, 46% in treatment D and 60% in treatment E relative to the herbage accumulation rate of 52 kg DM ha^{-1} day^{-1} in treatment A (Table 3.7). During February-early March, 1999 (Cut 5, Table 3.7), a reduction in herbage growth rate of 38% and 25% on tracks in treatments E and C, respectively relative to the herbage accumulation rate of 16 kg DM ha^{-1} day^{-1} on tracks in treatment A may have resulted from both plant and soil damage under heavy stocking intensity in January, 1999. During the same period, treatment D grazed at medium stocking intensity in January produced 24% greater herbage accumulation rate relative to the herbage accumulation rate of 16 kg DM ha^{-1} day^{-1} in treatment A, indicating that grazing at medium stocking can enhance pasture growth. During February-March (Cut 6), a herbage accumulation rate of 11 kg DM ha^{-1} day^{-1} in treatment A, which was 50% lower than in treatment B and 35% lower than in treatments C and D, but similar to in repeatedly trodden treatment E, may have resulted due to higher proportion of dead tissue of the tillers. A reduction of 52% herbage accumulation rate from Cut 7 and 55% averaged herbage accumulation rate over 9 months on tracks in treatment E relative to herbage accumulation rate of 33 kg DM ha^{-1} day^{-1} and averaged herbage accumulation rate of 38 kg DM ha^{-1} day^{-1} in treatment A, indicates a prolonged carry-over effect of the heavy treading under the wet management regime over the previous four years.

Average herbage accumulation rates (kg DM ha^{-1} day^{-1}) on slopes, over the 9-month period were reduced by 20% in treatment B, 7% in treatment C, 24% in treatment D and increased 9% in treatment E compared to that of 22 kg DM ha^{-1} day^{-1} in treatment A (not significant, Table 3.8). This suggests a lower impact of cattle treading on slopes of hill pastoral systems than on tracks. Except for the slopes in treatment E, which had 37% greater average herbage accumulation rate compared to the 15 kg DM ha^{-1} on treatment E tracks, slopes of all other treatments had a trend of a 32-35% lower average herbage accumulation rate than on tracks over the 9 months trial period (Table 3.7 and

3.8). Lower herbage accumulation rates on tracks in treatment E was probably due to damage of soil structure and reduced tiller number.

Over nine months (7 cuts), compared to the 5.97 tonnes DM ha^{-1} contour-adjusted herbage accumulation from tracks and slopes (in proportion of 1:4) in treatment A, the loss in herbage dry matter was 1.1 tonnes (or 18%) in treatment B, 0.4 tonnes (or 7%) in treatment C, 1.5 tonnes (or 25%) in treatment D and 0.7 tonnes (or 11%) in treatment E (Table 3.9). Whereas treatment E tracks grew very slowly compared to tracks on other treatments, these slopes grew at the same rate as in treatment A which experienced no treading damage by cattle. This is likely due to the high content (not significantly different) of ryegrass in treatment E slope pasture – a trend not so apparent in treatment D that was severely damaged only once (Figure 3.2 slopes). Except in treatment B which produced a relatively lower herbage mass, despite not being trodden in August, the overall pattern is clear that the effect on herbage dry matter yield of cattle treading on wet soil at a high stocking density was greater than with low stocking density in dry or moist soil management regimes. Low replication number probably prevented detection of significant differences between treatments.

The relatively greater losses in herbage dry matter yield in moderately trodden treatment B compared to treatments A and C is most likely be due to the carry-over effect from the previous four years of grazing wet-medium management that caused B to have more bare ground during this trial period.

The single severe-treading in winter, followed by three moderately stocked treading events on moist soils (treatment D) resulted in substantial loss of pasture production. Authors (Campbell, 1966; Curll and Wilkins, 1983; Hamilton and Horne, 1988) have also reported reductions in herbage yield with increased animal stocking, although with sheep. Drewry *et al.* (1999) observed greater dry matter accumulation in intensively stocked winter-grazed treatments, compared with nil winter-grazed treatments.

The combined effect of grazing and treading on the wet soil in August, followed by treading at a moderate stocking density in the following months (November, January and March) (treatment D), resulted in relatively less herbage accumulation than in both the repeatedly trodden intensively-stocked pastures (treatment E) and the more lightly stocked treatments. It needs to be noted that the repeatedly trodden management (E) had been in place for four years prior to commencement of this present trial. For this reason, it is most interesting that the 11% relative loss of potential productivity compared to treatment A (untrodden), over the 9-month period, was much less than the 25% relative loss of potential pasture growth of treatment D that was severely trodden only once in August 1998. This may be because the repeatedly-trodden pasture was likely to have attained some equilibrium in species composition, different from the untrodden pasture, whereas the once-only trodden/damaged pasture in wet soil is likely to have experienced a greater disturbance to the tiller population density. Thus the reasons for the decline in productivity potential of treatments D and E are likely to be somewhat different. That is, treatment D probably lost tillers from treading-intolerant species that were not immediately replaced by treading-tolerant species such as ryegrass. Indeed, in autumn, there is a pattern for D to have a greater ryegrass content on slopes than treatments A, B and C (Figure 3.2 c slopes), which, however, is lower than the more productive treatment E.

3.4.3. Pasture cover, botanical composition and tiller density

The restored pasture cover in treatment D suggests that given an opportunity (less frequent grazing and at a low stock density) pasture growth can improve following severe treading in winter. As bare ground in treatment B and C did not exceed 25% at any time of the year, this indicates that pastures which are not grazed during winter wet conditions can maintain reasonable vegetative cover, regardless of the relatively lower herbage dry matter yield in treatment B than in C. More than 30% bare ground created in treatment D (in September) following treading on wet soil in August, and at all measurement times in repeatedly trodden treatment E was similar or more than that previously observed by Monteath *et al.* (1977) in cattle-trodden pastures.

The removal of 40-50% pasture cover to expose bare ground in treatments D and E (Figure 3.3), one week after treading in late August, suggests that tiller density would have been reduced more in these highly trodden areas. The open spaces created by animal treading can be a focal point for pasture regeneration, and this emphasises that both hoof action and defoliation regime can influence subsequent pasture growth.

Compared to other treatments, the lower stability of bare ground in treatments B and C during the July-September period (Appendix 3.4) when these treatments were not trodden indicate that bare ground which was present in July, was replaced by pasture species in September. By contrast, in treatment E, a high proportion of bare ground which was measured in July remained as bare ground in September following the single severe treading event in August. This indicates that cattle probably walked on these already damaged areas, such as the well-formed stock tracks that were sparsely vegetated throughout the trial period. The lower stability of bare ground in treatments A and C compared to other treatments, between September and October measurements, shows that the bare ground measured in September had been replaced by pasture. From July to September, the switch from vegetative cover to bare ground occurred at 49% of the measurement sites in treatment D (cattle trodden only in August). This treatment had not previously been damaged by cattle treading, whereas, treatment E that had been repeatedly damaged during the previous four years gained only 37% more bare ground and the treatments that were not cattle-trodden in August, gained only 10-20% more bare ground from sites that had been vegetated (Appendix 3.2 and 3.3). In treatment E, about 40% of the total bare ground had not revegetated since the previous grazing in July. In many instances this probably reflected the compact nature of the soils on the stock tracks that had been sparsely populated by pasture species for long periods.

Excluding the bare ground category, the winter and spring cattle-treading treatments had no effect on the stability quotient of any pasture species or groups of species (Appendix 3.4). The probability of finding a species, or bare ground, at exactly the same point a month later was less than 0.5 (Appendices 3.5). This shows that the pasture systems to provide first-hit cover were dynamic, even when bare ground was not created by treading disturbance. Perennial ryegrass is the species reported to be least affected by treading among other dominant species (Edmond, 1964) and it was expected that ryegrass should have been able to fill more bare ground during the recovery period following treading damage. However, data from this trial was not able to confirm this greater tolerance of ryegrass (Appendix 3.4).

This was possibly due to an artifact of the method, by which first-hit describes the canopy and not the contributors to total pasture mass. This first-hit technique is thus likely to be most robust when comparing loss and generation of bare ground, than change amongst species.

Based on herbage dissection of cut regrowth a different conclusion was reached. In contributing cover, some high fertility responsive grasses such as Yorkshire fog and Poa, and broad leaf weed species changed readily, while others such as ryegrass and legumes changed little (Figure 3.3). This apparent contradiction relates to the fact that data in Figure 3.3 describes average cover, whereas data in Appendices 3.2 and 3.3 describe changes at points within the pasture.

The significantly lower stability of 'all species' contributing cover in treatment D for both July-September and September-October periods suggests that the tolerance of the species following their first and only severe treading is poor (Appendix 3.5). By contrast the stability of the species in treatment E compared to other treatments was significantly higher, indicating that this system had become quite stable as a result of treading disturbance over the previous four years.

Overall, more than 50 percent of the first-pin-hit cover measurements of the hill pastures, when measured next time at the same site, appeared as different species or groups of species indicating a very dynamic role of plants that provide cover.

Tiller growth, and leaf initiation and development of the various pasture components that contributed to canopy cover, may have been markedly affected by prevailing temperature and light. But as all pastures were grazed following each pasture cut (some grazed only by sheep), the differences between treatments will have been induced by different levels of hoof damage either directly on above-ground plant tissue, or indirectly via soil disturbance. Whatever the cause, there appeared to be strong competition amongst species to provide vegetative spread or cover across contours. The cause of changed species composition require investigation as an understanding of these factors may lead to a solution to limit or prevent damage by cattle grazing.

In general, lack of significant differences in the first-hit cover and botanical composition of individual species or group of species between treatments in this trial, may have been due to the high variability of the dominant species across the contour classes and stability within the contour classes, although leaf contribution to first-hit cover of each species was relatively more dynamic. Further, it appears that the species-change response to treading is not immediate, but evolves over periods of more than 9 months.

Results showing the greatest ryegrass content to be on tracks supports earlier findings of Lambert *et al.* (1986b). These authors observed greater tiller density of ryegrass in high fertility pastures which are mainly tracks and/or low slope areas of hill pastures. The greatest ryegrass content on tracks and that of 'other grasses' on steeper areas of hill pastures indicates that ryegrass presence appeared to be related to disturbance of the surface soil, and possibly higher fertility and greater soil moisture availability. This assumes cattle spend most of their time on tracks; as supported by the work of Sheath and Carlson (1998) that showed cattle avoid walking on steep inter-track (>25° slope) zones. The content of ryegrass can increase at higher stocking rates through its ability to survive treading damage (Edmond, 1964; Allan *et al.*, 1985) and because of high nutrient cycling through dung and urine return associated with higher stocking rates (Levy, 1970). Bates (1935) also noted that on heavier and wet soils, where puddling of the surface occurs in winter, the surface areas disturbed by treading were dominated by ryegrass.

The content of white clover in this pasture was low, not exceeding 10% in any season (both in cover and number of growing point measured at the end of trial). This may be because of poor propagation and persistence of this species due to climate, soil fertility management and grazing pressure, but conflicts with work of Lambert *et al.* (1983) who noted a legume content of 12-22% (varied with low to high fertiliser application) in moderately stocked pasture in paddocks adjacent to this trial. Continued observation in this present trial might also have shown an elevated legume content in response to treading damage.

It was originally expected that ryegrass would competitively reduce the cover of other species in hill pasture conditions, especially under repeatedly trodden treatments, because of ryegrass being more tolerant to treading than other species (Edmond, 1964).

In practice, however, all resident species persisted in all treatments. The results showed adaptation of ryegrass primarily in tracks, HRF grasses in tracks and medium slope areas and LFT grasses in high slope areas.

The repeated treading treatment (treatment E) had ongoing effects on pasture cover with more bare ground compared to untrodden and moderately-grazed treatments. In the repeatedly-trodden areas, the drying winds and heat to which the bared tracks were exposed gave rise to conditions that were often too dry to enable pasture species to colonise or to persist.

Factors such as species composition, stocking rate and grazing management apart from treading, slope, and aspect, variability in soil fertility and moisture may also have influenced plant population density. The higher content of ryegrass and HFR grasses found along the tracks, and areas associated with stock camping behaviour, is well known on hill country pasture (Suckling, 1975).

Regardless of the variability that is inevitably introduced due to available nutrient and moisture in soil, temperature and time of measurements, the observation of a significant plant species or group of species contributing cover under contrasting grazing management and slope classes is highly encouraging. The continuation of a range of 37-87% bare ground from month to month in treatment E (Figure 3.3) reflects the greater treading damage imposed by this treatment, while treatment D had less than 20% bare ground except in September, 1998.

Reduced pasture accumulation rate and cover on tracks in a severely trodden sward on wet soils is more likely to be the result of tiller losses due to treading, and further study is needed to confirm the tiller dynamics following treading of different species.

Two important facts have emerged from this study on change of species. Firstly, treading can cause reduction in cover. In this process, treading may have killed some of the tillers and caused loss of leaf of the surviving tillers. It is likely that reduction in tiller density and leaf area per tiller from treading contributed to reduce pasture cover. Secondly, there was considerable variation among the leaves of different species that volunteered to fill the bare ground during recovery. This was probably related to species adjacent to the bare ground, to buried and displaced tillers, and to buried or surface seed banks. Survival of the tiller population after treading and the rate of new tiller appearance during recovery may then reflect future treading impacts.

Treading treatments possibly did alter the tiller density of the species. The 53% greater ryegrass tiller density in light-to-medium-trodden treatment (B+C+D) but only 13% greater density in repeatedly trodden plots (Treatment E) compared to the 1430 tillers m^{-2} in the untrodden treatment A (Table 3.10), at the end of trial, suggests that treading with moderate cattle stock densities does enhance the content of ryegrass, although in this trial the differences were not significant, probably because of the low replication. This also indicates that a single severe treading on wet soils may enhance the ryegrass population in following seasons. A 34% lower tiller density of HFR grasses in the repeatedly-trodden treatment (E) and 18% in light-to-moderate-trodden treatments (B+C+D) compared to 3080 tillers m^{-2} in treatment A (mean across contour classes, Table 3.10) suggests that tillers of HFR grasses are not immune to treading damage. Mean total tiller population densities of 20,740 m^{-2} in treatments (B+C+D), 19,580 m^{-2} in treatment E, and 14,900 m^{-2} in treatment A, were almost double than the total tiller population ranged between 6000 to 10,000 tiller m^{-2} in a nearby trial (Russell *et al.*, 2001). These differences in total tiller population could have appeared due to the differences in micro-topography, grazing management and species composition.

In this study, tiller density of LFT grasses were greater on slopes compared to on tracks. LFT grasses (browntop, sweet vernal, crested dogstail and chewing fescue) are generally found in short, dense pastures formed in low fertility conditions developed under sheep grazing. These pastures, with dense tillers, might offer more protection against soil damage from treading than do more open pastures dominated by ryegrass and white clover developed under cattle grazing (Climo and Richardson, 1984), but the higher risk of these LFT species being lost from the pastures as a result of treading damage does little to sustain pasture performance.

Tiller density of dominant LFT grasses was lower on steep areas than on tracks and medium slope areas at the end of this trial. Factors like shallower soil, lower fertility, and drier conditions, for example in steep areas, (hold less water and take longer to rewet after a drought than do tracks and medium slope areas), might account for this lower tiller density of dominant LFT grasses (Table 3.10) resulting in slower herbage accumulation rates. Compared to medium slopes of treatment B+C+D, tiller density of HFR grasses was 48% greater in medium slopes of treatment E (Table 3.10), which probably resulted in faster herbage growth despite of the repeated grazing pressure in these areas. A 39% increase of legume population both in tracks and slopes of treatment E and 34% increase of that in slopes of treatment B+C+D compared to treatment A indicates that treading might enhance growth of legumes, although again, differences between treatments were not statistically significant due to the high variability in tiller density of grasses across slope classes.

Considerable bare-ground was created in the single severe trodden treatment D and repeatedly trodden treatment E for colonisation by new plants or tillers to occur. The gap size or open spaces can influence the rate of colonization which in turn influences the level and availability of light, moisture, and nutrients (McConnaughay and Bazzaz, 1990). This was probably the major reason for the relatively increased contribution of legumes in treatment E.

Experimental results demonstrate that the importance of the loss of herbage cover after treading should be recognised in extrapolations from experimental treading investigations into farm practice.

Results suggest that a single, or the repeated intensive stocking of hill pastures on wet soil had no remarkable short-term effects on species composition, their distribution across the slope classes, or their accumulation rate.

3.4.4. Relationship between pasture accumulation rate and pasture cover

The main effect of treatments on herbage growth appears to have been through loss of canopy cover, owing to destruction of plant tissues. The relatively strong relationship (r^2 = 0.76, Figure 3.4) between herbage accumulation rate and canopy cover of the treatments (B+C+D), compared to treatments A and E, suggest that pastures grazed by cattle at a medium stocking intensity and when soils were only moist or dry, maintained both canopy cover and pasture growth. As treatment A pastures were consistently in the range 92 to 98% cover, cover *per se* is unlikely to be a factor controlling this pasture's growth potential. Instead, the species contributing to growth are likely to be the limiting factor to growth. This is particularly likely, since species in A were predominantly LFT grasses which, when pre-trimmed to 5 cm for the determination of pasture accumulation, were left with very little leaf. In these predominantly sheep-grazed pastures (cattle grazed at a low stocking intensity in March 99 only) such severe defoliation does not happen in practice, and thus regrowth potential as measured in treatment A in this experiment, is likely to have been under-estimated and may certainly have contributed to the poor relationship between pasture cover and pasture accumulation rate. By contrast treatment E growth, with its higher ryegrass content on slopes, was most likely limited by its' lowered canopy cover.

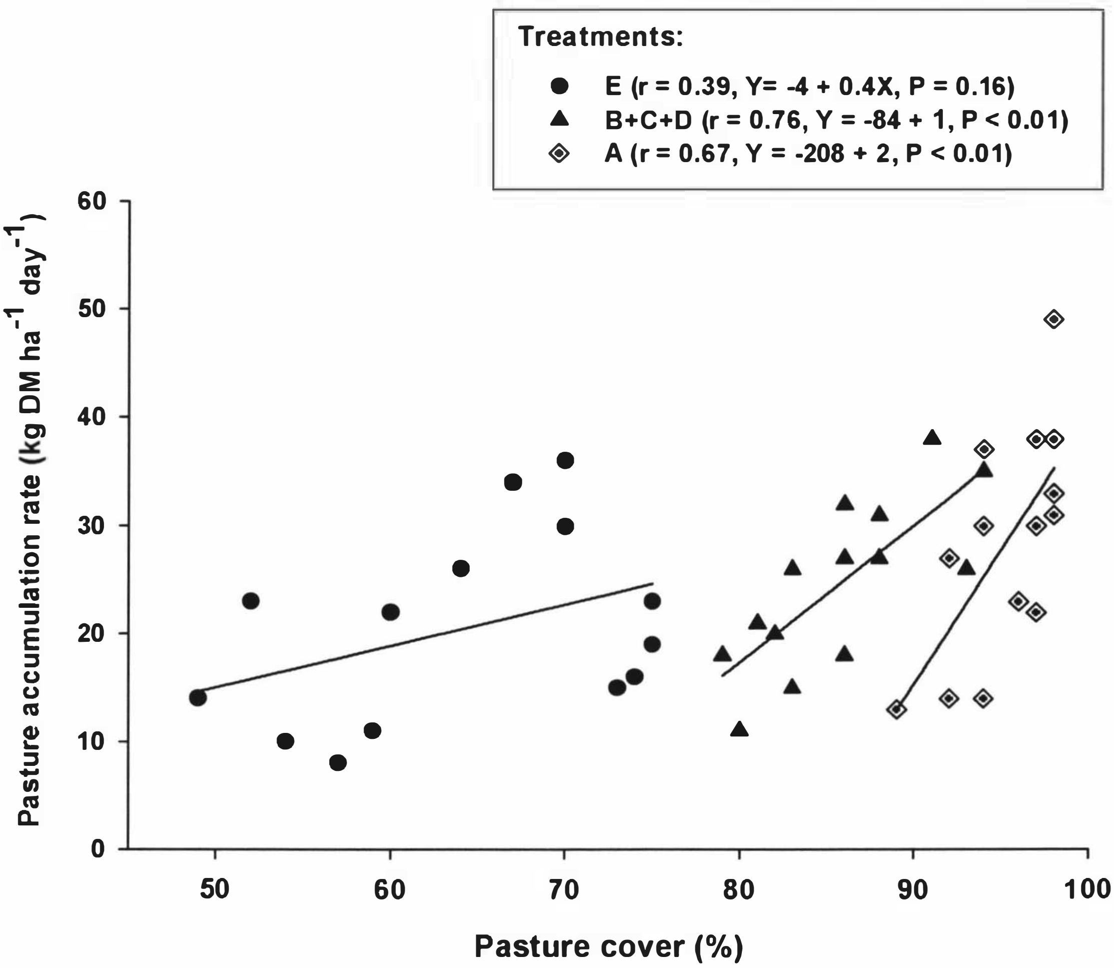

Figure 3.4 Relationships between pasture accumulation rate (kg DM ha^{-1} day^{-1}) and pasture cover (%) from treatment E, treatments B+C+D (data were pooled) and treatment A.

3.5. CONCLUSIONS

This work suggests that severity of soil and pasture damage from treading by grazing cattle appeared to be particularly great in wet soil conditions. The extent of the loss of pasture cover and hence pasture accumulation rate potential by treading, especially on tracks of hill pasture, is of considerable practical significance. It is clear that the effects of treading are an important fact of grazing management, since recovery of growth potential of the pasture trodden during winter when the soil was wet, was reduced.

Results suggest that cattle treading in hill country affects pastures particularly on tracks where the cattle walk during grazing, and this effect can cause seasonal deficits in pasture supply. Arguably, treading damage to wet soils by grazing cattle is a problem, particularly in pastures with high stocking intensities. Results also suggest that the first severe treading event on wet soil, causes a greater loss in pasture accumulation in the first 9 months than the loss resulting from several years of repeated damage. These losses in herbage accumulation are likely due more to above ground plant damage than to soil damage since treatment E grew more pasture than treatment D even though its' soils were more compact and had very slow infiltration rates, especially on tracks (unpublished data K. Betteridge, personal communication). It is also clear that even a single severe treading by grazing cattle on wet soils, in winter, can reduce spring pasture production and cover.

The first-hit pasture cover contributed mainly by leaves of pasture species was relatively more dynamic in all treatments, although tiller densities of pasture species across contour class were stable and botanical composition was not significantly affected by grazing/treading management. The content of ryegrass was greater on tracks in all seasons, despite greater hoof traffic on this contour class. From the findings of this trial it is difficult to draw strong conclusions about the role of the density and size of the tiller to pasture accumulation rate since the measurement of tiller weights was not made and also because tiller density was measured only at the end of the trial.

One of the main difficulties of estimating damage and recovery of pasture, in hill country especially, is the great variability in species composition and in growth rates across the contour classes, since treading damage was mainly on tracks whereas grazing pressure is likely to have occurred more on slopes toward the later half of grazing period (after fouling of grasses on tracks). The robustness of the technique was restricted only to the measurement of cover, which is controlled mainly by the leaves of each tiller.

The information on damage and recovery of tiller density and leaf area index from treading may provide a better understanding on the causes of loss of pasture production. Information on the weight of individual tillers following treading is also needed to understand the recovery trend of the tillers. The measure of tiller density, leaf area index, weight of tillers, canopy cover and soil physical properties following single cattle treading in winter when the soil is wet may help to answer the questions raised from this experiment.

CHAPTER 4

TREADING DAMAGE AND REGROWTH OF A DAIRY PASTURE

4.1. INTRODUCTION

A previous study (Chapter 3) showed that repeated cattle treading of hill country pasture when the soil was wet, reduced pasture cover and herbage production more than a single severe treading. The greatest herbage loss of these pastures was on tracks rather than slopes. However, the damage to herbage caused by a single cattle treading was recovered after seven weeks (Chapter 3; Pande *et al*., 2000).

Hunt (1979) observed that sheep treading in late June reduced tiller densities during the July-August-September period, and that tillers were detached by treading. Similarly, Carter and Sivalingam (1977) reported that reduced tiller density was associated with reduced pasture yield following sheep treading on a wet soil.

Defoliation disturbs the carbohydrate supply for plant growth by removing photosynthetic tissues. Carbohydrate for energy is in short supply in plants grazed closely with little leaf area left so that normal root function and growth may cease for several days (Evans, 1973). The rate of pasture regrowth depends on the amount of leaf area on the stubble of surviving tillers and on the recruitment of fresh young tillers.

Understanding the response of tiller dynamics and leaf area index (LAI) of ryegrass and 'other grasses' to treading by grazing cattle in dairy pasture is important for making management recommendations to farm managers i.e. should they choose treading-tolerant species and/or other best management options (e.g. on-off grazing). Quantification of the responses of both tiller density, tiller size and LAI of ryegrass and 'other grasses' following cattle treading in intensive dairy pasture would be useful to an understanding of the nature of damage and recovery.

This chapter describes an experiment designed to (a) measure the damage effect on soil and tillers, and LAI of grasses from a single treading (b) investigate the regrowth processes of tillers and LAI of ryegrass and 'other grasses' during recovery from treading (c) determine the effect of N fertiliser on herbage growth after grazing/treading.

4.2. MATERIALS AND METHODS

4.2.1. Soil and Pasture

The experiment was conducted at No.4 Dairy farm at Massey University, Palmerston North (latitude $40^0 23'$S; longitude $175^0 37'$E, altitude 60 m) from August to October 1999. The soil at the site is a poorly drained Tokomaru silt loam (Cowie, 1972) classified as Pallic Soils (Aeric Fragiaqualf), (McLaren and Cameron, 1996) with average pH 5.8 at 10 cm depth and Olsen P 62 μg P/g soil. The area selected for this study was mole and pipe drained. The trial site was a flat paddock of improved pasture (ryegrass, browntop, cocks foot, Yorkshire fog and white clover) sown 5 years earlier. The region is classified as temperate with an annual average air temperature of 13°C and an annual rainfall of 1000 mm with prevailing westerly winds. Joined

4.2.2. Trial Design and grazing/treading damage

The study paddock was 3 ha in area. It was subdivided equally into 4 blocks using electric fencing. The averaged soil water content vSWC) of readings taken from 12 randomly selected sites in each block before treading, using a Time Domain Reflectance (Parchomchuki, 1997) device was 33%, 35%, 34% and 28% in block 1, 2, 3 and 4 respectively. One hundred and fifty cows, with average body weight of 350 kg, were stocked for 24 hrs in the first Block (Grazing 1), 36 hrs in each of the second and third Blocks (Grazing 2 and 3), and 18 hrs in the fourth Block (Grazing 4) during 11-14 August. Rainfall during the 3-day grazing/treading period was 16 mm and the volumetric water content of the soil increased from 34 to 38%. Total rainfall for the experimental period (49 days) was 133 mm. Average soil temperature at 10 cm depth during the experimental period ranged from 8°C in August to 14°C in October.

After the completion of grazing/treading in all four blocks, treading damage was observed visually across the whole paddock. Based on visual observation on the soil and plant damage which followed soil surface roughness (Table 4.2), low-damaged, medium-damaged and high-damaged sites were ranked and marked with the help of coloured plastic pegs (Plate 4.1). To provide replication, eight plots from each of the trodden and untrodden areas, each of size 2 m x 1 m, were selected for each category of damage. Among the eight high-damaged sampling plots, six emerged in Block 2 and two in Block 3. Similarly among the eight medium-damaged sampling plots, five emerged in Block 3 and three in Block 1. Among the remaining eight low-damaged sampling plots, three emerged in Block 1 and five in Block 4. Eight untrodden plots was selected from the pasture under the electric fence separating the blocks, which was grazed but not trodden (here after named untrodden).

After the selection of plots in each of the trodden and untrodden areas, the visual selection of low-, medium-, and high-damaged plots were verified with soil surface roughness data and the validity of the selection of each damaged plot category was confirmed.

Each of the eight low-damaged (Low), medium-damaged (Medium), high-damaged (High) and untrodden plots was further subdivided into eight units of 0.25 m^2 size and at each sampling, two subunits were randomly selected; one for destructive harvests and another for tiller plug sampling (Figure 4.1). An area of 0.5 m^2 adjoining each of the 32 plots was selected and used for the measurement of pasture cover and basal cover. In these trodden and untrodden areas, the strategy was to quantify damage and recovery of soil and pasture following cattle grazing/treading management regimes.

Four damaged and untrodden plots were fertilised with urea at the rate of 25 kg N ha^{-1} at Days 7 and 30 after grazing/treading. The remaining four plots were not fertilised.

As a normal grazing management rule of the farm, at Day 29 (12 Sept., 1999) after the treading event the whole paddock, including study plots, was grazed lightly by 50 cattle ha^{-1} for 24 hrs while soils were dry (27-30% vol. vSWC). The strategy was to utilize the pasture and to minimise repeated treading effects in the study area.

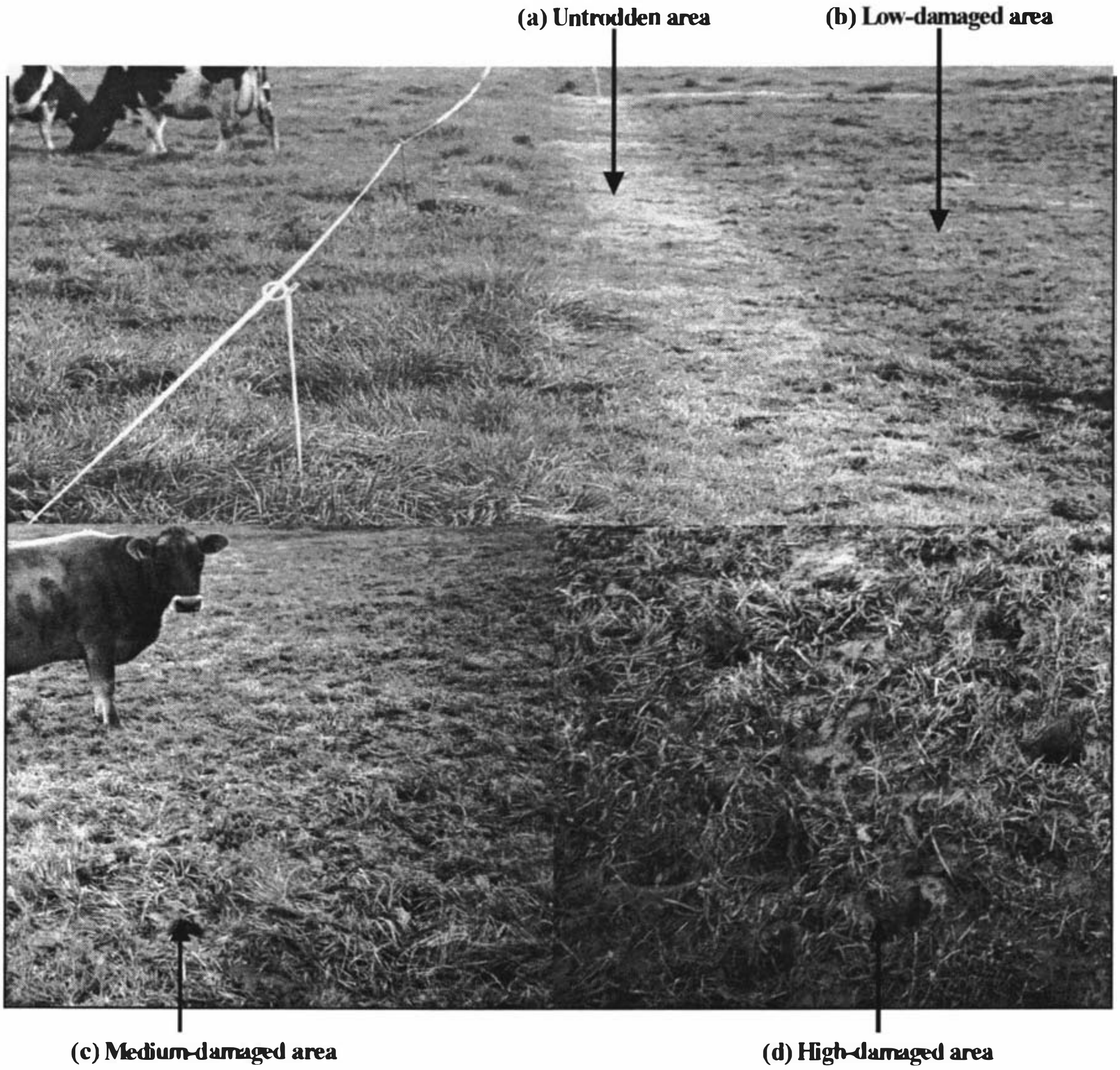

Plate 4.1 Cows grazing/treading in the upper left corner at No. 4 Dairy pasture and sites selected for the (a) untrodden (b) low-damaged, (c) medium-damaged, and (d) high-damaged areas to study damage and recovery of soil and pasture (August, 1999). Photos taken immediately after grazing and/or treading.

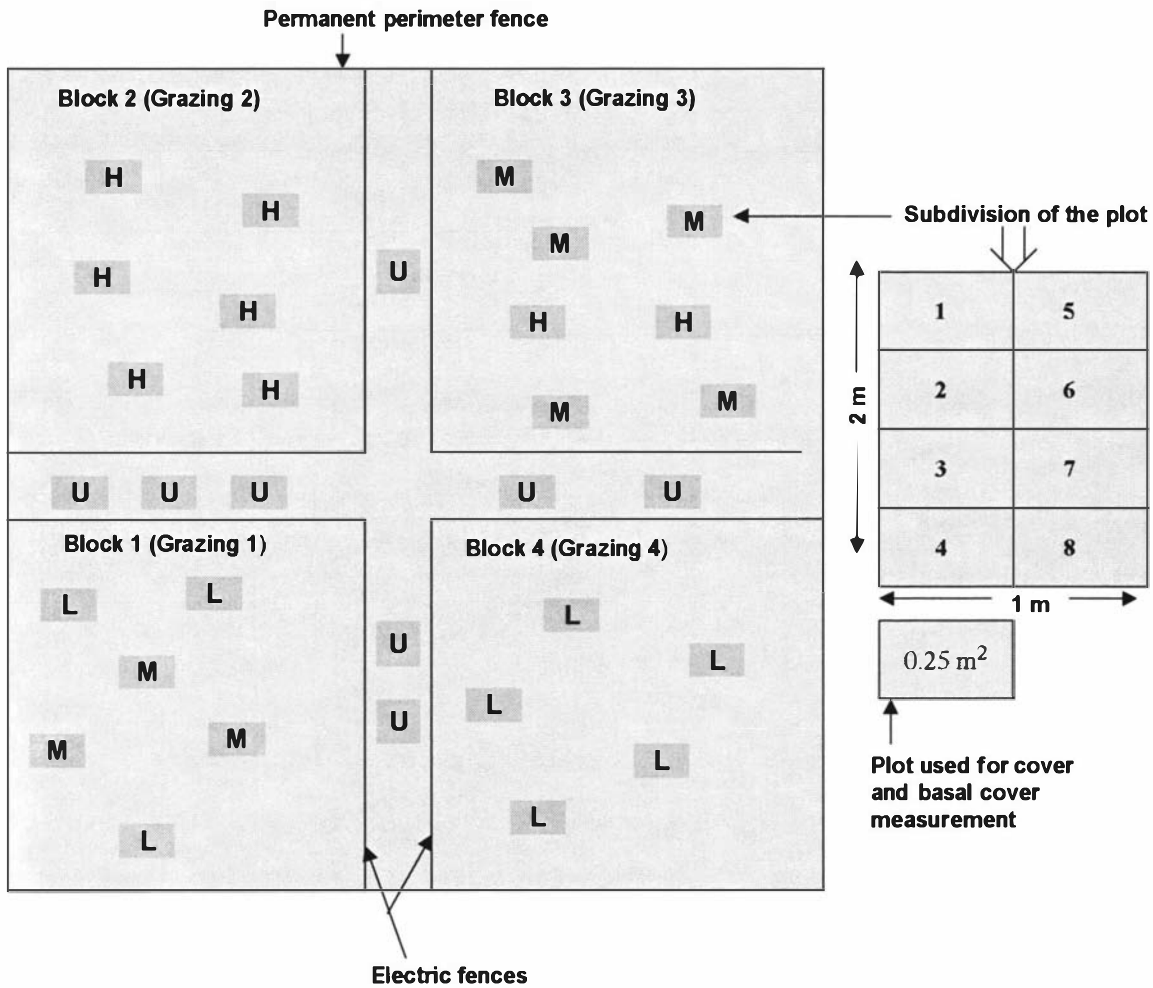

Figure 4.1 Plot selection and an example of subdivision of the plot for sampling, all carried out at Day 3 after treading, H, M, L, and U are the sample plots which denote high-damaged, medium-damaged, low-damaged and untrodden respectively.

4.2.3. Measurements

4.2.3.1. Soil moisture

Soil moisture was measured at 10-cm depth using Time Domain Reflectance (Parchomchuki, 1997). Pre-grazing/treading soil moisture was recorded at Day 1 before treading (see section 4.2.2 on method). Post-treading soil moisture was recorded at Days 3, 20 and 48 after treading. Four readings were taken at different locations on all trodden and untrodden plots.

4.2.3.2. Rainfall and soil temperature

Rainfall and soil temperature data (10-cm depth, recorded daily at 9.00 a.m.) during the experimental period were obtained from the AgResearch Meteorological Station, which is approximately 700 m from the experimental site. Post-treading soil temperature was also recorded at 10-cm depth using a thermometer in all trodden and untrodden plots at Days 3, 20 and 48 after treading. Four readings were taken at different locations on each plot.

4.2.3.3. Soil surface roughness

At Days 3, 18, and 33 after grazing/treading, four roughness measurements were taken from randomly selected subdivisions within each plot. A 130-cm long roller-link chain was placed on the ground in a straight line and moulded to the surface by pressing carefully along the surface with the fingers starting from a fixed end of the chain. Apparent loss in 'horizontal' length of the moulded chain was measured using a tape measure and the percent loss in length was calculated (P. Singleton, personal communication). Four measurements were taken from each plot.

4.2.3.4. *Soil dry bulk density, macroporosity and infiltration rate*

Soil bulk density and macroporosity were determined once at Day 15 after treading, and infiltration rate was determined at Day 5 and 50 after treading. To measure soil bulk density, cylindrical 98 cm^3 stainless steel rings (5 cm diameter x 5 cm height) were inserted into the topsoil by hammering and three cores were removed randomly from different locations of each trodden and untrodden plot. These were weighed before and after oven drying at 105°C for 48 hrs and dry bulk density was calculated from the sample oven-dry weights (Hillel, 1980). Three additional soil cores (5 cm diameter and 2 cm depth) were removed from different locations of each trodden and untrodden plot for macroporosity determination. All cores were carved into the soil following trimming of the grass to the ground surface, and excavation t the appropriate depth. The cores were equilibrated to −10 kPa on a pressure plate apparatus to measure macropores larger than 30 μm equivalent diameter (McLaren and Cameron, 1990).

The steady state infiltration rate was determined in *situ* using double-ring flooding infiltrometers (Hills, 1970). Water was poured through plastic buckets into both rings. After saturation, measurements of falling head were taken until steady-state conditions were achieved. Two measurements were taken from each of the trodden and untrodden plots and the mean of these values was used to estimate infiltration rate.

4.2.3.5. *Cover and basal cover*

The frequency (%) of bare ground or pasture cover was estimated using the point analysis method of Radcliffe and Mountier (1964). Cover was recorded by counting 'first-hit' touch of the pin on pasture cover or living tissue of the plant above ground. Basal cover was recorded by counting 'last hit' touch of the pin on living tissue of the plant or bare soil at ground level. A 0.5 m^2 100-point frame, made up as 10 x 10 grid, with each pin being 5 cm apart was used to measure both cover and basal cover.

4.2.3.6. *Pasture height*

Pasture height was measured at Days 20, 35, and 50 after grazing/treading using a simple 'sward stick' as described by Barthram (1986).

4.2.3.7. *Herbage mass, species composition and leaf area estimation*

Pre-grazing measurements were carried out two days before grazing/treading to estimate herbage mass, species composition and leaf area index from 40 samples taken randomly across the paddock. Post-grazing/treading measurements were made at Days 3, 18, 33, and 48 after the grazing/treading events. At each measurement day, cut herbage samples were taken from one randomly selected subdivision in each plot (Figure 4.1), but avoiding subdivisions previously sampled. Both pre- and post-grazing/treading herbage mass was obtained by cutting the pasture at 2 cm above ground level using 0.25 m^2 quadrats (Frame, 1993). Cut samples were sub-sampled into two fractions: (a) for botanical separation of ryegrass, 'other grasses', and 'other species' and dead material (b) for measurement of leaf area, leaf weight and sheath weight of ryegrass and 'other grasses'. Separated leaves from sub-samples were measured in a leaf area meter (LI-3100 Area Meter, 1979) for the estimation of LAI as the product of tiller population density and leaf area per tiller. In each sub-sample, there were approximately 20 tillers containing 30-50 leaves.

The entire sub-sample (i.e. separated leaves and stems of ryegrass and 'other grasses', leaves of ryegrass and 'other grasses' after measuring leaf area, separated species for botanical composition, and the remainder from the main sample) was oven dried separately at 80°C for 24 hrs and weighed for the estimation of the total dry weight.

4.2.3.8. Tiller density and unattached plant material

The population density of tillers of ryegrass, 'other grasses' and total grasses was recorded at Days 3, 18, 33, and 48 after the grazing/treading events from tiller cores taken by using a modified tiller corer (82.38 cm^2 area) with the procedure of Mitchell and Glenday (1958). Five plugs were taken to a depth of 8 cm at points selected at random from each of the 32 plots and the mean tiller population density per unit area was recorded for each plot.

The measurement of unattached plant material was done only once at Day 3 after grazing/treading. All the broken, unattached plant material was separated from each of the tiller cores taken for tiller density measurement, oven dried at 80°C for 24 hrs and weighed.

4.3. STATISTICAL ANALYSIS

Data were analysed using Repeated Measures Analysis of Variance, with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, 1990). Correlation analysis was carried out to show the relationship between soil surface roughness and soil water content

4.4. RESULTS

4.4.1. Pasture conditions before grazing/treading

Herbage mass in the paddock on 2 days before grazing/treading was 3540 kg DM ha^{-1}. Botanical separation at Day 3 before grazing/treading showed that the components of ryegrass and 'other grasses' in the pasture was 60% and 30% of the total herbage mass, respectively. The 'other grasses' component was comprised of mainly browntop (*Agrostis capillaris*), Yorkshire fog (*Holcus lanatus*) and cocksfoot (*Dactylis glomerata*). Since ryegrass and 'other grasses' accounted for about 90% of the total herbage mass, they were used for further analysis. White clover and flat weeds, which accounted for only about 10% of the total pasture dry matter, were included in total herbage mass but not measured separately for other parameters.

4.4.2. Rainfall, soil temperature and soil moisture

Daily rainfall and soil temperature data during the trial period are presented in Figure 4.2 (a) and (b), respectively. For a week before grazing/treading, total rainfall was 24 mm and soil temperature at 10 cm depth ranged between 4-8° C.

There were no significant differences for soil temperature between trodden and untrodden areas, and also no interaction of day and damage level (Table 4.1). Soil temperature decreased from Day 3 to Day 20 and then increased to Day 48.

At Day 3 after treading, soil was drier in untrodden and high-damaged compared to medium-damaged areas, but was significantly wetter in high-damaged areas at Day 33 and Day 48 than in the other trodden and untrodden areas (Table 4.1). The main effect of both damage level and day, and the interaction of day and damage level for the soil water content were significant ($P < 0.001$), low-damaged soil drying more quickly than high-damaged soil.

Figure 4.2 (a)

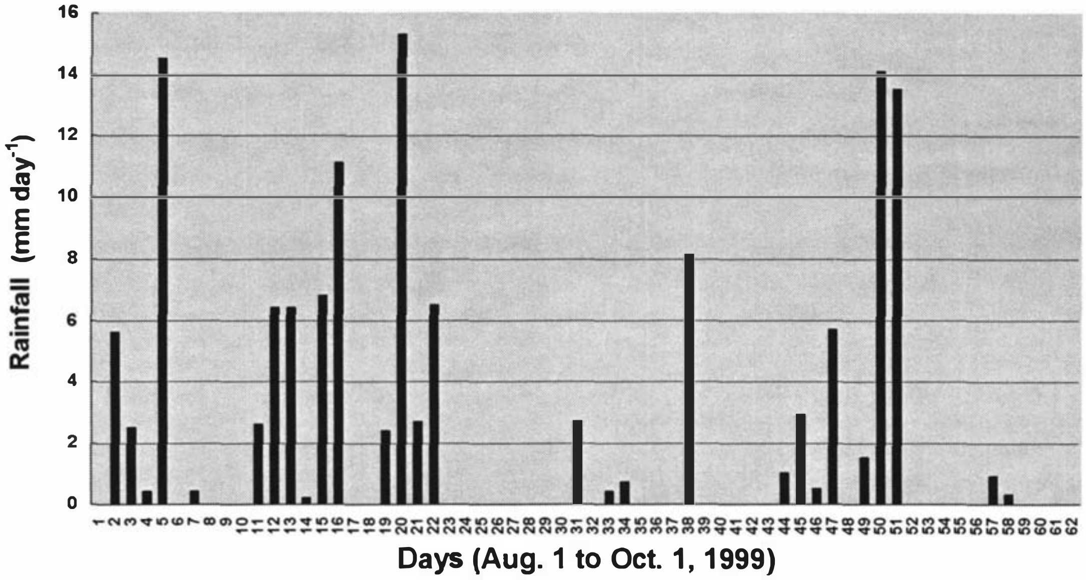

Figure 4.2 (b)

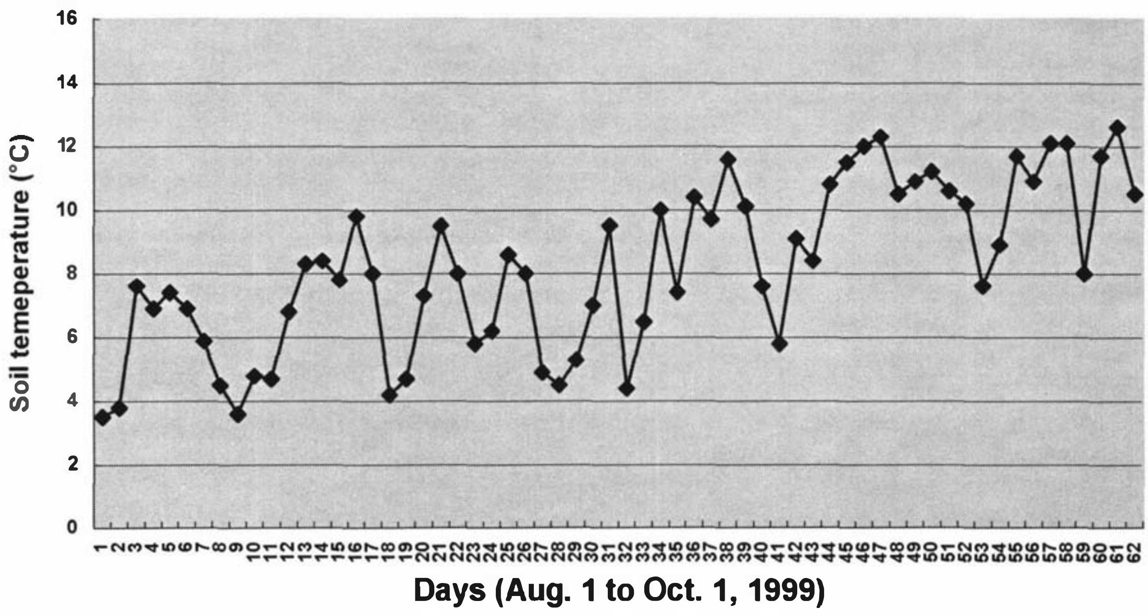

Figure 4.2 (a) Rainfall and (b) Soil temperature (10-cm depth) data recorded daily during trial period at the AgResearch Meteorological Station, Palmerston North, approximately 700 m from the experimental site.

Table 4.1 Mean volumetric soil moisture (%) and soil temperature at 10 cm depth at Days 3, 20, 33 and 48 after treading from untrodden, and low-, medium- and high-damaged areas.

Damage level	Soil moisture (%)				Soil temperature (° C)		
	Day 3	Day 20	Day 33	Day 48	Day 3	Day 20	Day 48
Untrodden	32^{c}	27	21^{c}	19^{b}	9.2	8.0	13.0
Low	34^{ab}	29	22^{bc}	19^{b}	8.9	7.7	12.8
Medium	36^{a}	30	23^{ab}	20^{b}	9.0	7.9	12.8
High	33^{bc}	28	26^{a}	23^{a}	9.1	7.3	12.9
sem	0.69	0.67	0.51	0.49	0.10	0.27	0.26
Significance							
Damage level	**	P = 0.05	***	***	ns	ns	ns

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
, * and ns denote P < 0.01, P < 0.001 significant level and not significant, respectively

4.4.3. Soil surface roughness

The differences in soil surface roughness between high-damaged and untrodden areas was highly significant (P < 0.001) at Days 3, 18 and 33 after treading (Table 4.2). The differences between low-damaged and untrodden, and between medium-damaged and untrodden areas declined in significance with time and disappeared at Day 33. The main effect of both day and damage level, and the interaction between days and damage level were highly significant (P < 0.001) for the decline in soil surface roughness during the recovery period.

Table 4.2 Mean roughness (percent decrease in chain length) at Days 3, 18 and 33 after treading from untrodden, and low-, medium-, and high-damaged areas.

Damage level	Day 3	Day 18	Day 33
Untrodden	3.7[d]	4.4[d]	3.4[b]
Low	7.8[c]	7.3[c]	5.4[b]
Medium	12.0[b]	9.6[b]	5.8[b]
High	23.3[a]	18.3[a]	14.0[a]
sem	0.72	0.62	0.84
Significance			
Damage level	***	***	***

Means within columns with different letters are significantly different at $P < 0.05$
sem = standard error of the least square means
*** denote $P < 0.001$ significant level

Based on the results of soil surface roughness and volumetric soil moisture content, measured from each sampling plot, there was strong correlation between soil surface roughness at Day 3 and soil moisture content at Day 33 after grazing/treading (Figure 4.3), the soil moisture content increased with the increase in roughness.

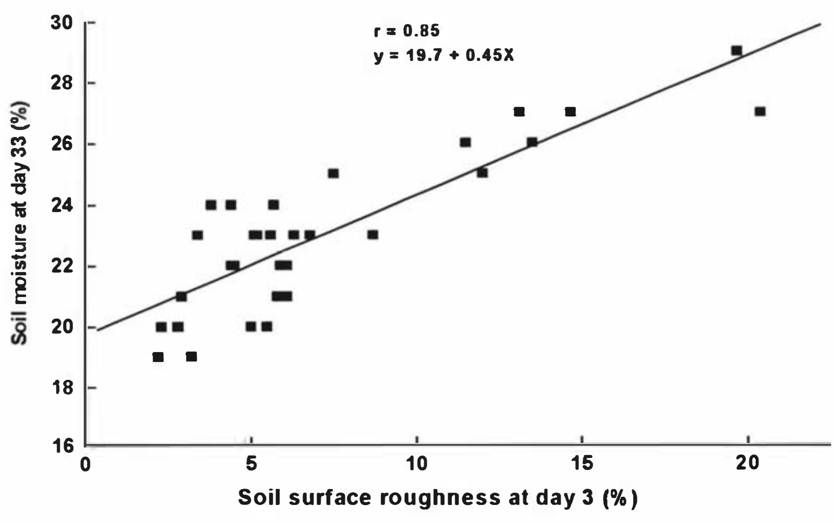

Figure 4.3 Relationship between soil surface roughness (%) at Day 3 and volumetric soil moisture content (%) in the 0-10 cm depth at Day 33 after treading.

4.4.4. Soil bulk density, porosity and infiltration rate

Soil bulk density increased with the increase in damage, but there was no significant difference between low-damaged and untrodden areas (Table 4.3). Soil macro-porosity was lowest in medium- and high-damaged areas, but there were no significant differences between medium- and high-damaged areas, and between low-damaged and untrodden areas.

Saturated infiltration rate was substantially slower in all trodden areas than in the untrodden areas at Day 5 ($P < 0.001$, Table 4.4). Infiltration rate was again substantially slower in medium- and high-damaged areas at Day 60 but the difference between low-damaged and untrodden areas was not significant.

Table 4.3 Soil dry bulk density (g cm^{-3}) and soil macroporosity (%) 15 days after treading

Damage Level	Bulk density (g cm^{-3})	Macroporosity (v/v)
Untrodden	0.98^{c}	6.91^{a}
Low	1.05^{c}	4.15^{a}
Medium	1.17^{b}	3.64^{b}
High	1.30^{a}	2.11^{b}
sem	0.027	0.820
Significance		
Damage level	***	**

Means within columns with different letters are significantly different at $P < 0.05$
sem = standard error of the least square means
, * denote $P < 0.01$, $P < 0.001$ significant level, respectively
Data supplied by David Horne

Table 4.4 Mean saturated infiltration rates (mm h^{-1}) from untrodden, and low-, medium-, and high-damaged areas at Days 5 and 50 after treading.

Damage level	Infiltration rates (mm h^{-1})	
	Day 5	Day 50
Untrodden	62.9^a	145.8^a
Low	30.8^b	152.1^a
Medium	9.5^c	21.9^b
High	12.4^c	30.8^b
sem	5.59	7.42
Significance		
Damage level	***	***

Means within columns with different letters are significantly different at $P < 0.05$
sem = standard error of the least square means
*** denote $P < 0.001$ significant level; Data supplied by David Horne

4.4.5. N fertiliser effects on pasture recovery

Differences in pasture cover, basal cover, pasture height, and herbage accumulation rates, tiller density and weight of the tiller of ryegrass and other grasses between + and – N fertiliser were small and not statistically significant. For this reason, the data were pooled.

4.4.6. Cover

As expected, pasture cover was lowest in the high-damaged areas (Plate 4.2) and intermediate in low- and medium-damaged areas at Days 3, 18 and 33 compared to that of the untrodden areas (Table 4.5). There were no significant differences in cover between low- and medium-damaged areas at all dates. The difference between low- and medium-damaged, and untrodden areas for cover declined in significance with time and disappeared at Day 48. There was an interaction between days and damage level (P < 0.01) for the cover, with recovery from loss of ground-cover being quickest from grazing without treading, intermediate in low- and medium-damaged and slowest in high-damaged areas.

Table 4.5 Mean cover (%) at Days 3, 18, 33 and 48 after treading from untrodden, and low-, medium-, and high-damaged areas.

Damage level	Day 3	Day 18	Day 33	Day 48
Untrodden	79^{a}	90^{a}	97^{a}	98^{a}
Low	54^{bc}	68^{b}	88^{b}	95^{a}
Medium	62^{b}	69^{b}	88^{b}	95^{a}
High	43^{c}	43^{c}	64^{c}	82^{b}
sem	5.8	3.2	1.9	1.4
Significance				
Damage level	***	***	***	***

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
*** denote P < 0.001 significant level

Plate 4.2 Recovery of pasture in high damaged areas at Day 30 after treading showing large areas of bare ground.

4.4.7. Basal cover

Basal cover tended to be lower in high-damaged areas at Day 3 but was lower in all trodden areas compared to untrodden areas at Days 18, 33, and 48 (Table 4.6). There were no significant differences between low- and medium-damaged areas for basal cover at all dates. There were main effects of day and damage level for the increase in basal cover with time in trodden areas ($P < 0.001$). Basal cover was reduced in all trodden areas at Day 18 compared to Day 3 and then increased over time leading to an interaction between day and damage level (P < 0.01). At Day 48, basal cover was lower in all trodden areas than that in untrodden areas.

Table 4.6 Mean basal cover (% of green tissue at the ground level) at Days 3, 18, 33 and 48 after treading from untrodden, and low-, medium- and high-damaged areas.

Damage level	Day 3	Day 18	Day 33	Day 48
Untrodden	45	46[a]	55[a]	71[a]
Low	34	27[b]	37[b]	45[b]
Med	40	30[b]	39[b]	52[b]
High	28	17[c]	22[c]	29[c]
sem	4.9	3.2	2.7	3.2
Significance				
Damage level	P = 0.10	***	***	***

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
*** denote P < 0.001 significant level

4.4.8. Pasture height

Pasture height was lower in untrodden compared to low- and medium-damaged areas at Day 20, and to all trodden areas at Days 35 and 50 after grazing/treading (Table 4.7), but there was no difference between untrodden and high-damaged areas at Day 20, and between all trodden areas at Day 35 and 50. The reduction in overall pasture height at Day 35 was mainly due to the grazing event at Day 29 after treading. There was an interaction between days and damage level (P < 0.05) for pasture height.

Table 4.7 Mean pasture height (cm) from untrodden, and low-, medium-, and high-damaged areas at Days 20, 35 and 50 after treading.

Damage level	Mean pasture height (cm)		
	Day 20	Day 35	Day 50
Untrodden	11.3[b]	5.7[b]	12.9[b]
Low	14.0[a]	8.8[a]	16.3[a]
Medium	14.8[a]	9.5[a]	18.3[a]
High	11.5[b]	8.7[a]	16.8[a]
sem	0.61	0.44	0.95
Significance			
Damage level	***	***	**

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
, * denote P < 0.01, P < 0.001 significant level, respectively

4.4.9. Herbage mass

Ryegrass herbage mass was greater in the medium-damaged areas compared to other trodden and untrodden areas at Days 3 and 18, but there were no significant differences between low-and high-damaged, and untrodden areas at Day 3 (Table 4.8). Ryegrass herbage mass tended to be greater in the medium-damaged areas at Day 48 compared to the untrodden areas, but was similar between trodden areas on this date. There were main effects of both day ($P < 0.01$) and damage level ($P < 0.001$) for the change in ryegrass herbage mass with time in all trodden and untrodden areas.

The herbage mass of 'other grasses' tended to be greater in the untrodden areas at Day 3, was greater at Day 18, and also tended to be greater at Day 48 than all trodden areas, but was similar between trodden areas at all dates (Table 4.8). There were main effects of both day ($P < 0.01$) and damage level ($P < 0.001$) for the initial decrease and then increase of 'other grasses' herbage mass with time in all trodden and untrodden areas.

Table 4.8 Mean herbage mass[1] (DM kg ha^{-1}) of ryegrass and 'other grasses' at Days 3, 18, 33 and 48 after treading from untrodden, and low-, medium-, and high-damaged areas.

Damage level	Ryegrass				'Other grasses'			
	Day 3	Day 18	Day 33	Day 48	Day 3	Day 18	Day 33	Day 48
Untrodden	220^{b}	290^{cb}	340	670	460	400^{a}	330^{a}	740
Low	310^{ab}	390^{ab}	590	910	250	130^{b}	160^{b}	390
Med	430^{a}	470^{a}	490	1022	190	70^{b}	170^{b}	300
High	180^{b}	200^{c}	510	700	150	50^{b}	110^{b}	370
sem	63.5	59.0	68.2	112.7	81.8	69.3	45.9	120.3
Significance								
Damage level	*	*	P=0.10	P=0.11	P=0.06	**	**	P=0.06

[1]Mean detached herbage mass (DM) at Day 3 after grazing/treading, which was ≈ 33% of these values is not included
Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
*, ** denote P < 0.05, P < 0.01 significant level, respectively

4.4.10. Botanical composition

Ryegrass (59%) and 'other grasses' (30%) were the dominant species of the dairy pasture before treading (Figure 4.4). The percentage of ryegrass was greater in all trodden areas compared to the untrodden areas at Day 3 ($P < 0.05$) and Day 33 ($P < 0.01$). Ryegrass percentage tended to be greater in medium- and high-damaged compared to the untrodden areas ($P = 0.07$) at Day 18, but was similar at Day 48.

The percentage of 'other grasses' tended to be greater in untrodden than medium- and low- damaged areas ($P = 0.05$) at Day 3, but was greater than in all trodden areas at Day 18 ($P < 0.05$) and Day 33 ($P < 0.01$). The percentage of 'other grasses' was similar between trodden areas at Days 18, 33, and between untrodden and trodden areas at Day 48.

The percentage of 'other species' was reduced in high-damaged compared to untrodden areas ($P < 0.05$) at Day 3, but there were no significant differences at Days 18, 33 and 48. There was no interaction of day and damage level.

The percentage of dead material was similar between damaged and untrodden areas at Day 18 and 33, but tended to be lower in high-damaged areas than other trodden and untrodden areas with time at Day 48 ($P = 0.07$). There was no interaction effect between day and damage level.

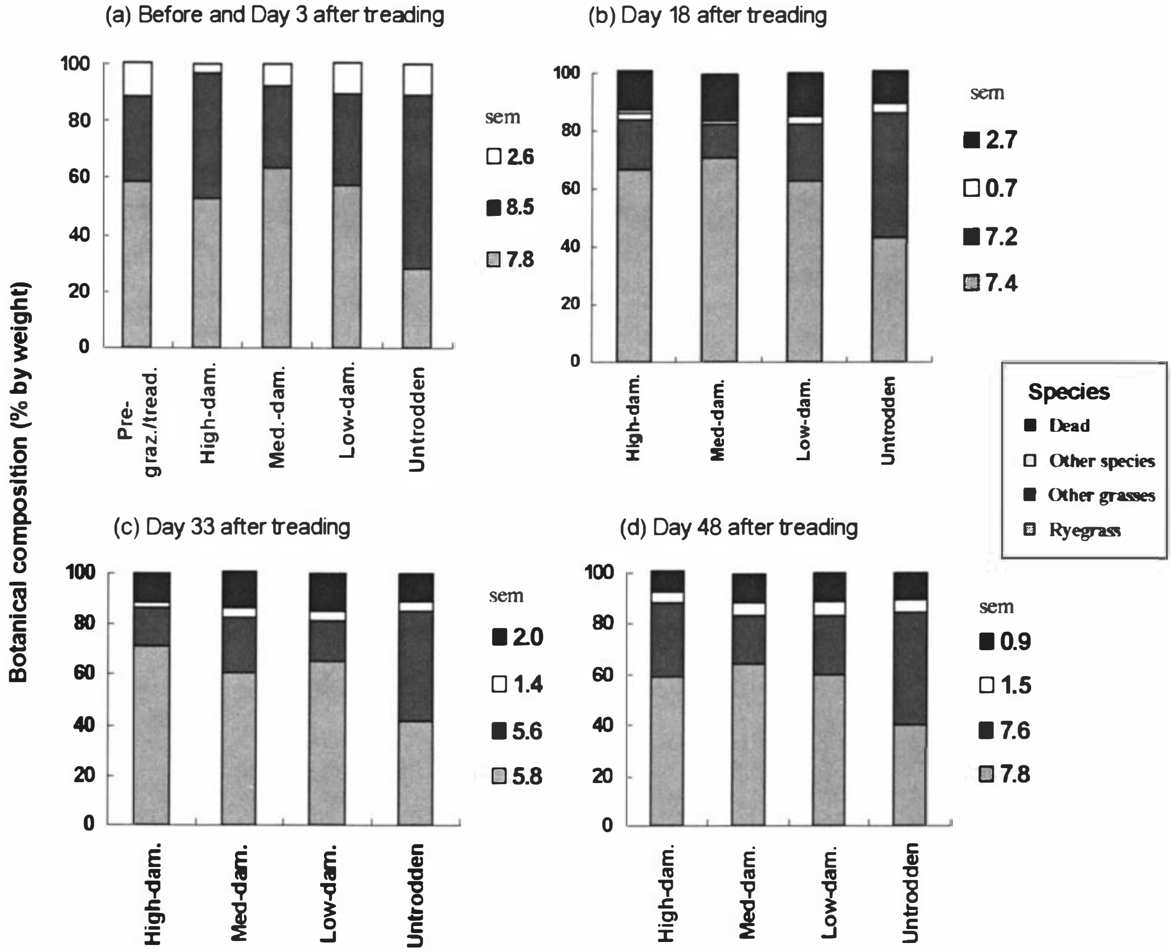

Figure 4.4 Effect of grazing/treading on the botanical composition of the swards at Days 3, 18, 33 and 48 after treading.

sem = standard error of the least square means

4.4.11. Detached plant material

There were no significant differences between trodden and untrodden areas in detached plant material remaining on the ground surface after grazing/treading (Table 4.9).

Table 4.9 Mean mass (DM kg ha^{-1}) of detached plant material on the pasture at Day 3 after grazing/treading.

Damage level	Detached plant material at Day 3 (DM kg ha^{-1})
Untrodden	130
Low	270
Medium	250
High	190
sem	46.9
Significance	ns

sem = standard error of the least square means
ns denote not significant

4.4.12. Herbage accumulation rates

There was no difference in ryegrass herbage accumulation rate between trodden and untrodden areas during Day 3 to Day 18 regrowth period after grazing/treading, but regrowth was lower in high-damaged compared to medium-damaged areas during Day 33 to 48 regrowth period (Table 4.10).

There were no differences in herbage accumulation rates of 'other grasses' during both Day 3 to 18 and Day 33 to 48 regrowth periods, but the mean values in all trodden and untrodden areas were negative from Day 3 to18.

Table 4.10 Mean herbage accumulation rate (kg DM ha^{-1} day^{-1}) of ryegrass and 'other grasses' during the regrowth periods Day 3 to 18 and Day 33 to 48 after grazing and/or treading from untrodden, low-, medium- and high-damaged areas.

Damage level	Ryegrass		'Other grasses'	
	Day 3-18	Day 33-48	Day 3-18	Day 33-48
Untrodden	5	22^{ab}	-4	27
Low	6	21^{ab}	-8	15
Medium	3	35^{a}	-8	8
High	2	13^{b}	-7	17
sem	4.6	6.5	5.0	6.7
Significance				
Damage level	ns	*	ns	ns

Means within columns with different letters are significantly different at $P < 0.05$
sem = standard error of the least square means
* and ns denote $P < 0.05$ significant level and not significant, respectively

4.4.13. Tiller density

Tiller density of ryegrass tended to be lowest in the high-damaged areas at Day 3, but there were no significant differences between other damaged and untrodden areas (Table 4.11). There were no significant differences in tiller density of ryegrass between trodden and untrodden areas at Days 18, 33, and 48. There was main effect of day ($P < 0.001$) for the increase or decrease of ryegrass tiller density, but no interaction effect between day and damage level.

Tiller density of 'other grasses' was lower in all trodden compared to the untrodden areas at Day 3 and these differences increased to Day 33, but declined by Day 48 (Table 4.11). Tiller density of 'other grasses' was lower in high- and medium-damaged compared to untrodden areas to Day 18 after treading but was similar between low-damaged and untrodden areas, and there were no significant differences between trodden areas. There was no interaction between day and damage level.

Table 4.11 Mean tiller density of ryegrass and 'other grasses' (No. m^{-2}) at Days 3, 18, 33 and 48 after treading from untrodden, and low-, medium-, and high-damaged areas.

Damage level	Ryegrass				'Other grasses'			
	Day 3	Day 18	Day 33	Day 48	Day 3	Day 18	Day 33	Day 48
Untrodden	1640	2430	2380	1759	6690^{a}	6310^{a}	7220^{a}	5140^{a}
Low	1980	2210	3520	3240	2560^{b}	3570^{ab}	1620^{b}	2100^{b}
Med	2440	2240	2560	2620	1840^{b}	2180^{b}	2760^{b}	2850^{b}
High	1230	1240	2590	2390	1620^{b}	780^{b}	1110^{b}	1880^{b}
sem	306	450	457	390	1040	1011	790	763
Significance								
Damage level	P=0.056	ns	ns	ns	**	**	***	*

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
*, **, *** and ns denote P < 0.05, P < 0.01, P < 0.001 significant level and not significant, respectively

4.4.14. Tiller weight

Tiller weight of ryegrass and 'other grasses' was calculated by dividing herbage mass (DM kg m^{-2}) by tiller density (tiller No. m^{-2}) per plot for each trodden and untrodden area.

The weight of individual ryegrass tillers was similar in all trodden and untrodden areas at Days 3, 18 and 33, but was smaller in high-damaged and low-damaged areas than in untrodden areas at Day 48 (Table 4.12). The weight of individual ryegrass tillers increased with time and there was interaction of day and damage level (P < 0.001).

The weight of individual tillers of 'other grasses' was greater in low- and high-damaged areas than in untrodden areas at Day 33, but was similar in all trodden areas (Table 4.12). Damage effects on other days were not significant. The weight of individual tillers increased with time, but there was no interaction of day and damage level.

Table 4.12 Mean tiller weight (mg) of ryegrass and 'other grasses' at Days 3, 18, 33 and 48 after treading from untrodden, and low-, medium-, and high-damaged areas.

	Ryegrass				'Other grasses'			
Damage level	Day3	Day18	Day33	Day48	Day3	Day18	Day33	Day48
Untrodden	1.3	15.9	17.9	48.3^{a}	0.2	5.5	4.6^{b}	16.5
Low	2.5	20.6	18.4	31.5^{b}	2.1	3.7	10.1^{a}	23.8
Med	1.0	22.6	21.4	43.0^{ab}	2.4	4.0	7.3^{ab}	10.1
High	2.1	19.2	19.5	29.8^{b}	1.2	6.0	11.3^{a}	18.6
sem	0.70	3.18	2.64	3.76	0.62	1.12	1.64	5.04
Significance								
Damage	ns	ns	ns	**	ns	ns	*	ns

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
*, ** and ns denote P < 0.05, P < 0.01 significant level and not significant, respectively

4.4.14. Leaf area index (LAI)

LAI of ryegrass was lower in high-damaged compared to low- and medium-damaged areas at Day 18, but there were no significant differences between high-damaged and untrodden areas (Table 4.13). LAI of ryegrass increased with time and was similar between trodden and untrodden areas at Days 33 and 48. There was no interaction between day and damage level.

LAI of 'other grasses' was lower in all trodden areas compared to the untrodden areas at Day 18 and 33 (Table 4.13). LAI of 'other grasses' also tended to be greater in the untrodden areas than in medium- and high-damaged areas at Day 48, but there were no significant differences between low-damaged and untrodden areas. The LAI of 'other grasses' increased with time (P < 0.001), but there was no interaction between days and damage level. Total grass LAI was least in high- and medium-damaged areas compared to the untrodden areas at Day 18 but was similar between all damaged and untrodden areas at Days 33 and 48 (Table 4.13). There was a main effect of time for the increase in LAI of total grasses (P < 0.001).

Table 4.13 Mean leaf area index (LAI) of ryegrass, 'other grasses' and total grasses at Days 18, 33 and 48 after treading from untrodden, and low-, medium- and high-damaged areas.

Damage level	Ryegrass			'Other grasses'			Total grasses		
	Day 18	Day 33	Day 48	Day 18	Day 33	Day 48	Day 18	Day 33	Day 48
Untrodden	0.4[ab]	0.5	1.0	0.8[a]	0.7[a]	1.6	1.2[a]	1.1	2.6
Low	0.5[a]	0.7	1.2	0.3[b]	0.3[b]	0.9	0.8[ab]	1.0	2.1
Medium	0.6[a]	0.7	1.5	0.1[b]	0.4[ab]	0.7	0.7[bc]	1.1	2.2
High	0.2[b]	0.8	1.2	0.1[b]	0.2[b]	0.8	0.3[c]	1.0	2.0
sem	0.08	0.11	0.19	0.15	0.10	0.26	0.14	0.13	0.18
Significance									
Damage level	*	ns	ns	*	*	P=0.06	**	ns	ns

Means within columns with different letters are significantly different at P < 0.05
sem = standard error of the least square means
*, ** and ns denote P < 0.05, P < 0.01 significant level and not significant, respectively

4.5. DISCUSSION

The objectives of this experiment focussed mainly on soil and plant damage from a single cattle treading event in winter, and regrowth of tillers during a recovery period of 7 weeks. The earlier study on the effect of different grazing regimes in hill pasture (Chapter 3) suggested that a number of factors could have contributed to the loss in herbage production following cattle treading in wet soil. There was evidence that plant damage resulting from hoof action in severely trodden areas was the cause of losses in production. This study has shown how treading by grazing cattle in winter can damage soil and pasture, affecting pasture growth in an intensive dairy farming system.

The trial design was such that there was no formal replication of the treatments. Selected high-, medium- and low-damaged sites were based on the visual assessment of damage effects within the same paddock. The reason for higher tiller density in untrodden areas may likely be due to a higher number of smaller tillers of browntop compared to those in trodden areas and/or due to the variability in tiller number of other species containing browntop between selected sampling plots. Within the untrodden area, choice of sampling plots for replication was limited compared to trodden areas. The variability in damage of trodden areas emerged mainly due to treading intensity. The variation in vSWC (%) between blocks of the paddock might also have had some effect on the variation in damage.

Lower residual herbage mass of ryegrass in untrodden compared to medium trodden areas at Day 3 and 18 after treading may likely be due to more ryegrass herbage being eaten in untrodden areas. The lower pasture height measured in untrodden compared to low- and medium-damaged areas at Day 20 after grazing/treading (Table 4.7) indicates that taller ryegrass tillers in untrodden areas would have been eaten close to the ground. Further, in untrodden areas, the cattle were grazed under a system of strict control so that the residues of dung and urine were not returned to the sward.

It could have happened by chance that the selected untrodden areas had greater tiller density and herbage mass of 'other grasses' than the trodden areas. The untrodden areas may have contained higher abundance of tillers of lower weight, mainly of browntop. So, pre-grazing/treading differences in the tiller density of 'other grasses' containing browntop between trodden and untrodden areas could have influenced the grazing/treading damage to some extent. In this experiment, pre-grazing/treading tiller population density was not recorded, because of logistical reasons. There was no clear pattern in relation to grazing behaviour on selection of the species in the past and the environmental preference of browntop primarily occupying niches at specific locations of the paddock. However, a more balanced design of the experiment with treatment replications and separation of treading effects from grazing could solve these problems. Also, a time period which allow full recovery of pasture in the trodden treatments would be helpful to understand the damage effects carried forward for example in tiller density of grasses and growth of individual tillers.

Effects of N fertiliser application on pasture regrowth after grazing/treading, at least in the short term, were small implying that the fertility of these soils was high. Also N fertiliser as urea was applied at the rate of 25 Kg N ha^{-1} across the paddock two weeks before the grazing/treading treatments (G. Evans, personal communication).

4.5.3. Soil conditions

Increased soil bulk density (0-50 mm) in medium- and high-damaged areas (Table 4.3), indicate that the integrity of the soil structural profile can be modified by treading. Bulk densities recorded in high damaged areas may have reduced the pasture growth. Animal hoof action can diminish the pore volume in the plant-rooting zone that can store oxygen and plant available water (Mullins *et al.*, 1990). Kelly (1985) showed that treading by grazing cattle compacted soil to the top 15 cm and reduced pasture growth. Mullholland and Fullen (1991) also reported that deeper damage resulted from cattle treading, which impose higher hoof pressures on the soil surface (Willat and Pullar, 1983).

The effects of treading on soil structure have been gauged by reduction in infiltration rates in medium- and high-damaged areas. Compared with untrodden areas, saturated infiltration rates were reduced by 80% and 85% at Day 5, and 79% and 85% at Day 60 in medium- and high-damaged areas respectively (Table 4.4). These values are similar to 82% decrease in cattle trampled sandy loam soil reported by Mulholland and Fullen (1991). Evidence of reduction in water infiltration rates in sheep grazed pasture was also reported by Willat and Pullar (1983) and Proffitt *et al.* (1993) and in cattle grazed pasture by Lisa *et al.* (1997).

In this study, soil macroporosity varied from 2% in high trodden to 4% in low trodden areas compared to that of 7% in untrodden areas (Table 4.3). Macroporosities were reduced to less than 10% of total soil volume; a value often regarded as defining critical conditions of aeration (Gradwell, 1968; Cannell, 1977). In such conditions plant and microorganism growth can be restricted (Singleton and Addison, 1999). Reduced macroporosity in the 0-5 cm soil depth by intensive winter grazing treatments (Drewry *et al.*, 1999) may restrict root growth and activity and therefore the uptake of water and nutrients. Because the effect of treading is greatest at the soil surface, this can lead to deterioration in topsoil structure through decreased soil permeability of both air and water (Proffitt *et al.*, 1995a). These conditions may reduce pasture production (Gradwell, 1965). Lowered rates of water infiltration may lead to higher rates of surface runoff during heavy rains and to greater soil erosion, a problem often related to increased animal stocking during wet weather (Gradwell, 1968; Proffitt *et al.*, 1993).

Soil surface roughness measured at Day 3 after treading helped to confirm the visual selection and ranking of low-, medium- and high-damaged areas. This study indicates that a soil surface roughness of 4% under untrodden flat dairy pasture can increase up to 25% if trodden by cattle during the winter wet period. Damaged plots with increased roughness and reduced cover held more moisture (i.e. were poorly drained) than untrodden plots with low roughness and higher pasture cover or basal cover (Figure 4.3). This appears not to improve pasture growth since at low vSWC of 18-22%, growth in high-damaged pasture was still slower than in the less-damaged but drier pastures. Higher tiller population in untrodden areas can transpire more water, as the fraction lost to crop transpiration decreases with the decrease in plant population (Persuad and Khosla, 1999). The nature of the carbon pathway for photosynthesis (C3 versus C4) and the harvest index are the important plant characteristics, which also determine water transpiration (Singh, 1999). The relationships between atmospheric factors, transpiration water loss from plant leaves and the carbon dioxide uptake by the plant, and between plant size, plant population, harvest index and soil evaporation have to be considered .

Low- to medium-damage with 8% to12% soil surface roughness at Day 3 after treading showed relatively faster growth of ryegrass whereas high-damaged areas with more than 15% soil surface roughness indicated a degree of treading damage which can reduce pasture growth. However, lower herbage accumulation rate of ryegrass in high-damaged areas compared to medium-damaged areas (Table 4.10) during regrowth period of Day 33 to 49 show that damage effect from treading can last longer than 7 weeks.

4.5.4. Pasture conditions

By 7 weeks after treading, the lower basal cover in the high-damaged areas (Table 4.6) was reflected in a lower tiller density of 'other grasses' (Table 4.11). To a large extent tiller density controls basal cover, and thus, herbage production. The lower basal cover, lower tiller density of 'other grasses' and lower leaf area index of ryegrass and 'other grasses' in high-damaged areas at Day 18 (Table 4.6, 4.11 and 4.13), suggest that the decrease in basal cover and tillers of 'other grasses' continues even after treading.

Compared to 18% in untrodden areas after grazing, a 58% detached plant material of the total residual herbage mass in high-damaged areas (Table 4.8 and 4.9) after treading on the same day suggest that treading can break off the plant parts which may be due to shearing by hoof action. In trodden areas, there is a possibility that some detached tillers may have been pushed or buried into the soil by hoof action. The on-going effects of treading damage that resulted in low basal cover and tiller number of 'other grasses' in high-damaged areas 7 weeks after treading shows that the effect of treading on vegetation can be very protracted.

The lower residual mass and percentage of ryegrass in the untrodden areas compared to low- and medium-damaged areas at Day 3 after grazing (Table 4.8) reflects both the presence of lower ryegrass tillers and the very high grazing pressure on these areas when adverse weather conditions combined with the severe treading effect reduce available feed in the main trodden areas.

The decline in pre-grazing/treading herbage mass of 3540 kg ha^{-1} to the residual mass of 740 kg ha^{-1} in untrodden areas at Day 3 after grazing indicates that the pasture was eaten close to the ground. The 51%, 41% and 47% lower residual mass of total grasses in high-damaged than in untrodden, low- and medium-damaged areas respectively at Day 3 after treading (Table 4.8), clearly indicates a degree of defoliation severity and plant damage by hoof action. The total tiller density of grasses in untrodden areas was 8330 m^{-2} at Day 3 after treading. The reduction in total tiller density of grasses by 46% in low-damaged areas, 49% in medium-damaged areas, and 66% in high-damaged areas (Table 4.11) on the same day may be due to the effect of both treading and variation of the species content across the selected areas. The loss in total residual herbage mass of 41% and 47%, respectively, in high-damaged compared to low- and medium-damaged areas was associated with the loss of 37 and 33% total tiller density of grasses, respectively, at Day 3 after treading (Table 4.8 and 4.11). Results show that the reduction in herbage mass observed in the high-damaged areas is consistently associated with tiller population density.

The relatively lower herbage accumulation rate of ryegrass in high-damaged areas compared to untrodden and low-damaged areas during regrowth Period 1 (Day 3-18, Table 4.10) was mainly because of lower tiller density. Whereas slow growth of ryegrass in high-damaged compared to medium-damaged areas during regrowth Period 2 (Day 33-48) was likely to be due to newly emerged tillers of lower weight in the treading disturbed areas. The relatively slow initial growth of ryegrass in medium-damaged compared to low-damaged and untrodden areas could be because of the death of some damaged tillers. However, regrowth of ryegrass in low- to medium-damaged areas was not suppressed by treading. Overall, treading had little impact on pasture production in low- to medium-damaged areas, and these results, were in line with the observation of Campbell (1966) that moderate levels of treading have no detrimental effect upon pasture production. Increased herbage growth through N transfer via excreta is recorded by Curl and Wilkins (1983) where treading by sheep had negligible effect and by Brown (1968) in trodden areas subject to moderate stocking in spring.

During 7 weeks regrowth period, the losses of accumulated herbage mass and total tiller population were 9% and 37% in low-damaged areas was, and 9% and 39% in medium-damaged areas respectively (Table 4.8 & 4.11) compared to those from untrodden areas. The lower losses of accumulated herbage mass in respect of total tiller population was mainly due to the presence of higher number of ryegrass tillers. Results suggest that presence of bigger ryegrass tillers may have contributed more to the herbage mass even if they are low in number than that did by the presence of higher number of tillers of less weight of 'other grasses'.

Based on the results (Table 4.8), over 7 weeks period after treading, the levels of damage translate to a reduction in total accumulated herbage mass of 1180 kg DM ha^{-1} or 34% in high-damaged areas compared to untrodden areas. Reduced spring herbage accumulation rates can have significant impact on cattle performance since this is a time when supply of forage is at a premium (Sheath *et al.*, 1987).

Experimental results also showed that the decrease in herbage mass and tiller density of grasses in high-damaged areas compared to other trodden and untrodden areas is associated with the decrease in leaf area index for the first three weeks after treading.

Marked effects of treading on the yield and tiller density of dairy pasture have been demonstrated and this yield:density relationship followed the same trend reported by Brougham (1960), and Bircham and Hodgson (1984). In this study, pasture responded to the very severe treading damage by losses in tiller population and LAI, and therefore by losses in yield. Treading can damage growing points and photosynthetic surfaces of tillers (Brown and Evans, 1973), and this further indicates that the key in understanding the intrinsic sources of variability in herbage regrowth after treading is the difference in the surviving tiller numbers and in residual leaf area index.

With 'other grasses', there was a consistent pattern in reduction of herbage mass and tiller density, especially in high-damaged areas. The reduction of 52% in tillers of 'other grasses' tillers from Day 3 to Day 18 in high-damaged areas (Table 4.11) suggesting the susceptibility of these grasses to treading damage. Under heavy treading, Edmond (1964) reported more tolerance of ryegrass over browntop, cocksfoot and Yorkshire fog which were categorised as 'other grasses' in this experiment.

The herbage accumulation rate of 'other grasses' was negative in all trodden and untrodden areas for the period Day 3-18 (Table 4.10) suggesting that the level of grazing/treading was not favourable to recovery of these species. The relatively lower herbage accumulation rate of ryegrass during the Day 33-48 period in high-damaged areas compared to other trodden and untrodden areas also indicated that the effects of treading damage had not disappeared. These results suggest that the loss of herbage mass was characterised by the initial loss in tillers and subsequent poor recovery. The recovery trend was reflected through increased tiller number and leaf area.

Slow recovery of the pasture in high-damaged areas than in low- and medium-damaged areas, was mainly due to lower tiller density, lower herbage accumulation rate and possibly a higher soil disturbance (Plate 4.2). Treading effects would have lasted longer in high trodden areas, because the differences in pasture cover produced initially by treading can last a year (Horne and Singleton, 1997). Soil and pasture measurement could not be continued for longer than 7 weeks recovery period after treatments imposed due to the farm management rules being practiced.

The early regrowth characteristics of ryegrass in trodden areas may probably be due to the early appearance of new tillers from those buried under the soil surface during treading. Grazing under the fence in untrodden areas was so severe that the initial ryegrass tiller population could have been reduced and as a consequence, resulted in an initial loss in herbage regrowth. The similarity of herbage growth in low- to medium-damaged pasture with that of the untrodden plots was due to the contribution of ryegrass. Edmond (1963) also recorded faster regrowth of ryegrass than other species, where moderate treading damage was exerted.

Treading did not suppress tiller density and herbage mass of ryegrass, but rather enhanced regrowth in low- to medium-damaged areas during the recovery period. It seems that early recovery of both tiller density (3 weeks) and herbage mass (5 weeks) of ryegrass (Table 4.11 and 4.8) observed in low- and medium-damaged areas may probably be due to the treading disturbance created, and productivity of a low to moderate level of treading in ryegrass dominated dairy pasture. Ryegrass showed the special characteristics of robustness, stability, and ability of better colonisation in damaged areas compared to other grasses. This regrowth efficiency of ryegrass in low- to medium-damaged areas aligns well with the relatively high tolerance of ryegrass to damage reported by Lambert *et al.* (1986a). Vickery (1972) emphasized that pasture production was highest at his moderate stocking rate, and that this could have been due to moderate treading disturbance. However, plants in small, but less stressed, gaps may take more advantage of the increased availability of light and nutrients for their regrowth. At the heart of this concept, open spaces created by treading (Table 4.5) may have enhanced the appearance and growth of ryegrass tillers. Larger tillers of ryegrass in untrodden and medium-damaged areas observed at Day 48 after treading indicate that growth of individual tillers was also enhanced in these areas following treading.

The results of this study clearly show that it is possible to damage pasture plants by a single, severe cattle treading during winter when the soil is wet, and supports the earlier findings of Charles (1979) that intensive cattle treading can have deleterious effects in terms of direct damage to plants through hoof action. However, they also show that a certain level of damage may be beneficial for the development of faster growing pasture species such as ryegrass.

In summary, net production of herbage mass of grasses was reduced by 34% in high-damaged areas compared to untrodden areas (Table 4.8) as a result of decreased tiller density (Table 4.11) and initial losses in LAI of both ryegrass and 'other grasses' (Table 4.13). Effects on tiller density and LAI resulted in net herbage production of ryegrass per unit area being generally greatest in low- and medium-damaged areas. The lower yield and canopy cover observed in the earlier experiment (Chapter 3) in high-damaged areas could be explained in terms of reduced tiller number and LAI. A value of LAI = 3 can be considered as a limiting value for tillering for a sward which is allowed to accumulate dry matter. Below this level soil and environmental conditions may be expected to promote tillering; above this level there will be no positive effect since tiller populations may begin to decline sooner as a result of the self-thinning process (Yoda *et al.*, 1963).

The initial decrease in the herbage mass of ryegrass in the untrodden areas and that of 'other grasses' in trodden areas may probably be explained by variability of the species presence between the trodden and untrodden areas before grazing, hard grazing in the untrodden areas which affected ryegrass tillers, and more losses of 'other grasses' by treading in trodden areas. The lower weight of individual tillers of 'other grasses' at Day 33 in untrodden areas may have resulted from relatively higher tiller number per unit area, thereby maintaining tiller size compensation (Davies, 1988; Chapman and Lemaire, 1993), but the smaller tillers of ryegrass in high-damaged areas at day 48 may have been a consequence of treading damage where there was no short-term compensation. However, results show that ryegrass can tolerate low- to medium-damage, and maintain growth better than 'other grasses' following a single severe cattle treading. Plant species may vary both in their ability to resist being damaged by treading and their ability to recover following treading damages.

Grazing management practices like grazing on a time basis (or 'controlled grazing') during wet periods have long been promoted in New Zealand, not only to protect the soil but also to improve pasture production (Gradwell, 1968). Direct damage to plant growing points, uprooting and breaking of the tillers by hoof action, and loss of photosynthetic surfaces due to sheep treading were demonstrated by Brown and Evans, (1973). Damage to growing points and tillers leads to a lower leaf area index, which in turn leads to a lower herbage accumulation. The main effects of treading damage on herbage growth appeared to have been through loss of tillers and cover, and differences in the regrowth response of ryegrass and 'other grasses' were found to be important.

4.6. CONCLUSION

The important aspects of this trial are that the clearest demonstration of the deleterious effects of treading can be seen in both soil physical properties and pasture variables. The increase in soil surface roughness and bulk density, reduced infiltration rate and macroporosity caused by treading may have affected the regrowth of pasture especially in high-damaged areas.

The impact of single treading in winter by cattle on pastures is reflected in a number of equations of plant survival and performance. Tiller density and pasture dry matter yield was reduced in high-damaged areas, while losses were negligible in light to medium-damaged areas. The effects on canopy and basal cover, herbage yield, tiller density, and weight of individual tillers resulting from management practices can have implications to techniques used in estimating treading impacts on dairy pasture.

Reduction in residual herbage mass (high at Day 3) and tiller density of ryegrass in high-damaged areas after treading was tended to recover during a 7-week regrowth period (Tables 4.8 and 4.11), but those of 'other grasses' did not recover. There is a direct impact of the animal hoof on the pasture causing damage to tillers. Soil damage may be the main cause for the slow recovery of pasture in the high-damaged areas. However, treading had a limited promotive effect on tiller density and cover of ryegrass, but tended to have depressive effect on those of 'other grasses'.

On a practical level, these results indicate that even though soil moisture status at the time of grazing/treading was still below the saturation point, grazing pasture after rain when vol. vSWC is between 35–40%, can result in major treading damage. The soil in high-damaged areas of a paddock, which can hold more moisture during recovery, may promote the incidence of repeated treading, thereby causing further loss in yield and tillers.

Results from this study draw attention to the need for detailed studies of the growth of ryegrass tillers following treading in dairy pasture. Unlike the hill pasture (Chapter 3) and this experiment, an experiment with more formal design and replication of the treatments together with pre-treading measurements and given longer recovery period could answer questions about the losses and regrowth of tillers of ryegrass and other species following treading.

CHAPTER 5

EFFECT OF CANOPY HEIGHT AND CATTLE TREADING ON HERBAGE GROWTH PARAMETERS

5.1. INTRODUCTION

The results of the two previous cattle treading experiments (Chapter 3 and 4) suggest that severe cattle treading on wet soil seriously reduces herbage production both in hill pasture and flat dairy pasture because of reduced tiller density and pasture cover. However, a single severe cattle treading had no effect on the weight of an individual tiller of ryegrass over a 33 day period (Table 4.12) after treading.

Pastures recovered earlier in low- and medium-damaged areas and produced greater herbage mass compared to untrodden and high-damaged areas 49 days after treading (Chapter 4). Recovery of these low- and medium-damaged pastures is explained more by fast growing ryegrass tillers, which produced a greater leaf area index. In high-damaged areas, slow recovery may have been due to a carryover effect of soil damage by treading. Edmond (1963) observed that damage to ryegrass in a pasture defoliated to 2 inches before treading was less than that inflicted on a pasture defoliated to 1 inch. Defoliation height at the time of treading may influence the damage sustained by the pasture and/or subsequent recovery of the pasture.

Experiment 2 (Chapter 4) was designed to get preliminary information on the effect of treading damage on both soil and pasture. The results have raised a number of questions relating to damage and recovery of tillers following treading. For example, in high-damaged areas, recovery of ryegrass tillers compared to other grasses was mainly due to production of new tillers. The explanation of individual tiller growth between treatments could be valuable information. Lower ryegrass tiller weight in high-damaged compared to untrodden areas 49 days after treading could be due to the differences in individual tiller growth, caused by soil damage. Again, there are questions on the design of the experiment without formal treatment replication and the short experiment period of 7 weeks, when the experiment was terminated before achieving full recovery of both soil and pasture.

Also, results indicated that pasture residual height at the time of treading may affect regrowth of ryegrass tillers. Tiller population densities and average tiller weight of ryegrass calculated from dividing the herbage mass by tiller density were recorded throughout Experiment 2, but the detailed measurement of individual tiller growth, tiller emergence and tissue turnover measurements between treading treatments were not followed throughout the regrowth period.

The following experiment was set up under field conditions to investigate the underlying adjustment by tillers to canopy height and treading severity. Pasture covers from the site were brought into the glass house to study tiller appearance rate and growth of new tillers. The response of treading on different canopy height was measured in terms of herbage production, tiller numbers of all species, and tiller size, leaf and stem extension rate, the appearance of daughter tillers (new tillers) from parent tillers (existing tillers).

5.2. MATERIALS AND METHODS

5.2.1. Site

The experiment was carried out at No. 4 Dairy farm (Plate 5.1) at Massey University, Palmerston North (40°23'S; 175°37'E) from August to November 2000. The trial site was an area of paddocks dominated by ryegrass. Browntop, small quantities of Yorkshire fog and cocksfoot and legume (White clover) were included in group named 'Other species'. The Tokomaru silt loam (Cowie, 1972) is classified as a Pallic soil (Aeric Fragiaqualf), (McLaren and Cameron, 1996). The soil (at10 cm depth) had a pH of 5.9 and Olsen P status of 63 $\mu g\ g^{-1}$ soil. The paddocks selected for this study were mole and pipe drained. The region is classified as temperate with an annual average air temperature of 13°C and an annual rainfall of 1000 mm with prevailing westerly winds. Rainfall two days before treading was 29 mm. Average soil temperature at 10 cm depth during the experimental period ranged from 7°C in August to 13°C in November.

Plate 5.1 A view of the study site.

5.2.2. Design and treatments

A block of 16 m x 24 m was selected from each of four paddocks. Each block was divided equally into 6 plots of 8 m x 8 m. Randomly selected plots of each block were mown to 4 cm (Short canopy height) or 8 cm (Tall canopy height) above ground using a motor mower at 4 Days before treading. Cut herbage was removed. All treatment plots were fenced to allow animal treatments to be applied and blocks were fenced to exclude stock from unwanted grazing (Figure 5.1).

A single cattle treading was imposed on 14 August, 2000, following a 15 mm rainfall event on the preceding day. Treading treatments in all four blocks were carried out on the same day. One plot of each canopy height of each block was left as the untrodden treatment. Remaining plots of each canopy height were damaged by walking three (Light stocked) or six (Heavy stocked) cows around the plots. The cows were in late-pregnancy and of an average 600 kg live weight. The cows were walked constantly within the plots for 9 minutes; a period judged to be sufficient to create damage. The cows were then moved onto the next plot. The same group of cows were used for all plots in a block. Cattle were grazed elsewhere prior to the treatment to reduce appetite. Almost no eating took place and the loss of pasture by grazing was ignored.

The experimental design was 3 x 2 randomised complete block design with 4 replicates. The six treatments were designated as shown in Table 5.1.

Table 5.1 Treatment combinations used in trial 3.

Treading intensity	Canopy height
None	Short
	Tall
Light	Short
	Tall
Heavy	Short
	Tall

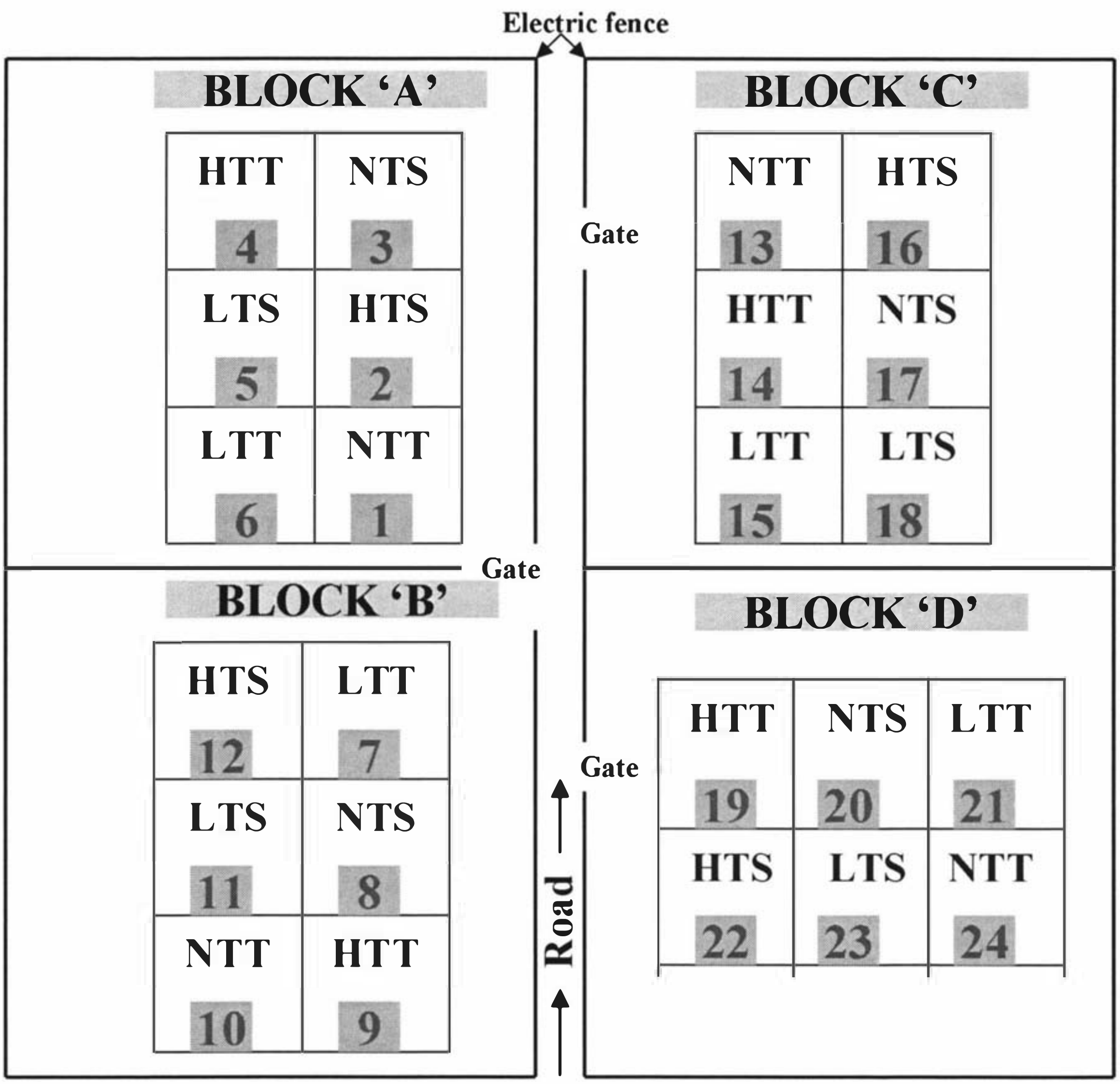

Figure 5.1 Layout model of experimental area.

Note: Numbers 1 to 24 are the treatment plots
Blocks 'A' 'B' 'C' 'D' are the treatment paddocks for treatment replications
Letter codes are the treatments where;
NTS = No Treading damage Short canopy height
NTT = No Treading damage Tall canopy height
LTS = Low Treading damage Short canopy height
LTT = Low Treading damage Tall canopy height
HTS = High Treading damage Short canopy height
HTT = High Treading damage Tall canopy height

The regrowth of the pasture after treading was compared over two successive regrowth periods; regrowth Period 1 (20 Aug. to 18 Sep.) followed by regrowth Period 2 (15 Oct. to 9 Nov.). Pastures of all plots were cut to 8 cm using a hand mower between these regrowth periods. Clippings were removed.

5.2.3. Measurements

5.2.3.1. Soil moisture content

Soil moisture was measured at 10-cm depth using Time Domain Reflectance (Parchomchuki *et al.*, 1997). Pre-grazing/treading soil moisture was recorded at Day 1 before treading (see section 4.2.2 on method). Post-treading soil moisture was recorded at Day 4 after treading. From each treatment plot, four readings were taken at different locations.

5.2.3.2. Surface roughness

Soil surface roughness was measured at Day 2 before and Day 2 after treading as in Experiment 2.

5.2.3.3. Basal cover

Basal cover was estimated using the point analysis method of Radcliffe and Mountier (1964). A modified point analyser 'contometer' with 40 pins developed by Betteridge *et al.* (1999) was used for recording basal cover. Each pin of the 'contometer' was pressed down at the ground level and the living tissue of the plant touched or hit by the pin was recorded.

5.2.3.4. *Soil compaction, unsaturated hydraulic conductivity and compressibility*

Soil compaction was assessed from penetrometer reading (a measure of soil strength). A modified field penetrometer based on that described by Soane (1973) and Billot (1982) was used to measure soil penetration depth (mm) pre- and post-treading. Three cores (core ring 70 mm high and 120 mm in diameter as a measure of hardness) were collected for the determination of unsaturated hydraulic conductivity. All cores were carefully carved into the soil following trimming of the grass to the ground surface, and excavation to the appropriate depth. Unsaturated hydraulic conductivity followed the method of Perroux and White (1988) using tension infiltrometers on cores which had equilibrated on a tension table (Ψ 5 mm, 20 mm, 40 mm and 100 mm). Soil compressibility was measured by applying pressure of 300 KPa to the cores for 15 minutes and then the pressure removed and rebound was measured for 5 minutes. This was done at 100 mm tension. The distance the ram moved was measured in mm every 10 seconds.

5.2.3.5. *Plant population density*

The tiller numbers of ryegrass and other grasses (mainly *A. capillaries* and a small proportions of *D. glomerata, H. lanatus)*, white clover, and individual weeds were counted to estimate plant population density (No. m^{-2}). Thirty turf plugs of 50 mm diameter was taken from each plot 2 Days before treading, and 52 and 86 Days after treading as described by Mitchell and Glenday (1958). At Day 4 after treading, ten turf plugs of 120 mm diameter were taken into the glasshouse to measure tiller emergence and tiller growth. Bigger turf plugs were taken on this occasion to handle with disturbed soil surface.

5.2.3.6. Herbage mass

Herbage mass was determined by cutting the pasture to 2 cm 2 days before treading, and 4, 49, 52 and 86 days after treading. Three 0.1 m^2 quadrats were cut in each plot (Frame, 1993). Cut samples were sub-sampled into two representative fractions: (a) for botanical separation of ryegrass, 'other grasses', white clover and other broad leaf species, and (b) for the separation of twenty ryegrass tillers to be dissected into leaf and stem. Separated leaves and pseudostems or stems of ryegrass were measured in a leaf area meter (LI-3100 Area Meter, 1979) for the estimation of leaf area per tiller and pseudostem or stem planar area per tiller.

Separated leaves and stems of ryegrass, separated species from the sub-sample taken for botanical composition, and the remainder from the main sample was oven dried separately at 80°C for 24 hrs and weighed. Based on the dry matter of leaf, stem, and total weight of individual ryegrass tiller and weight of 'other species', the herbage mass per unit area (DM kg ha^{-1}) was estimated.

5.2.3.7. Leaf and pseudostem extension

After treading, two fixed transects, each 2 m in length, were located in each plot with fixed pipes inserted at the end points. Fifteen ryegrass tillers located along each transect, at 10 cm intervals, were marked by coloured plastic rings. Leaf and pseudo stem length (Thomas, 1980) of the marked tillers and leaf length of daughter tillers of those marked tillers were measured three times, at about ten-day intervals, in each regrowth period (Figure 5.2). After the third measurement, each marked tiller and its daughter tillers were cut at ground level and dissected into leaf and stem components. These were then used to measure leaf-area and pseudostem or stem planar area and dry weight.

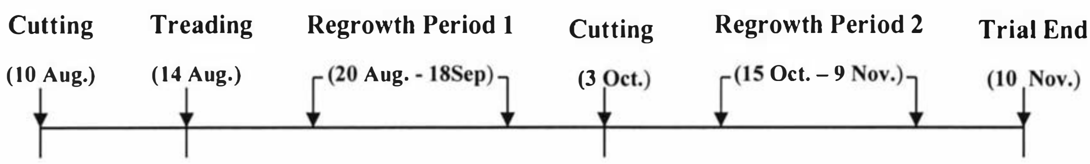

Figure 5.2 Time-line of cutting, treading, regrowth Period 1 and regrowth Period 2.

Tiller appearance from each marked tiller used for leaf extension measurement and leaf appearance from both marked parent tiller and daughter tillers of these marked tillers were recorded for the estimation of Tiller appearance rate (TAR) and leaf appearance rate (LAR) during regrowth period 1.

5.2.3.8. *Appearance of new tillers*

Ten, 120 mm diameter turf plugs (see 5.2.3.4) were taken from each plot after treading and moved to a glasshouse for the measurement and closer study on the appearance of new tillers. In the glasshouse, the established ryegrass tillers in the plugs of each treatment taken from the field were loosely tagged at Day 3 after treading. As tillers emerged during the periods from Day 3-18 and Day 19-33, they were loosely tagged at Day 18 and Day 33 so that the new tillers could be related to their established mother tillers. For tagging of tillers at each date, a different set of coloured plastic rings was used. Of the 10 tiller plugs of each treatment, established and new tillers from five of the turf plugs were harvested at Day 33 and separated into the three colour coded groups, and oven dried for the calculation of mean individual tiller weight within each age group. The remaining five tiller plugs of each treatment were left in the glasshouse. Emerged tillers during period 2 (Day 34-65) were cut and classified as one group and harvested at Day 65. All other remaining tillers from the cores which were marked at Day 18 and Day 33 were also harvested at Day 65. All the harvested tillers of different age groups were oven dried and weighed.

5.2.4. Statistical analysis

Data were analysed by Analysis of Variance using the General Linear Model procedure of the Statistical Analysis System (SAS Institute, 1990). The six treatment combinations of three treading intensities and two canopy heights were analysed as a randomised complete block (RCB) model with four replicates and separate analyses were carried out for each harvest and observation date. Comparisons of means were made using Duncan's New Multiple-Range Test (Steel and Torrie, 1980).

5.3. RESULTS

A. Results from Field

5.3.1. Pasture conditions before treading

The percentage of the species content in the plots before treading were ryegrass 62%, other grasses 27% (*A. capillaris* 18%, *H. lanatus*, *Poa*, and *D. glomerata* together 9%), *T. repens* 8%, and flat weeds 3%. For the analysis and interpretation, ryegrass was kept separate, but all other species were pooled and named 'Other species'.

5.3.2. Rainfall, soil temperature and soil moisture

Daily rainfall and soil temperature data during trial period are presented in Figures 5.3 (a) and (b) respectively.

Figure 5.3 (a)

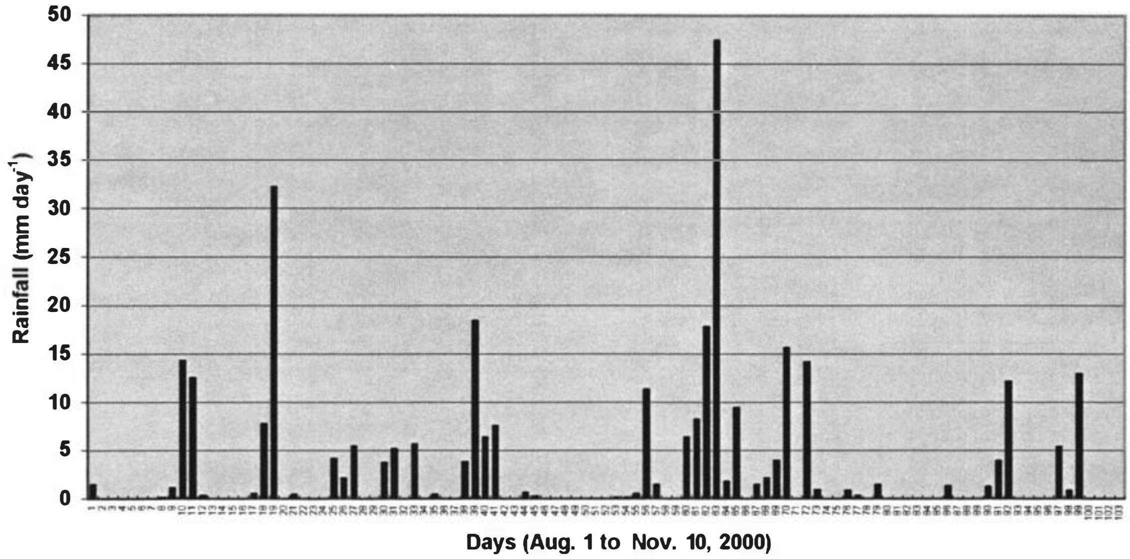

Figure 5.3 (b)

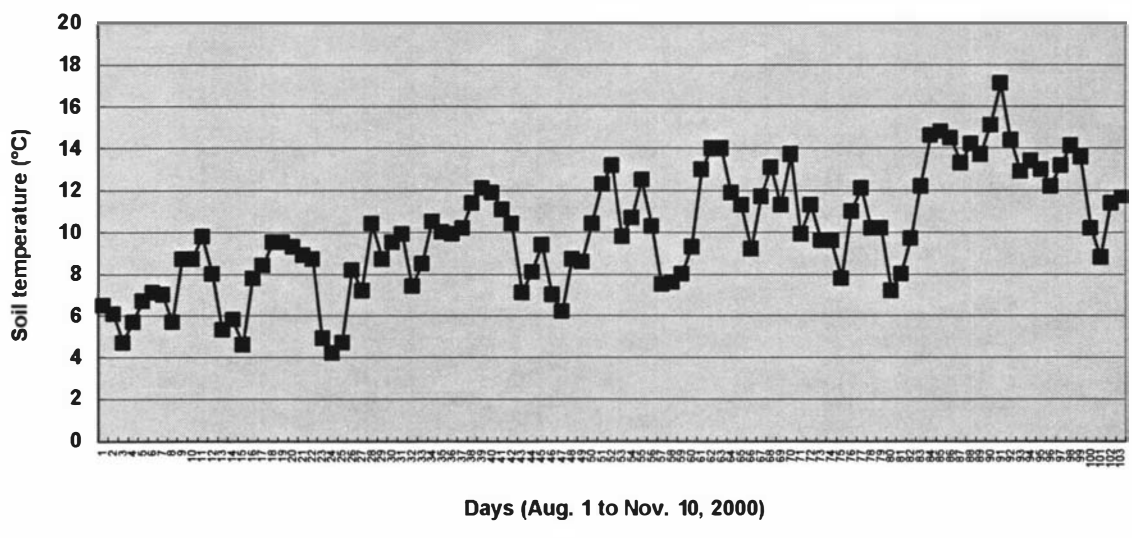

Figure 5.3 (a) Rainfall data and (b) soil temperature (10-cm depth) data, both recorded daily during the trial period (1 Aug. to 10 Nov., 2000) at the AgResearch Meteorological Station, Palmerston North, approximately 1200 m from the experimental site.

Soil moisture content was similar between treatments before treading. Soil moisture content was higher in trodden compared to untrodden treatments and was also higher in short compared to tall treatments at Day 4 after treading (Table 5.2).

Table 5.2 Mean volumetric soil moisture content (%) on two days before treading and four days after treading.

Treatments		Day	
Treading	Canopy ht.	-2	4
None	Short	44	42
	Tall	41	40
Light	Short	42	43
	Tall	42	42
Heavy	Short	41	42
	Tall	43	43
sem		1.1	0.4
Significance			
Treading (Tread)		ns	**
Canopy height (Can ht)		ns	*
Tread x Can ht		ns	ns

sem = standard error of the least square means
*, ** and ns denote P < 0.05, P < 0.01 significant level and not significant, respectively

5.3.3. Soil Surface Roughness

There were no differences in soil surface roughness between treatments before treading. Soil surface roughness increased with the increase in treading intensity at Day 2 after treading, but there was no effect of cutting height (Table 5.3).

Table 5.3 Mean soil surface roughness (%) two days before treading and two days after treading.

Treatments		Soil surface roughness percent (%)	
		Day -2	Day 2
None	Short	2.2	2.3
	Tall	2.5	2.0
Light	Short	4.7	5.4
	Tall	4.1	5.0
Heavy	Short	3.0	8.9
	Tall	4.2	8.3
sem		0.62	0.83
Significance			
Treading		ns	***
Canopy height		ns	ns
Tread x Can ht		ns	ns

sem = standard error of the least square means
*** and ns denote P < 0.001 significant level and not significant, respectively

5.3.4. Basal cover

Basal cover was lower in heavy trodden compared to light trodden and untrodden treatments at Day 2 after treading but there was no difference between light and untrodden treatments (Table 5.4). The differences in basal cover between treading treatments had disappeared by Day 86. Canopy height had no effect in basal cover at Day 2, but was greater in short compared to tall treatments at Day 86 after treading.

Table 5.4 Basal cover (percent of green tissue at the ground level) at Days 2 and 86 after treading.

Treatments		Basal cover %	
		Day 2	Day 86
None	Short	67	89
	Tall	58	67
Light	Short	58	82
	Tall	74	81
Heavy	Short	52	87
	Tall	52	66
sem		4.3	5.01
Significance			
Treading		*	ns
Canopy height		ns	**
Tread x Can ht		*	ns

sem = standard error of the least square means
*, ** and ns denote $P < 0.05$, $P < 0.01$ significant level and not significant, respectively

5.3.5. Soil compaction

There was no significant difference in soil penetrometer reading between treatments before treading and Day 3 after treading (Table 5.5).

Unsaturated hydraulic conductivity was reduced in trodden treatments compared to untrodden treatments at Day 3, at 5, 20, 40 and 100 mm tensions, but there was no difference between light and heavy treading treatments (Table 5.6). Canopy height had no effect on unsaturated hydraulic conductivity. There was no effect of treading and canopy height treatments in compressibility (maximum and rebound) at Day 3 after treading (Table 5.6).

Table 5.5 Difference in pre- and post-soil penetration depth (mm) 2 days before treading and at Day 3 after treading.

Treatments		Difference in pre- & post-soil penetration depth (mm) Day -2	Day 3
None	Short	45	46
	Tall	45	46
Light	Short	44	48
	Tall	42	44
Heavy	Short	42	46
	Tall	43	48
sem		2.1	2.3
Significance			
Treading		ns	ns
Canopy height		ns	ns
Tread x Can ht		ns	ns

sem = standard error of the least square means
ns denote not significant

Table 5.6 Effect of canopy height and treading treatments on mean unsaturated hydraulic conductivity under 5 mm, 20 mm, 40 mm and 100 mm supply potential tension and compressibility of soil at Day 3 after treading.

Treatments		Hydraulic Conductivity 5mm	20mm	40mm	100mm	Compressibility Maximum Compression (mm)	Rebound (mm)
None	Short	187	162	128	87	19	17
	Tall	173	107	75	55	17	15
Light	Short	122	74	54	40	17	16
	Tall	141	86	60	43	17	16
Heavy	Short	123	68	59	39	17	16
	Tall	132	94	55	41	16	15
sem		11.3	13.6	14.7	8.0	0.8	0.9
Significance							
Treading		***	**	*	**	ns	ns
Canopy height		ns	ns	ns	ns	ns	ns
Tread x Can ht		ns	*	ns	P = 0.08	ns	ns

sem = standard error of the least square means
*, *, **, *** and ns denote P < 0.05, P < 0.01, P < 0.001 significant level and not significant, respectively

5.3.6. Herbage mass and accumulation rates

Pre-treading total herbage mass and ryegrass herbage mass was less in the short compared to the tall treatments, but herbage mass of 'other species' was similar (Table 5.7). At Day 4 after treading, herbage mass of ryegrass, and total herbage was less in short compared to tall treatments, but this difference declined to Day 49 and disappeared at Day 52 after cutting to 8cm height at Day 50. The difference in herbage mass of 'other species' between canopy height treatments at Day 4 was small and this difference disappeared at Day 49, earlier than for ryegrass.

Treading reduced both total and ryegrass herbage mass at Day 4, but the reduction in herbage mass of 'other species' was low (Table 5.7). On this Day, the reduction in total herbage mass was greater with increase in treading intensity, but there were no significant differences in the mass of ryegrass or 'other species' between light and heavy treading. At Days 49 and 52, the herbage mass of ryegrass and 'other species' was similar between trodden and untrodden treatments, but the total herbage mass was still lower in heavy trodden compared to untrodden treatments although the difference had declined. On these days total herbage mass between light-trodden and untrodden treatments was similar.

At Day 4, there was an interaction effect of treading and canopy height on both total and ryegrass herbage mass, but there was no such effect for other species. At Day 52, there was also an interaction of treading and canopy height on ryegrass herbage mass.

Herbage accumulation rate of ryegrass was greater in trodden compared to untrodden treatments during the period from Day 4 to 49 after treading (Table 5.9). Canopy height and treading tended to show an interaction for this increase in herbage accumulation rate. At the same period, canopy height and treading tended to have an interaction for the increase of total herbage accumulation rate in trodden compared to untrodden treatments.

Herbage accumulation rates of 'other species' were not effected by canopy height and treading treatments. There was no effect of canopy height and treading treatments and their interaction for the ryegrass, 'other species' and total herbage accumulation rate during the period Days 52 to 86.

5.3.7. Tiller density

Total plant population density, tiller density of ryegrass and 'other species' were reduced in trodden compared to untrodden treatments at Day 4 after treading, but there were no significant differences between light and heavy trodden treatments (Table 5.8). The differences in plant population densities after treading (Plate 5.2) had disappeared by Day 52 between treading treatments, but total plant density was greater in short compared to tall treatments on this date.

Table 5.7 Effect of canopy height and treading treatments on herbage mass (kg DM ha^{-1}) of ryegrass, 'other species' and total herbage. Date and days are given for pre-treading, and the start and end of two growth periods after treading.

Treatments		Ryegrass					'Other species'					Total herbage				
		Day -2	Day 4	Day 49	Day 52	Day 86	Day -2	Day 4	Day 49	Day 52	Day 86	Day-2	Day 4	Day 49	Day 52	Day 86
None	Short	390	410	1380	960	3650	470	310	1480	1270	3580	860	720	2870	2230	7220
	Tall	1280	1330	2030	1670	5160	540	390	1270	790	1750	1830	1710	3310	2460	6910
Light	Short	450	220	1500	1520	4920	330	140	1200	810	2530	780	360	2700	2320	7450
	Tall	1160	700	1710	1210	4920	500	260	1310	950	2340	1660	960	3010	2150	7270
Heavy	Short	450	150	1260	1170	4140	500	110	770	910	3010	940	250	2030	2080	7150
	Tall	1240	540	2110	1380	4520	390	200	940	740	2470	1630	630	3050	2120	6980
sem		110.8	72.7	200.8	155.1	457.4	83.6	53.1	240.3	139.9	513.4	85.2	47.5	207.4	90.5	499.1
Significance																
Treading		na	***	ns	ns	ns	na	**	ns	ns	ns	na	***	*	*	ns
Canopy height		***	***	**	ns	ns	ns	*	ns	ns	ns	***	***	**	ns	ns
Tread x Can ht		ns	**	ns	*	ns	na	ns	ns	ns	ns	na	***	ns	ns	ns

sem = standard error of the least squares means
*, **, *** and ns denote P < 0.05, P < 0.01, P < 0.001 significant level and not significant, respectively
na denote not applicable

Table 5.8 Effect of canopy height and treading treatments on tiller density (No. m^{-2}) of ryegrass, 'other species' and total herbage. Date and days are given for pre-treading and post–treading periods.

Treatments		Ryegrass				'Other species'				Total herbage			
		Day -2	Day 4	Day 52	Day 86	Day -2.	Day 4	Day 52	Day 86	Day -2.	Day 4	Day 52	Day 86
None	Short	2820	2870	2530	1750	5290	4300	4900	3860	8100	7170	7440	5610
	Tall	3410	3150	2690	1970	4160	3720	4430	3380	7570	6860	7120	5350
Light	Short	3080	1540	3180	1660	4720	1420	4740	3450	7800	2960	7920	5100
	Tall	3090	1740	2460	1440	5040	1580	3740	3810	8130	3310	6200	5260
Heavy	Short	3590	1120	3010	2090	5430	1690	4850	4220	9020	2810	7860	6320
	Tall	2320	1440	2780	1740	4550	1410	3660	3020	6860	2850	6440	4760
sem		294.6	276.2	417.5	246.3	710.0	252.9	545.3	637.7	652.6	380.5	556.0	652.6
Significance													
Treading		na	***	ns	ns	na	***	ns	ns	na	***	ns	ns
Canopy height		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns
Tread x Can ht		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

sem = standard error of the least squares means
*, *** and ns denote $P < 0.05$, $P < 0.001$ significant level and not significant, respectively
na denote not applicable

Table 5.9 Effect of canopy height and treading treatments on herbage accumulation rate (kg DM ha^{-1} day^{-1}) of ryegrass, 'other species' and total herbage during the period Day 4 to 49 and Day 52 to 86 after treading.

Treatments		Herbage accumulation rate (kg DM ha^{-1} day^{-1})					
		Day 4 to 49			Day 52 to 86		
		Ryegrass	'Other sps.'	Total	Ryegrass	'Other sps.'	Total
None	Short	22	26	48	75	36	139
	Tall	16	20	36	97	27	123
Light	Short	28	24	52	95	48	142
	Tall	22	23	46	103	39	142
Heavy	Short	24	14	38	83	58	141
	Tall	37	17	54	87	48	135
sem		4.4	5.0	5.0	20.2	13.0	14.5
Significance							
Treading		*	ns	ns	ns	ns	ns
Canopy. height		ns	ns	ns	ns	ns	ns
Tread x Can ht		P = 0.07	ns	*	ns	ns	ns

sem = standard error of the least square means
* and ns denote P < 0.05 and not significant, respectively

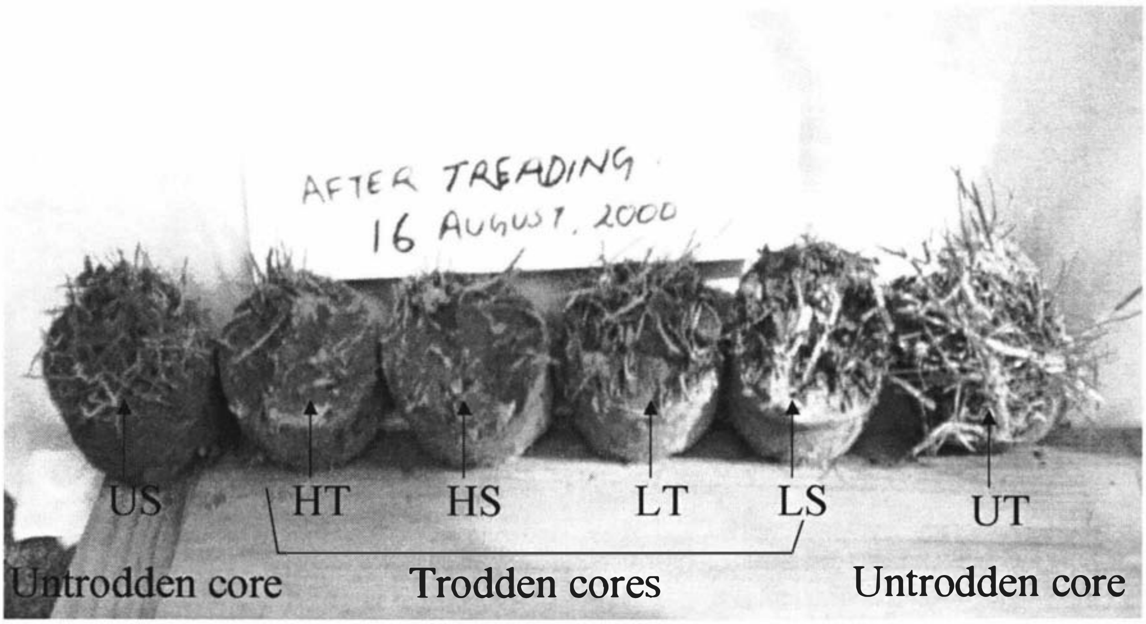

Plate 5.2 Tiller cores after treatment shows loss in tillers as a result of treading compared with untrodden tiller cores on the right and left (US = Untrodden Short, UT = Untrodden Tall, HT = Heavy Trodden Tall, HS = Heavy Trodden Short, LT = Light Trodden Tall, LS = Light Trodden Short). .

5.3.8. Tiller weight and leaf area of ryegrass

Total tiller weights were lower in trodden compared to untrodden treatments at Day 4 after treading, but there was no difference between light and heavy treading (Table 5.10). There were no significant differences in tiller weights between light and heavy trodden treatments. The differences in tiller weight between canopy height disappeared by Day 49. There were no interactions between canopy height and treading treatments.

Leaf area per tiller of ryegrass was less in short compared to tall treatments before treading. At Day 4 after treading, leaf area per tiller of ryegrass was reduced in the trodden compared to the untrodden treatment, but was similar between light and heavy trodden treatments (Table 5.11). There were no significant differences for the leaf area of ryegrass at Day 49 and no interaction between canopy height and treading treatments.

Table 5.10 Mean dry weight of leaf, pseudo-stem and total weight of ryegrass tillers (mg) observed two days before treading and at Days 4 and 49 after treading.

Treatments		Day -2			Day 4			Day 49		
		Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
None	Short	4	5	9	7	5	12	19	10	29
	Tall	12	9	21	14	11	25	19	13	32
Light	Short	5	5	9	5	4	9	22	11	33
	Tall	11	8	20	11	9	20	21	16	37
Heavy	Short	4	5	9	6	4	9	21	10	31
	Tall	11	9	20	11	9	20	20	14	33
sem		0.6	0.6	1.0	0.5	0.6	0.9	1.0	1.7	2.4
Significance										
Treading		na	na	na	***	*	***	na	ns	ns
Canopy height		***	***	***	***	***	***	ns	*	ns
Tread x Can ht		na	na	na	ns	ns	ns	ns	ns	ns

sem = standard error least squares means
*, **, *** and ns denote P < 0.05, P < 0.01, P < 0.001 significant level and not significant, respectively
na denote not applicable

Table 5.11 Mean leaf area (cm^2) $tiller^{-1}$ of ryegrass observed 2 days before treading and at Days 4 and 49 after treading.

Treatments		Day -2	Day 4	Day 49
None	Short	0.76	1.51	4.16
	Tall	1.96	2.76	4.32
Light	Short	0.78	1.18	5.02
	Tall	1.83	2.30	4.63
Heavy	Short	0.72	1.19	4.41
	Tall	1.92	2.14	4.81
sem		0.097	0.102	0.263
Significance				
Treading		na	***	ns
Canopy height		***	***	ns
Tread x Can ht		ns	ns	ns

sem = standard error of the least square means
*** and ns denote P < 0.001 significant level and not significant, respectively
na denote not applicable

5.3.9. Leaf and pseudo-stem extension rate of ryegrass

Overall, the leaf extension rate increased with time in Period 1 and decreased in Period 2. Leaf extension rate was greater in trodden compared to untrodden treatments during the first half (15-26 Oct) of regrowth Period 2, but was similar during the second half (27 Oct-9 Nov). There were no effects of canopy height treatments on the leaf extension rate of ryegrass during regrowth Periods 1 and 2 (Figure 5.4). There were also no effects of treading treatments on the leaf extension rate during regrowth Period 1.

Overall, the pseudostem and stem extension rates increased with time. Pseudostem extension rates were not affected by treading during regrowth Period 1, but stem extension rates were greater in trodden compared to untrodden treatments during Period 2. There were no effects of canopy height treatments on pseudostem and stem extension rate of ryegrass during regrowth Period 1 and 2 respectively (Figure 5.5).

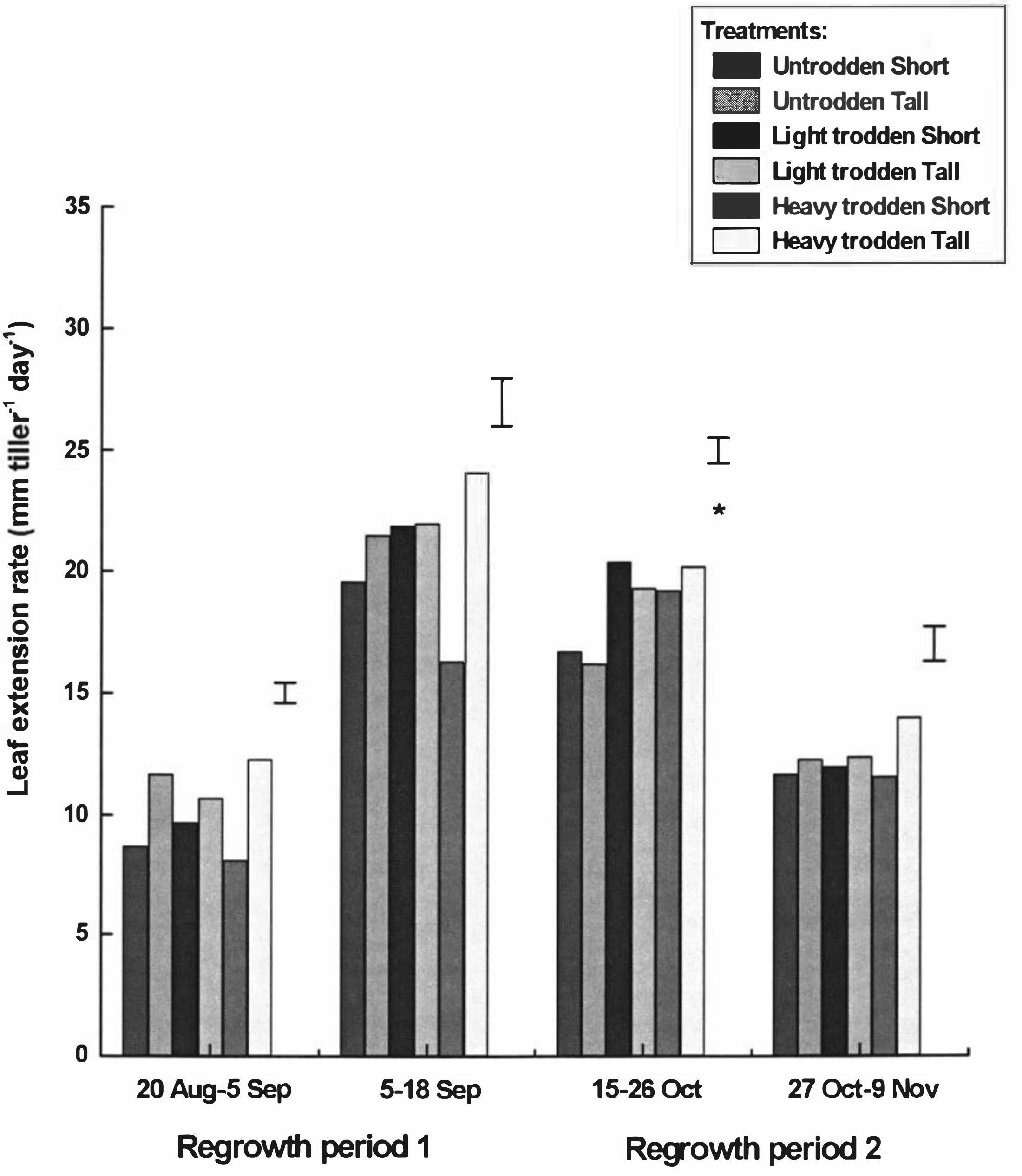

Figure 5.4 Effect of canopy height and treading intensity on ryegrass leaf extension rate (mm day^{-1}) marked over regrowth period 1 (20 Aug to 18 Sep) and regrowth period 2 (15 Oct to 9 Nov), respectively.

vertical bar show standard error of the least square means (sem)
* denote P < 0.05 significant level for treading treatments

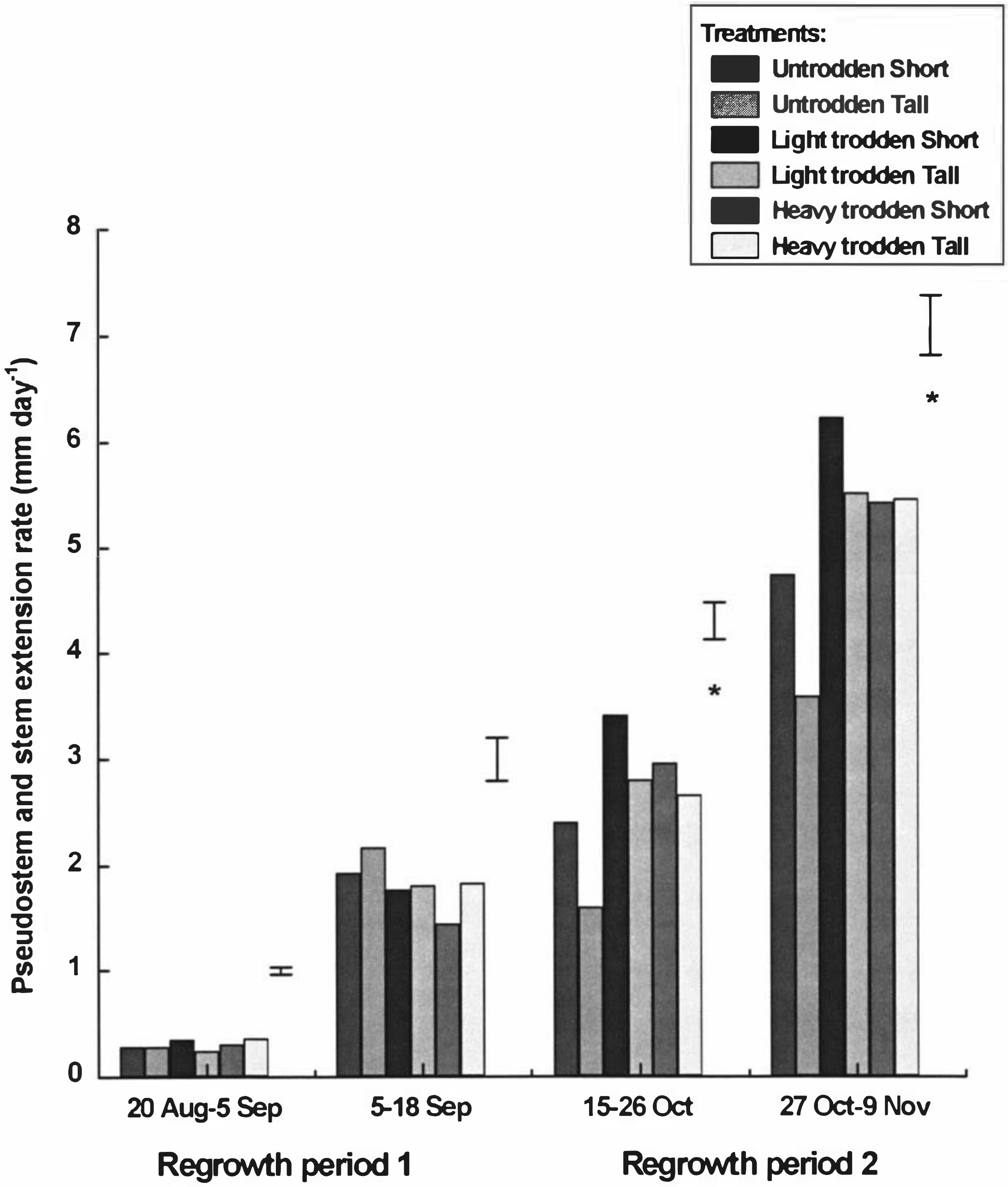

Figure 5.5 Effect of canopy height and treading intensity on ryegrass pseudostem and stem extension rate (mm day^{-1}) marked over regrowth period 1 (20 Aug to 18 Sep) and period 2 (15 Oct to 9 Nov), respectively.

vertical bar show standard error of the least square means (sem)

* denote P < 0.05 significant level for treading treatments

5.3.10. Weight of mother and daughter tillers of ryegrass

There were no effects of treading treatments on the weights of leaf, stem, dead tissue and on total weight of mother tillers of ryegrass at Day 35 (20 Sep, Period 1) after treading. The weight of ryegrass tillers was greater in tall compared to short treatments (Table 5.12).

The weights of leaf and stem of daughter tillers were greater in trodden compared to untrodden treatments at Day 35 after treading. The weight of daughter tillers was greater in trodden than in untrodden treatments. There was no difference in weight of daughter tillers between light and heavy trodden treatments.

The weights of leaf, stem, and dead tissue of the mother tillers were greater in trodden compared to untrodden treatments at Day 86 (9 Nov.), thereby resulting in heavier tillers in trodden treatments but there were no differences between light and heavy trodden treatments (Table 5.13). The weight of mother tillers was greater in trodden than untrodden treatments, but there was no effect on the weight of daughter tillers, and there was no effect of canopy height. There was no interaction between canopy height and treading treatments for the change in weight of both mother and daughter tillers during both regrowth Period 1 and Period 2.

Table 5.12 Mean dry weight (mg) of leaf, pseudostem, dead tissue and total weight of mother tillers marked on 20 Aug and harvested on 18 Sept and mean dry weight of daughter tillers (mg) produced by marked mother tillers during regrowth period 1.

Treatments		Mother tillers				Daughter tillers		
		Leaf	Stem	Dead	Total wt.	Leaf	Stem	Total wt
None	Short	37	21	8	66	20	10	30
	Tall	45	32	16	93	19	13	32
Light	Short	38	26	10	74	34	23	57
	Tall	50	35	18	103	26	18	44
Heavy	Short	38	23	8	69	37	25	62
	Tall	51	35	17	103	29	19	48
sem		1.9	2.5	1.3	4.2	4.7	2.6	7.05
Significance								
Treading		ns	ns	ns	ns	*	*	*
Canopy height		***	***	***	***	ns	ns	ns
Tread x Can ht		ns	ns	ns	ns	ns	ns	ns

sem = standard error of the least squares means
*, *** and ns denote P < 0.05, P < 0.001 significant level and not significant, respectively

Table 5.13 Mean dry weight (mg) of leaf, stem, dead tissue and total weight of mother tillers marked on 15 Oct (Day 61) and harvested on 9 Nov (Day 86) and mean dry weight of daughter tiller (mg) produced by marked mother tillers during regrowth Period 2.

Treatments		Mother tillers				Daughter tillers			
		Leaf	Stem	Dead	Total wt.	Leaf	Stem	Dead	Total wt.
None	Short	38	75	16	129	4.5	4.1	4.5	12.7
	Tall	38	66	17	121	2.9	3.2	0.4	6.5
Light	Short	52	117	21	190	6.6	4.5	2.1	13.2
	Tall	47	119	21	187	9.1	6.0	5.0	20.1
Heavy	Short	46	101	18	165	8.4	7.3	8.5	24.2
	Tall	51	105	23	179	9.9	7.8	7.5	25.2
sem		3.6	10.2	1.7	14.1	2.62	2.42	3.04	7.56
Significance									
Treading		*	***	•	***	ns	ns	ns	ns
Canopy height		ns	ns	ns	ns	ns	ns	ns	ns
Tread x Can ht		ns	ns	ns	ns	ns	ns	ns	ns

sem = standard error of the least squares means
*, *** and ns denote P < 0.05, P < 0.001 significant level and not significant, respectively

5.3.11. Leaf and pseudo-stem area of mother and daughter tillers of ryegrass

Leaf area, pseudo-stem area and total area of marked mother tillers were less in short compared to tall treatments at Day 35 (18 Sep) after treading, but there were no effects of treading nor any interaction of canopy height and treading treatments (Table 5.14). Leaf area, stem area and total tiller area were greater in trodden compared to untrodden treatments at Day 86 (9 Nov, Table 5.14), but were similar between light and heavy trodden treatments. The differences in stem area and total tiller area were greater than those in leaf area.

Leaf area, pseudo-stem area and total tiller area of daughter tillers were greater in short compared to tall treatments at Day 35 (18 Sep, Table 5.14). On this date, also leaf area, pseudo-stem area and total area of daughter tillers were greater in heavy trodden compared to untrodden treatments, but were similar between light trodden and untrodden treatments. Leaf area of daughter tillers was also greater in trodden compared to untrodden treatments at Day 86 (9 Nov, Table 5.14), but was similar between light and heavy trodden treatments. There was no effect of treading treatment on stem area on this date. Total shoot area of daughter tillers tended to increase in trodden compared to untrodden treatments. There was no effect of canopy height and no interaction of canopy height and treading at Day 86.

Table 5.14 Mean leaf area, stem area and total area of mother tillers marked on 20 Aug and 15 Oct and mean leaf, stem and total area of their daughter tillers (cm^2) that appeared during regrowth periods, harvested on 18 Sep (Period 1) and 9 Nov (Period 2) respectively.

		Mother Tiller						Daughter tiller					
		18 Sep			9 Nov			18 Sep			9 Nov		
Treatments		Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total	Leaf	Stem	Total
None	Short	6.4	1.0	7.4	7.1	2.6	9.7	5.1	1.4	6.5	0.9	0.2	1.1
	Tall	7.8	1.5	9.3	7.2	2.4	9.6	3.3	1.1	4.3	0.9	0.3	1.1
Light	Short	6.3	1.1	7.4	9.5	3.6	13.2	6.2	2.0	8.2	2.5	0.6	3.1
	Tall	8.3	1.5	9.7	8.5	3.5	11.9	5.1	1.6	6.8	1.8	0.4	2.2
Heavy	Short	5.9	1.0	6.8	8.1	3.0	11.1	8.0	2.4	10.4	2.0	0.6	2.2
	Tall	9.4	1.5	10.9	9.8	3.4	13.1	5.3	1.4	6.8	2.1	0.6	2.7
sem		0.54	0.12	0.63	0.62	0.27	0.82	0.70	0.22	0.90	0.40	0.17	0.62
Significance													
Treading		ns	ns	ns	*	**	**	*	*	**	*	ns	P=0.06
Canopy height		***	***	***	ns	ns	ns	**	**	**	ns	ns	ns
Tread x Can ht		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

sem = standard error of the least squares means
*, **, *** and ns denote P < 0.05, P < 0.01, P < 0.001 significant level and not significant, respectively

5.3.12. Leaf appearance rate (LAR), tiller appearance rate (TAR) and sites occupied by new tillers (TAR/LAR)

During the period from Day 5 to 35 after treading, TAR and LAR were similar between treading and canopy height treatments (Table 5.15). There was interaction effect between treading and canopy height treatments for both tiller appearance and leaf appearance rates. At the same period, the sites occupied by new tillers (TAR/LAR) were smaller in heavy trodden than other treatments.

Table 5.15 Effect of treading and cutting height on leaf appearance rate (LAR) and tiller appearance rate (TAR) per mother tiller, and sites occupied by new tillers (TAR/LAR) during the period Days 5 to 35 after treading.

Treatments		LAR[1]	TAR[1]	TAR/LAR
None	Short	0.161	0.084	0.522
	Tall	0.148	0.082	0.554
Light	Short	0.197	0.096	0.488
	Tall	0.167	0.073	0.439
Heavy	Short	0.144	0.066	0.457
	Tall	0.212	0.089	0.421
sem		0.0142	0.0082	0.0374
Significance				
Treading		ns	ns	*
Canopy height		ns	ns	ns
Tread x Can ht		*	*	ns

[1]Both LAR & TAR are per marked tiller day^{-1}
sem = standard error of the least square means
* and ns denote P < 0.05 significant level and not significant, respectively

B. Results from Glasshouse

5.3.13. Ryegrass tiller appearance

Tiller appearance rate, and weights of established and new tillers were similar between light and heavy trodden treatments. Because of this, data from the Treatments 3 and 5 were pooled and named 'Trodden short', and data from Treatments 4 and 6 were pooled and named 'Trodden tall'. Treatment '1' was designated 'Untrodden short' and treatment '2' 'Untrodden tall'.

5.3.13.1. Appearance of new tillers

During the period Day 3 to 18, the number of new tillers increased greatly in the pasture plugs from trodden compared to untrodden treatments, but there was no effect of canopy height (Figure 5.6). Both canopy height and treading treatments had no effect on emergence of ryegrass tillers during the period Day 19 to 33. There was no interaction between canopy height and treading for both periods. The number of new tillers was greater in tall compared to short treatments during the period Day 34 to 65, and there was an interaction between canopy height and treading (P < 0.05) for this period.

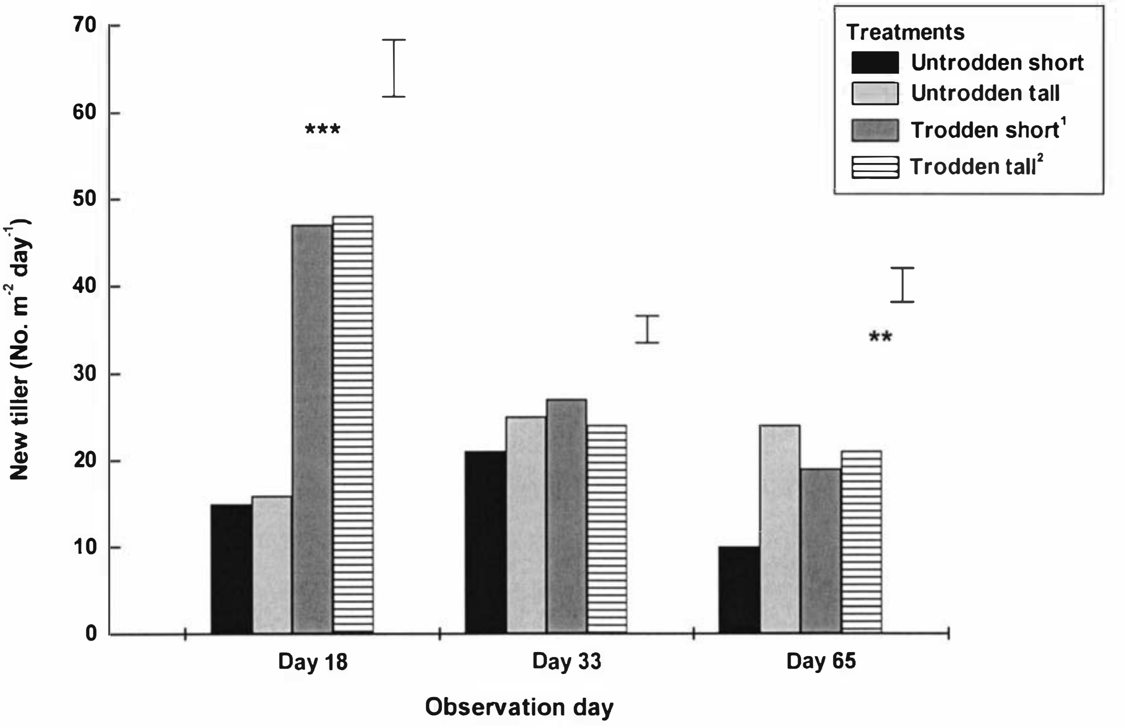

Figure 5.6 Mean tiller appearance rate (No. m^{-2} day^{-1}) of ryegrass from trodden and untrodden treatments observed at three different periods (Days 3 to 18, Days 19 to 33 and Days 34 to 65) after treading.

[1]Data from Treatments 3 and 5 were pooled; [2]Data from Treatments 4 and 6 were pooled
vertical bar show standard error of the least square means (sem)
, * denote P < 0.01, P < 0.001 significant level, respectively

5.3.13.2. *Weight of established and new tillers in glasshouse*

At harvest on Day 65, established tillers marked at Day 3 were heavier than tillers marked at later dates (P < 0.05). The weight of new tillers first marked on Day 18 in the plugs from trodden treatments was heavier than those from untrodden treatments (Figure 5.7). There were no effects of canopy height, and interaction of canopy height and treading for the weight of established and new tillers. The weight of new tillers marked at Day 33 and Day 65 were similar.

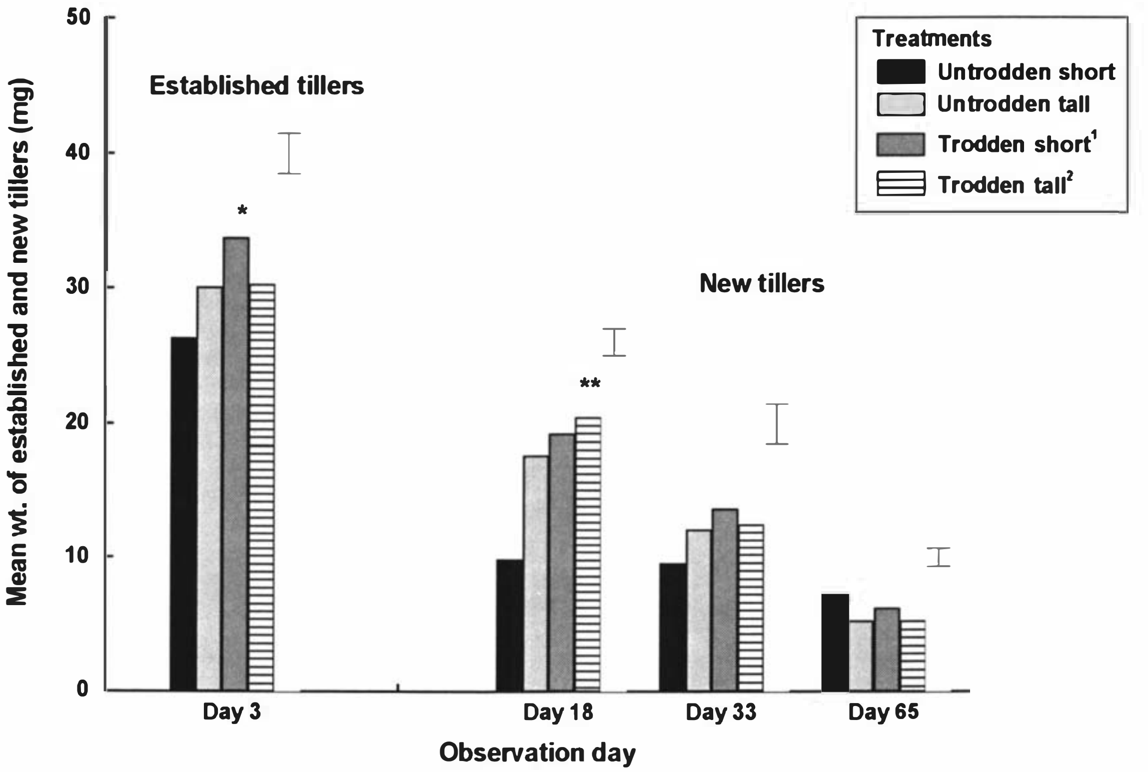

Figure 5.7 Mean tiller weight (mg) at harvest on Day 65 of successive cohorts of ryegrass tillers from trodden and untrodden treatments, marked at Day 3 (established tillers), and at Days 18, 33 and 65 (new tillers) after treading.

[1]Data from Treatments 3 and 5 were pooled; [2]Data from Treatments 4 and 6 were pooled
vertical bars show standard error of the least square means (sem)
*, ** denote $P < 0.05$, $P < 0.01$ significant level, respectively

5.4. DISCUSSION

5.4.1. Soil conditions

The increased soil surface roughness with the increase in treading intensity at Day 4 after treading in this experiment (Table 5.3) further confirms our earlier result (Chapter 4) that roughness increases with the increase in damage. These results were in line with the observation of Betteridge *et al.* (1999) that treading by grazing cattle, increased roughness of the soil surface.

The reduction in basal cover in heavy-trodden treatments at Day 2 after treading was lower than the losses in tiller density at Day 4. Similar basal cover between light-trodden and untrodden treatments at Day 2 despite the greater loss in tiller population density in light trodden treatment is likely to be due to the presence of broken or damaged tillers which later may have died. Compared to tall, the increased basal cover in short canopy height treatments at Day 86 (Table 5.4) is likely to be due to increased tiller density at Day 52. Basal cover would have determined pasture cover and/or ground cover in this pasture but the pasture was not measured separately in this experiment. Reduction in pasture cover can increase runoff and soil loss (Lang and McCaffrey, 1984), which ultimately could reduce pasture growth.

Similar penetrometer reading between treatments at Day 3 after treading showed that soils of the experimental site were not compacted (Table 5.5). This may be because of better structural stability of this soil, which may have mediated competing degrading and regenerative forces created due to treading.

Effects of treading on hydraulic conductivity (Table 5.6) showed that pore space is the important soil physical property related to treading. The losses in pores, due to treading, were greatest with 5 mm and minimum with 100 mm supply potential tension (Table 5.6). Greenwood *et al.* (1997), by using measurement of unsaturated hydraulic conductivity at a range of tensions, concluded that porosity losses caused by grazing were related to a decrease in the number of pores with an equivalent cylindrical diameter greater than 1.2 mm. The losses in the number of pores can restrict water and air movement (Soane *et al.*, 1981). In their review, Gifford and Hawkins (1978) showed considerable evidence of reduction in infiltration due to reduction in pore space caused by trampling. However, in this study, losses of pore spaces did not affect the growth of individual tillers.

5.4.2. Pasture dry matter yield and tiller dynamics

Ryegrass was the single most dominant species, contributing 64% of the total herbage mass, although ryegrass tiller density was only 39% of the total plant density of 7910 m^{-2}. The content of ryegrass in the present experiment was thus close to the estimate of 60% in Experiment 2. In both experiments, the content of white clover was less than 10%.

Initial loss in residual herbage mass measured in trodden treatments was mainly due to the reduction in tiller numbers. The differences in total herbage mass between heavy trodden and other treading treatments were smaller but were still evident at Days 49 and 52 (Table 5.7), though the effect of canopy height in the heavily trodden treatments had disappeared by this time. For the reduction in total herbage mass from Days 4 and 49, tall canopy height had no protective effect in heavily trodden treatments but the losses in light trodden tall treatments were 50% less than in light trodden short treatments. Thus, a tall canopy is beneficial to save losses from light treading but not from heavy treading. Brown (1968) compared treading with and without the protective cover and reported that pasture trodden when 25 mm high was much less productive than pasture trodden when up to 127 mm high.

Total herbage loss by treading at Day 4 was 50% in short and 44% in tall treatments (Table 5.7). For the first 49 day period. The reduction of 26 kg DM ha^{-1} day^{-1} (or 36%) of total herbage in the heavy trodden short compared to the untrodden short treatment, and 27 kg ha^{-1} day^{-1} (or 27%) in the heavy trodden tall compared to the untrodden tall treatments (Table 5.7) clearly shows the major effect of treading. For the same period, a reduction of 11 kg DM ha^{-1} day^{-1} (or 15%) in the light trodden short treatment compared to the untrodden short treatment, and 21 kg DM ha^{-1} day^{-1} (21%) in light trodden tall compared to untrodden tall treatment suggests that, under light treading, short pasture can recover quickly compared to tall pasture. For the total herbage mass of Day 4 and Day 18, the reduction of 22 kg DM ha^{-1} day^{-1} in trodden compared to untrodden treatments, and of 24 kg DM ha^{-1} day^{-1} in short compared to tall treatments (Table 5.7) shows the effect of both treading and canopy height treatments. Such a reduction in early spring pasture growth can have a significant impact on cattle performance since this is a time when the supply of forage is at a premium (Sheath and Boom, 1997).

The use of herbage mass measurements as a tool for monitoring treading damage by grazing animals is often suggested. The subsequent herbage accumulation may vary depending on the intensity of animal stocking. In this experiment for the total average herbage mass of Days 4 and 49 after treading, heavy treading increased losses by 15% compared to light treading (Table 5.7). For the highest treading intensity of 119 sheep/ha, Brown (1968) observed 40-50% less net herbage accumulation in spring. But when trodden by sheep on a defoliated ryegrass white clover mixed pasture, Curll and Wilkins (1983) observed losses of 4% and 10% net herbage accumulation rate at low stocking rate (25 sheep ha^{-1}) and 10% at medium stocking rate (50 sheep ha^{-1}) respectively.

A reduction of 56% ryegrass herbage dry matter in the trodden short canopy height was associated with 54% lower tiller density from that in untrodden short canopy height treatments at Day 4 after treading (Table 5.7 and 5.8). Similarly, a reduction of 53% ryegrass herbage dry matter in the trodden tall treatment was associated with 41% lower tiller density from those in the untrodden tall treatment. Thus, it is clear that the amount of herbage dry matter produced in these pastures is more related with the tiller population density than the tiller weight.

During the regrowth period of 49 days, the herbage accumulation rate of ryegrass was increased by 11 kg DM ha^{-1} day^{-1} (or 39%) in heavy trodden, 6 kg DM ha^{-1} day^{-1} (or 27%) in light trodden treatments compared to 17 kg DM ha^{-1} day^{-1} in untrodden treatments. These increases in herbage accumulation rate in trodden treatments were mainly due to the increase in replacement tillers (Table 5.8) and full recovery of leaf area per tiller of ryegrass (Table 5.11).

For the herbage mass of 'other species' except ryegrass, a reduction of 61% in trodden short and 41% in trodden tall treatments was associated with 64% and 60% lower tiller density respectively from those in untrodden short and tall treatments at Day 4 after treading. The reduction of 33% herbage dry matter of 'other species' in trodden short and 12% in trodden tall treatments at day 49 was associated with 14% and 16% lower tiller density respectively to those in untrodden short and tall treatments.

A lower herbage accumulation rate of 8 kg DM ha^{-1} day^{-1} (or 33%) of 'other species' in heavy trodden, compared with 23 kg DM ha^{-1} day^{-1} in untrodden treatments from Day 4 to Day 49 period (Table 5.9) suggests slow recovery of 'other species' in heavy trodden treatments. For the same period, the increase in total herbage accumulation rate of 4 kg DM ha^{-1} day^{-1} (or 10%) in heavy trodden and 7 kg DM ha^{-1} day^{-1} (or 17%) in light trodden treatments than that of 42 kg DM ha^{-1} in untrodden treatments was mainly due to the increase of ryegrass component. These data demonstrate faster recovery of ryegrass than 'other species' in the trodden treatments which contributed to higher pasture growth.

The decline in residual herbage mass and associated decline in tiller density, was the immediate effect of cattle treading. The loss in herbage accumulation was mainly due to the loss of tillers (Table 5.8). A reduction in tiller density and yield in a mixture of subterranean clover and annual ryegrass pasture by sheep treading was reported previously by Carter and Sivalingam (1977). For the first recovery period of 49 Days after treading, the loss of average herbage dry matter of 25% from both light and heavy trodden treatments is associated with loss in tillers of 29% compared to untrodden treatments (Table 5.8), suggesting one major cause of the loss of herbage productivity was reduction in tiller density. For the same period, an increase of 15% in average tiller number of both light and heavy trodden short treatments compared to that of light and heavy trodden tall treatments was able to make up the earlier deficit in herbage accumulation due to canopy height differences.

Total herbage mass was reduced in both short and tall canopy height treatments as a result of treading, and the interaction of canopy height and treading was significant for the reduced herbage dry matter (Table 5.7). The interaction of canopy height and treading treatment effect on total pasture mass appeared to be mainly due to the ryegrass component rather than that of 'other species'. This is likely to be due to smaller tiller size and lower contribution to total herbage mass of the non-ryegrass component of the sward. Similarly, the effect of canopy height treatment on the yield of ryegrass lasted longer than on 'other species'.

In this experiment, weight of both leaf and stem of ryegrass tillers decreased following treading (Table 5.10). Leaf area per tiller of ryegrass was also reduced in trodden compared to untrodden treatments (Table 5.11). The reduced leaf weight, pseudo-stem weight and leaf area in trodden treatments at Day 4 after treading clearly indicates the effect of hoof action on surviving tillers. The initial loss in tiller weight, leaf area, and tiller number of ryegrass due to treading had disappeared at Day 49, and the weight of individual tillers was actually greater in trodden than untrodden treatments at Day 86, suggesting a compensatory growth response to treading damage (Figure 5.8). The loss in initial weight of ryegrass tillers in the present experiment contrasts with observation in experiment 2 that treading did not affect the weight of ryegrass tillers over a 35 day regrowth period. The differences in weight and leaf area per tiller of ryegrass between short and tall canopies disappeared by Day 49. These results were in line with the observation of Bircham and Hodgson (1983) that the response of a ryegrass sward to different intensities of defoliation can involve changes in individual tiller growth.

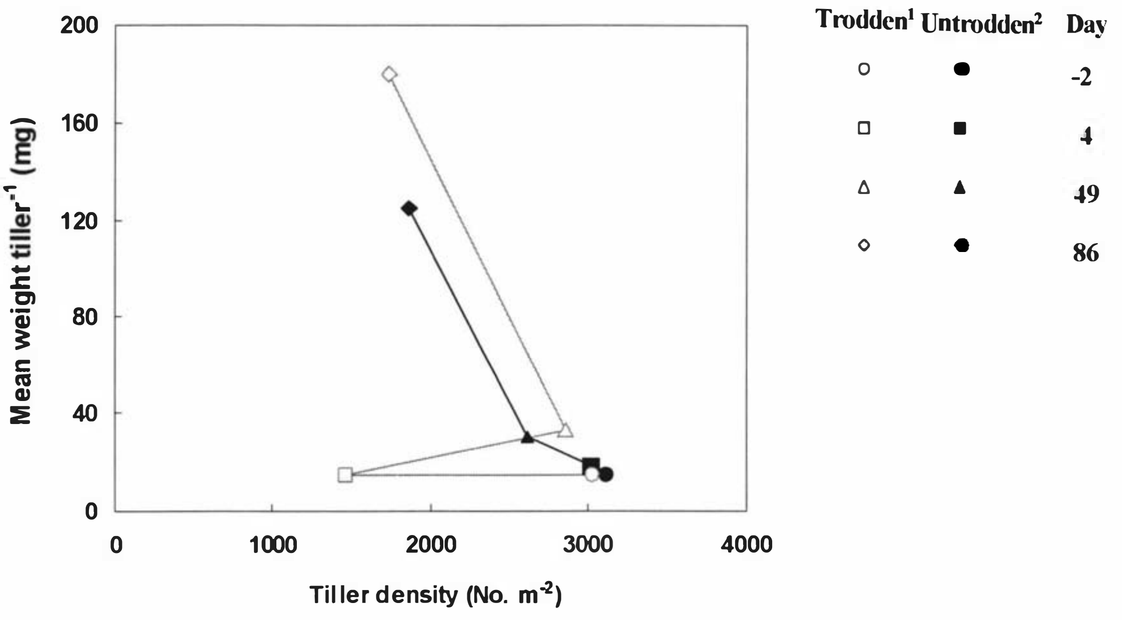

Figure 5.8 Relationships between mean weight per tiller and tiller density of ryegrass from trodden and untrodden treatments observed two days before treading (-2) and at Days 4, 49 and 86 after treading.

[1]Data from both short and tall canopy height untrodden treatments were pooled
[2]Data from light and heavy treading of both short and tall canopy height treatments were pooled.

The weight of individual tillers was unaffected by treading when measured at Day 35 after treading (Table 5.6), but the effect of initial differences in canopy height on the weight of tillers lasted longer than the effect of treading.

In this work, increase in both leaf and stem of ryegrass tillers in trodden treatments contributed to the increased weight of tillers during regrowth Period 2 (Table 5.7). The greater weight of stem relative reflects the pre-flowering stem elongation of the ryegrass plants which contributed to larger tiller size during regrowth Period 2.

Leaf extension rate plays a central role in tiller growth because of its direct influence on leaf size, tiller density and herbage mass. The rates of leaf extension of ryegrass during regrowth Period 1 and the second half of regrowth Period 2 were similar in all treatments (Figure 5.4) suggesting that treading impacts on leaf extension rates are not always immediate. The increase in leaf and pseudostem elongation rates during regrowth Period 1 in both trodden and untrodden treatments could have been influenced by the seasonal increase in temperature.

Evidence of greater leaf and stem elongation rates on trodden than untrodden treatments in period 2 (Table 3.4) indicate that treading damage can enhance tiller size in the long term. Open spaces created by treading in mid August may have contributed to a better light environment for surviving tillers.

The maximum leaf extension rates measured in this field study were almost double with those in other field studies in the UK reported by Thomas and Norris (1979) and in Australia by Kemp *et al.* (1989) but were less than those measured by Parsons and Robson (1980). The latter grew their plants in a glasshouse that was heated whenever temperatures declined to -2° C. In contrast, plants in the field were subject to frequent severe freezing that may have caused invisible injury and reduced their potential for leaf growth.

In a time sequence after treading, leaf regrowth in established plants assumes the highest priority, as evidenced by immediate extension of leaves in all plants. This was followed by commencement of daughter tiller initiation. For all treatments, the average rates of leaf extension of ryegrass were greatest during the second half of regrowth Period 1, and first half of regrowth Period 2 (Figure 5.4). The relatively high rates of leaf extension recorded at these times are probably a reflection of greater potential for leaf extension of ryegrass associated with reproductive development (Peacock, 1975). The maximum leaf extension rates of ryegrass were reached earlier than those of stem extension rates (Figure 5.4 and 5.5). Thus, greater average rates of stem extension and the decrease in the average rates of leaf extension during the second half of regrowth

Period 2 might have been associated with the seed head development of the tiller. Other reasons could be moisture stress and increase in temperature (Korte and Chu, 1983). Further study is needed to clarify the effect of treading stresses on the flower and seed head of reproductive tillers.

At first glance, it appears surprising to find notable differences for leaf and pseudo-stem extension rate between trodden and untrodden treatments in Period 2, given that treading occurred two months previously. The increase in leaf and pseudo-stem might have been influenced by an initial increase in area of open spaces created by treading. Hoof indentations can remain evident 3 years after a treading event (Davies and Armstrong, 1986) and so might also affect rate of leaf and stem extension. Similarly, results in this experiment have shown associated increases in the weight of leaf and stem of the mother tillers, and the weight of daughter tillers in trodden plots. potential

The average number of ryegrass leaves and new tiller developed per tiller per day between the treatments during the period Days 5 to 35 after treading ranged from 0.14 to 0.21 and from 0.07 to 0.10 respectively (Table 5.15). Davies (1974) showed that leaf extension (leaf appearance rate through intact sheath tubes) was reduced only when two or more whole lamina per tiller were removed. However, in this present experiment, similar leaf appearance rates between treading and canopy height treatments during regrowth Period 1 suggests that reducing canopy height of ryegrass by up to 4 cm may not affect leaf appearance rate.

Brock and Hay (1993) have argued that it is beneficial to maintain a hard defoliation regime in spring in order to establish a high tiller population density for summer. The rapid increase in the daughter tillers in trodden plots during 18 days period after treading (Figure 5.6) suggests that the appeared daughter tillers other than from the marked parent tiller could have contributed by a large number of buried ryegrass tillers due to treading. However, results indicate that the major way in which ryegrass recovered in trodden plots was mainly due appearance of new daughter tillers.

It is important that tillers assume a high priority in trodden plots during regrowth, since initiation of tillers and leaf growth increases pasture cover. Results indicate that seedling recruitment after treading offers an effective strategy to maintain ryegrass in the sward of mixed grasses (Table 5.8). Results also showed that for at least 5 weeks period after treading, the appearance of leaves and tillers per tiller of ryegrass were not affected by treading and canopy height treatments, although there was an interaction between these treatments. In trodden pastures, surviving tillers might have received more light, and soils may have become warmer compared to tillers and soils of untrodden pasture.

Ryegrass tillers in untrodden plots were potent enough to develop leaves and tillers, and tiller population density in these plots could have maintained mainly due to natural thinning process. Thus the increase in tillers to fill the gaps in trodden plots could have mainly developed from buried tillers and the seeds or plant parts under the soil surface. Ryegrass follows a seasonal pattern of tillering in response to light regimes (Mitchell, 1953) and changing temperature (Hunt and Field, 1978).

It is shown that the rates at which potential tiller sites occupied by growing tillers for ryegrass (site filling) in these pastures are ranged from 0.42 to 0.55 (Table 5.15). These values were below than the 0.693, the tillering potential of perennial ryegrass in terms of site filling tillers per tiller per leaf appearance interval observed by Neuteboom and Lantinga (1989).

In the glass house, it was observed that some of the buried ryegrass tillers in cores from trodden treatments gave birth to new tillers. It was an important observation to note that buried ryegrass tillers showed potential to give rise to new tillers and these tillers contributed to recover tiller population density.

Similar ryegrass tiller appearance rate after week three between trodden and untrodden treatments shows faster recovery strategy of ryegrass pasture as in earlier findings (Chapter 4). Data collected in the current study help to explain how tillers lost during treading damage are replaced.

The average new tiller appearance rate of 48 m^{-2} day^{-1} in trodden treatments during the first 18 days after treading in this study (Figure 5.6) was greater than that of 28 tillers m^{-2} day^{-1} in pastures grazed at low to high stocking densities in winter observed by (L'Huillier, 1987). This greater tiller appearance rate in trodden compared to that of 14 tiller m^{-2} day^{-1} in untrodden treatments during the same period was probably due to the emergence of more buried tillers by hoof action. It is clear that these new tillers can contribute to fill the position of the lost tillers during early regrowth.

5.4.3 Growth of established and new tillers

The weight of established tillers, and the emergence and growth of newly emerged tillers in the glasshouse were similar between heavy and light treading suggesting that both of these treatments had a similar impact. The increased weight of individual established tillers of ryegrass from trodden treatments at 65 days' growth in the glasshouse environment indicate that treading can enhance the tiller growth of ryegrass, which could be the function of hoof action or created open spaces (Figure 5.7).

In this experiment, the greater increase of new tillers in trodden treatments for the first 18 days after treading brought the mean density of new tillers per unit area to a value characteristic of the damage regime, but some new tillers appeared independently with that of starting tiller density. The increase in the appearance rate of new tillers in the trodden treatments and the interaction of treading and cutting height for this increase has occurred at a time when weights of new tillers were similar between treatments.

The trend to both an increased weight of new tillers and a greater tiller number in the trodden treatments during the initial period of 18 days was similar. Initial new tiller number in the untrodden tall canopy height treatment was low compared to trodden short and tall canopy height treatments, but the weight of tillers was similar. In the untrodden short canopy height treatment, the low number of new tillers produced was associated with low tiller weight and these tillers behaved differently than other treatments.

5.5. CONCLUSIONS

Reduction in cutting height reduced herbage dry matter yield and tiller size but did not reduce herbage accumulation rate. Leaf, pseudostem and stem extension rate of ryegrass was not affected by cutting height.

The major effect of treading was on tiller population density. Treading severely reduced tiller population density for ryegrass and other grasses. The weight of surviving tillers was little affected. Differences in total herbage mass between heavy trodden and untrodden treatments declined at Day 49 and 52, but disappeared when measured at Day 86 after treading. The difference in tiller density between treatments disappeared earlier than the difference in herbage mass.

In these pastures, treading had sealed up larger diameter pore spaces of soil but these processes did not disturb ryegrass tiller growth and would have not disturb tiller growth of other grasses as well. Besides pasture growth, there could be other consequent effects of treading on plants and soils such as in botanical composition and soil physical properties in the long term.

Ryegrass was less seriously affected by treading than other species. On a practical note the results show that at least a 7 week ungrazed recovery period is necessary for full recovery after treading damage.

The overall effect on subsequent herbage production was largely determined by the rate of development of replacement tillers. The evidence from both field and glass house studies suggests that initial tiller appearance and tiller growth which give rise to LAI, and thus pasture cover underlies the recovery strategy in response to treading. The differences appear to be linked with the environmental factor that new tillers of ryegrass in the trodden cores appeared faster in the glass house than in field conditions. The appearance of new tillers in short canopy height treatments would have improved the quality of the pasture.

CHAPTER 6

GENERAL DISCUSSION AND CONCLUSIONS

6.1. PASTURE PRODUCTION

The primary aim of this study was to identify the causes of loss of pasture productivity by cattle treading, and to identify the mechanisms of subsequent pasture recovery following treading. Many authors (Brown, 1968; Cluzeau *et al.*, 1992; Ledgard *et al.*, 1996; Sheath and Carlson, 1998; Drewry and Paton, 2000b) have reported that animal treading can cause decreases in pasture production. Results here from both hill country and dairy pasture have obviously confirmed this effect of treading.

Results have shown a substantial reduction in residual herbage mass immediately after treading on moist and wet soil. Damage was high in the areas where cattle were stocked for longer periods or trodden by a high density of stock. The reduction in pasture production due to treading was greatest on tracks of hill pasture contour classes and in high-damaged areas of intensive dairy pastures. This was mainly due to multiple hoof pressure. Overall, the impact of treading was variable, but differences in subsequent herbage accumulation rates reported were frequently not significant.

In experiment 1, one treatment was designed such that cattle were grazed at a heavy stocking intensity only once when the soil was wet in winter. In the second experiment, cattle were used for repeated treading with heavy stocking intensity six times over nine months. Similarly, stock was maintained for longer than normal practice in paddocks to create high-damaged areas in Experiment 2. Other treatments were designed in such a way that the effective stock densities used were similar to those which are found in normal farm management conditions.

The impact of the grazing animal can be separated into two components: defoliation and physical damage from treading. These effects are involved in a complex set of interactions which translate into reduction in herbage yield (Figure 6.1) and the succeeding recovery response (Figure 6.2).

Eating and treading are different impacts of the grazing animal in grasslands. The eating action involves biting and breaking off the plant parts causing defoliation and some tiller loss. Treading action involves physical damage of both plants and soils by the hooves of grazing animals. Physical damage of plants for any reason causes loss in pasture cover.

6.2. PASTURE COVER

Ecologists and physiologists, for example, Monsi and Saeki (1953) have recognised the role of canopy structure in intercepting the available light. Results reported in Chapter 3 and 4 showed that the main effect of treading was reduction in LAI which in turn led to losses in pasture production. The pasture cover loss is more substantial in winter, in repeatedly trodden treatments and at high stocking rates (Moorefield and Hopkins, 1951).

Good pasture growth requires an adequate and substantial proportion of leaves produced to remain in the sward to contribute to photosynthesis (Parsons and Johnson, 1986). Pasture cover and leaf area index (LAI) decreased with the increase in treading damage (Figure 6.1). The greater the loss in pasture cover the longer the pasture took to recover.

Results showed that a ground cover percentage of 70-75% (Figure 3.3, Table 4.5) was a critical value, below which loss in herbage mass in spring after treading increased markedly. A similar value was proposed for runoff and soil loss for grazed land on the southern tablelands of New South Wales (Costin, 1980). In present studies, lower percentage of pasture cover following treading was attributed to decreased plant density.

6.3. TILLER DYNAMICS AND REGROWTH

The main effect of treading damage was a reduction in the tiller population (Figure 6.1). The reduction in tiller density was due to direct plant damage, and plant burial (Chapter 4 and 5). It is clear from results that the lower leaf area index in high-damaged areas was a consequence of both lower tiller number (Table 4.11 & 5.8) and lower leaf area per tiller (Table 5.11).

The relationship of the regrowth parameters which contribute to pasture production is presented in Figure 6.2. Lower tiller population density of ryegrass resulting from treading resulted in a much greater tiller appearance rate. Davies (1971) and Robson, (1973) have demonstrated that the rate of appearance of new tillers increases until the proportion of incident radiation absorbed by the leaves approaches maximum.

The tiller losses to treading with wet soil were greater than losses reported under dry conditions. Losses of ryegrass plants or tillers due to pulling have often been associated with cattle grazing in summer-autumn when the soil is dry (Hughes and Jackson, 1974;

Thom *et al.*, 1986a). During summer, a removal of up to 11% ryegrass tiller density due to grazing cattle was observed by Bahmani *et al.* (2001), and these authors also reported that pulling levels increased with the application of nitrogen fertiliser but irrigation treatments had no effect.

Experiment 3 separated the effects of grazing from treading by imposing cutting treatments in a factorial design (Chapter 5). About 60% tiller loss was found in trodden treatments compared to untrodden treatments (Table 5.8). The loss of tillers due to treading was one of the reasons for the disappearance of the size-density relationship (Chapter 4 and 5). The remaining 40% tillers in the field after treading were able to recover mainly by producing basal daughter tillers, and recovery was mainly related to the faster growth of ryegrass tillers (Figure 6.2).

The increase in ryegrass tillers in trodden plots during the regrowth period in the present studies (Experiment 2 and 3) demonstrates both the regenerative potential of ryegrass and the favourable environment for tillering created by opening up the pasture (Figure 6.2). Data from these trials show that the promotion of tillering in the trodden treatments compensated for the direct effects of treading. Data is given elsewhere (Table 4.11 & 5.8). A quicker recovery of treading damaged areas from actively growing plants was also observed previously by Warren *et al.* (1986a). However, except in severely damaged areas, fast recovery of pasture in trodden plots was attributed to the similar herbage accumulation rates.

The increase in tiller population density in short relative to tall canopy height treatments during the recovery period indicate that short residual pasture height provided a better tillering environment. Changes in the amount and quality of light penetrating to tiller bases under the contrasting defoliation patterns and consequent effects on tiller initiation and appearance can cause the differences in tiller population density (Mitchell, 1953; Langer, 1963). The most important aspect of light quality which determine plant growth is the amount of light in the photosynthetically active region of the spectrum (McCree, 1972a). The tiller density and the light potential available to these tillers would have influenced tillering and recovery.

The effect of treading on individual tillers was minimal and could not explain the losses of residual herbage mass. Edmond (1963) observed increased soil bulk density in trodden plots and raised the possibility that reduced soil permeability and aeration may negatively impact on plant growth. An increase in the weight of existing ryegrass tillers and daughter tillers produced after treading was mainly due to over compensation of tiller production. The greater tiller size in trodden against untrodden treatments was attributed to greater leaf, pseudostem and stem extension rates.

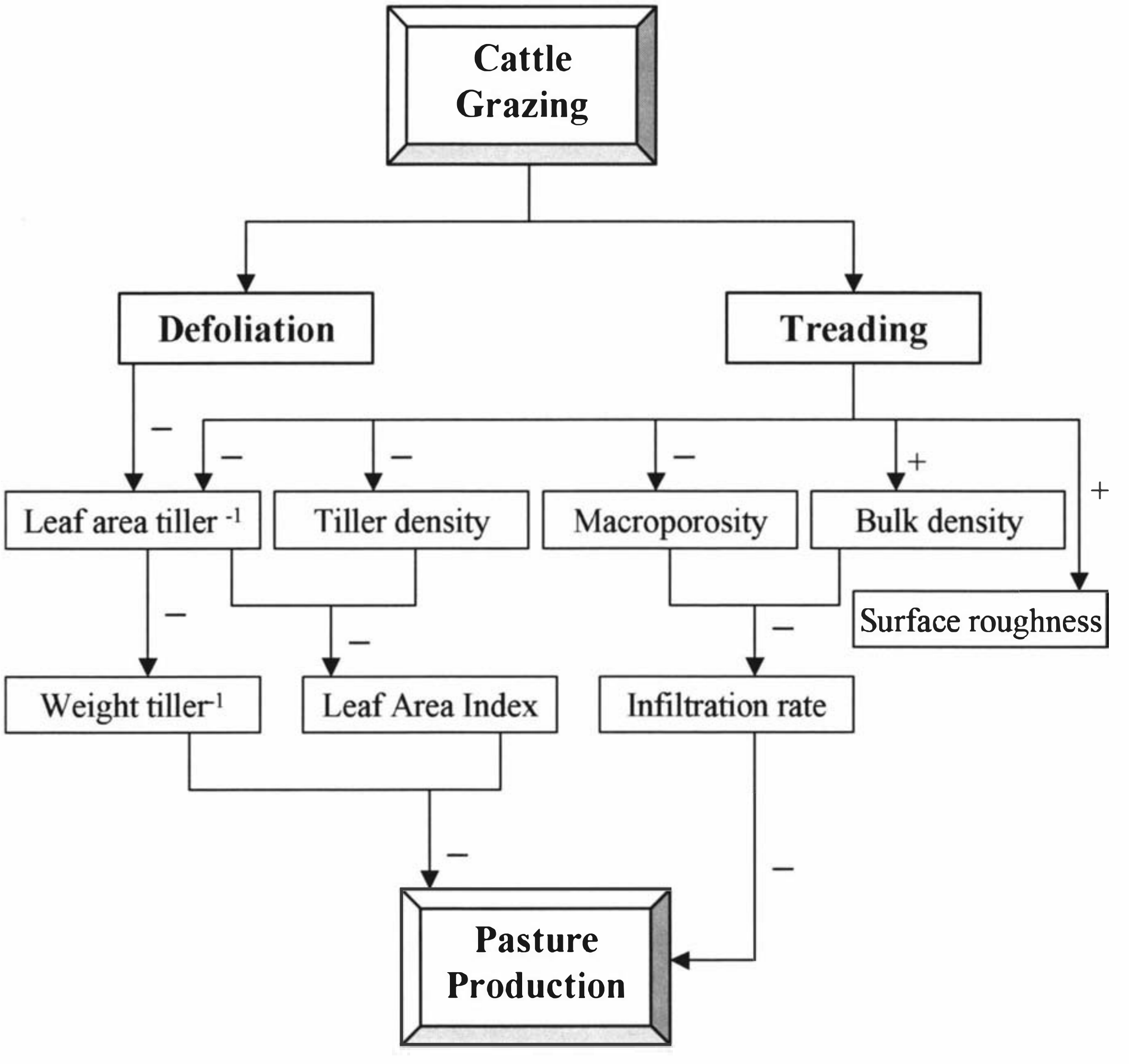

Figure 6.1 Relationship between effects of grazing cattle on soil physical properties and sward structural characteristics of ryegrass.

Note: Positive (+) or negative (-) impact of treading on soil physical properties and sward characteristics

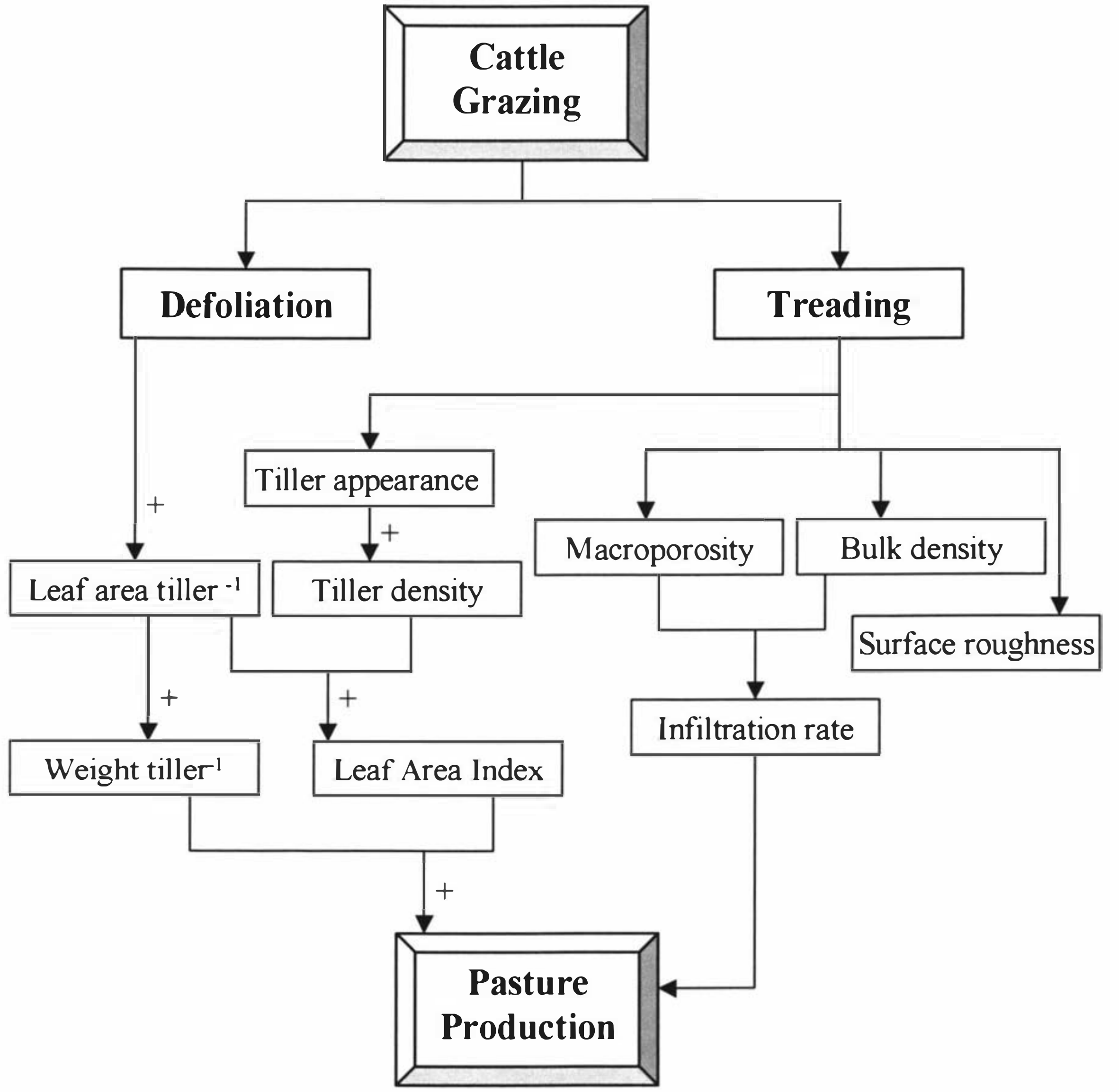

Figure 6.2 Recovery trend of ryegrass pastures after grazing.

Note: Positive (+) impact of treading on sward characteristics during recovery period

6.5. SOIL IMPACTS

Treading effects on soil physical properties were noticeable at the soil surface (Figure 6.1). The soil physical properties that depend on pore continuity, such as macroporosity and infiltration were sensitive to treading and the effects were greater in high-damaged areas compared to low to medium-damaged areas.

The changes in soil physical properties due to treading could affect the growth of pasture in the long term. Slow pasture growth in high-damaged areas of dairy pasture is likely to be cumulative effect of both pasture and soil damage. The hill pasture tracks would have had slow growth because of both lost tillers and soil damage, causing anaerobic soil conditions (Gradwell, 1965; Climo and Richardson, 1984).

The increase in soil moisture content in high-damaged areas after treading could be explained by ponded rain water in pugged hoof marks. Reduced cover with lower tiller population density in these areas would also have reduced evapo-transpiration.

6.6. SPECIES COMPOSITION

Grazing animals can change botanical composition (Milton *et al.*, 1994) and pasture species can differ in their reaction to treading. But in these studies, treading had little effect on botanical composition. The dominant ryegrass tillers were less susceptible to treading damage compared to other grass species and could recover quickly. Bates (1935 and 1951) observed that ryegrass was especially prominent wherever animal treading was heavy.

Browntop development can be influenced by tillering and rhizome production (Levy, 1924), and the build up of its large buried seed populations in soil (Harris, 1978), aiding the invasion of surrounding pasture. Rapid colonising ability of white clover in bare soil areas may also be important in regeneration and change in botanical composition. However, the browntop-containing "other grasses" component and white clover did not develop during the regrowth period in the current studies. Grubb (1977) pointed the importance of regeneration, which influences the ability of plants to take advantage of niches created within a pasture.

Overall, it can be concluded that grass dominant pastures, with little clover present, encourage ingress of ryegrass after treading especially in low- to medium-damaged areas. In the long-term, this may result in marked botanical change, although this was not apparent during these study periods. Both field and glass house studies (Chapter 5) showed that ryegrass-dominant pastures recovering from treading damage are reliant on the emergence and growth of new tillers.

6.7. MANAGEMENT STRATEGIES

The reduction of residual herbage mass to less than 500 kg ha^{-1} by grazing and treading activity in high-damaged areas slowed regrowth, and these pastures took longer to recover after treading than less damaged pastures. Damaged treatments with more than 700 kg ha^{-1} residual herbage mass, recovered within a 7 weeks regrowth period (Chapter 5). Relative to high-damaged areas, higher residual herbage mass in low- and medium-damaged areas would have caused faster plant regrowth. But total pasture production from these treatment plots would have been reduced compared to pastures with higher residual herbage mass. Bircham and Hodgson (1984) showed that on a grazed area with less than 1000 kg DM ha^{-1} herbage mass, pasture growth was seriously affected.

The data show that dairy pastures with ryegrass can withstand treading damage with a rotational grazing management system and a moderate stocking density. The relative tolerance of ryegrass under heavily trodden treatments and its recovery growth after treading in this study were similar to other field measurements (Edmond, 1963; Vickery, 1972).

It is clear that the effects of treading are an important factor of grazing management, since whenever hill land beef pastures or flat dairy pastures were trodden at a high stocking density, the recovery, in terms of production, was reduced. Furthermore, the combined impacts of treading and grazing proved even more detrimental to subsequent pasture recovery. It could be argued that by reducing stocking density and/or grazing time, the detrimental effect of treading will be lessened.

On a practical level, reduction in animal load per unit area of pasture to minimise the losses in tiller density due to treading by grazing cattle when the soil is wet and to reduce length of recovery would be helpful. On pastures of moist to wet soils, where a single treading occurs with no serious damage to soil structure but with the losses in tiller population density and herbage dry matter, management options of choosing right grass species such as perennial ryegrass may be effective to restore the losses caused by treading. Also to ensure sustained pasture productivity, especially to counter severe treading damage to pasture cover and to achieve faster regrowth after damage, it is important that management strategy should be focused on species which are persistent and fast growing. This will require the species to be chosen carefully for each farm, and the right ones to be selected to cope with wetter and drier than average years.

Further study is required on the effect of treading on interrelationships between soil and pasture growth in the long term, especially the root growth environment and its influence on tiller growth. Also information on what attributes cause persistence of different species and their sustainability under treading and their length of recovery in treading-sensitive areas and/or soils would be helpful in making farm management decisions. Light interception and photosynthetic activity of pasture plants between different canopy structure in treading disturbed areas will provide better knowledge in understanding pasture regrowth.

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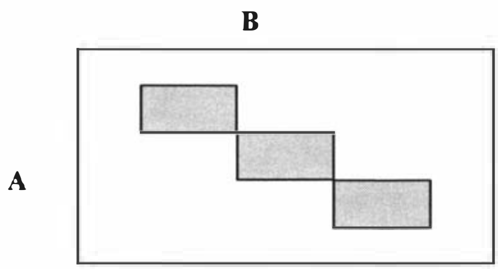
APPENDICES

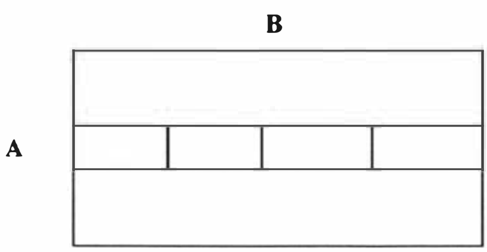
Appendix 3.1 The guide to read the data in Appendices 3.2 and 3.3: (a) diagonal shaded data in the table represents the stability of the species or species group contributing cover, (b) unshaded data in rows represents the loss of species or species group from the previous measurement (left-hand column) (c) unshaded column data represents the cover gained from different species or species group relative to those present at the earlier date (rows).

(a) No Change



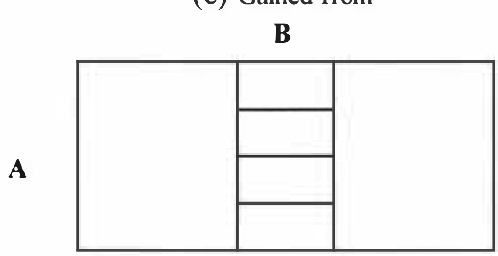
(a) Values in the highlighted diagonal data represents the stability of the species or species group data from measurement date A to date B.

(b) Lost from



(b) Unshaded values in rows represents the species or species group gained at measurement date B relative to date A.

(c) Gained from



(c) Unshaded values in columns represent the species or species group gained at measurement date B relative to the different species that were present at date A.

Appendix 3.2 Count of change in species classification between July (pre-treading) and September (post-treading) for treatments and contour classes. Rows represents the counts of species in July and columns represent the counts of species in September.

Trt[1].	Sept / July	Track						Tot.	Slope						Tot.	Grand
		Bare	HFRG	Leg.	LFTG	Lol	Ots.	July	Bare	HFRG	Leg.	LFTG	Lol	Ots.	July	Total
A	Bare	1[2]	1	1				3	12	4	2	1		1	20	23
	HFRG	1	16	1	3	7	1	29	7	47	6	14	7	5	86	115
	Leg.		1	2	1	1	1	6	3	11	12	11	3	5	45	51
	LFTG	1						1	13	16	7	39	7	1	83	84
	Lol	2	8	4	3	30	3	50	9	13	2	9	19	4	56	106
	Ots.		1			1	1	3	2	1	4	3		8	18	21
Total Sept		5	27	8	7	39	6	92	46	92	33	77	36	24	308	400
B	Bare	9	5	2	2	4		22	25	12	7	15	8	3	70	92
	HFRG	5	11	3	3	4	1	27	7	16	2	4	2	3	34	61
	Leg.	2	2	6		4		14	9	2	7	5	3	2	28	42
	LFTG	2	4		2	1		9	14	11	3	38	2	5	73	82
	Lol	9	9	4	6	25	1	54	3	3	2	8	17	2	35	89
	Oths.		1		1		0	2	5	8	4	2	3	10	32	34
Total Sept		27	32	15	14	38	2	128	63	52	25	72	35	25	272	400
C	Bare	2	1	1	2	2		8	18		5	16	4	2	45	53
	HFRG		13		1	4	1	19	8	26	4	8	3	6	55	74
	Leg.	1	1	2	2	3	1	10	4	5	11	10	4	2	36	46
	LFTG	2	1	3	3			9	24	18	9	55	15	11	132	141
	Lol	5	3	1	4	24	1	38	5	3	3	4	11		26	64
	Oths.		1	1			0	2	5	1	2	2		10	20	22
Total Sept		10	20	8	12	33	3	86	64	53	34	95	37	31	314	400
D	Bare	7			1		1	9	10		1	7	1	3	22	31
	HFRG	14	6		2	1	3	26	26	8	2	4	2	6	48	74
	Leg.	6		2	4	2	1	15	24		3	5	4	3	39	54
	LFTG	8	3	3	4	3	2	23	53	8	5	26	11	11	114	137
	Lol	25	1	1	2	12	2	43	9	1	4	3	7		24	67
	Oths.	3		1	1		0	5	20	1	1	4	1	5	32	37
Total Sept		63	10	7	14	18	9	121	142	18	16	49	26	28	279	400
E	Bare	20	3	2	1		1	27	36	4	1	4	4	1	50	77
	HFRG	15	10	1	1	3		30	33	21	2	6	5	5	72	102
	Leg.	3		0		1		4	5	2	4	7	3	2	23	27
	LFTG	7	2	2	2	3	1	17	31	13	3	39	2	4	92	109
	Lol	9	3		1	25	1	39	7	2	1	5	7		22	61
	Oths.	1			1		1	3	5	3		3	1	9	21	24
Total Sept		55	18	5	6	32	4	120	117	45	11	64	22	21	280	400

[1]Refer to Table 3.1 for definition of treatment codes.
[2]On tracks in treatment A, 1 pin hit on bare ground in July was still on bare ground in September. There had been 3 hits on bare ground in July (row subtotal) whereas there were 5 hits in September (Column subtotal).
Numbers in the shaded diagonal represent no change at a particular site. Numbers in unshaded areas represent a changed score of species at a pin site.

Appendix 3.3 Count of change in species classification between September (post-treading) to October (regrowth period) between treatments and contour classes. Rows represents the count of September and columns represent the count of October.

Trt.[1]	Oct	Track						Tot.	Slopes						Tot.	Grand
	Sept	Bare	HFRG	Leg.	LFTG	Lol	Ots.	July	Bare	HFRG	Leg.	LFTG	Lol	Ots.	July	Total
A	Bare			1	1	3		5	2	15	7	11	8	3	46	51
	HFRG	3	13	1	1	6	3	27	3	45	12	10	19	3	92	119
	Leg.		1	2		4	1	8		11	8	4	7	3	33	41
	LFTG		2	3		2		7	3	12	13	29	8	12	77	84
	Lol	1	12	4	1	21		39	1	14	1	5	14	1	36	75
	Oths.		1			2	3	6	1	6	2	5	4	6	24	30
Total Oct.		**4**	**29**	**11**	**3**	**38**	**7**	**92**	**10**	**103**	**43**	**64**	**60**	**28**	**308**	**400**
B	Bare	5	5	3	3	10	1	27	11	10	9	19	7	7	63	90
	HFRG	4	14	2	3	6	3	32	4	24	3	8	8	5	52	84
	Leg.	1	7	3	1	3		15	2	4	6	6	4	3	25	40
	LFTG		3	1	4	5	1	14	4	10	4	34	14	6	72	86
	Lol	3	7	3		25		38	1	11	5	4	13	1	35	73
	Ots.		1			1	0	2	1	3	6	1	4	10	25	27
Total Oct.		**13**	**37**	**12**	**11**	**50**	**5**	**128**	**23**	**62**	**33**	**72**	**50**	**32**	**272**	**400**
C	Bare	0	1	1	3	4	1	10	3	14	8	24	10	5	64	74
	HFRG	1	9	2	2	5	1	20	3	24	8	10	5	3	53	73
	Leg.		3	4	1			8	1	7	12	5	7	2	34	42
	LFTG	1	4	3	2	1	1	12	5	13	14	44	10	9	95	107
	Lol	1	10	4	1	16	1	33	1	8	6	7	13	2	37	70
	Oths.					1	2	3	1	6	7	3		14	31	34
Total Oct.		**3**	**27**	**14**	**9**	**27**	**6**	**86**	**14**	**72**	**55**	**93**	**45**	**35**	**314**	**400**
D	Bare	10	14	3	11	21	4	63	29	24	18	36	24	11	142	205
	HFRG	3	3	2	1	1		10	2	6	1	2	6	1	18	28
	Leg.		1	3	1	2		7	3	3	5		4	1	16	23
	LFTG	1	1	3	5	4		14	3	5	4	28	7	2	49	63
	Lol	1	3	5		9		18	4	3	3	4	11	1	26	44
	Oths.	2	3	2		1	1	9	1	5	5	7	6	4	28	37
Total Oct.		**17**	**25**	**18**	**18**	**38**	**5**	**121**	**42**	**46**	**36**	**77**	**58**	**20**	**279**	**400**
E	Bare	19	15	1	7	11	2	55	35	23	11	17	18	13	117	172
	HFRG	1	9	1	4	3		18	2	20	5	7	8	3	45	63
	Leg.			4	1			5		4	4	2	1		11	16
	LFTG		1	1	2	1	1	6	3	3	11	35	5	7	64	70
	Lol		9	1	2	20		32	3	3		5	11		22	54
	Ots	1	1	1			1	4	2	4	3	1	6	5	21	25
Total Oct.		**21**	**35**	**9**	**16**	**35**	**4**	**120**	**45**	**57**	**34**	**67**	**49**	**28**	**280**	**400**

[1]Refer to Table 3.1 for definition of treatment codes.

Numbers in the shaded diagonal represent no change at a particular site. Numbers in unshaded areas represent a changed score of species at a pin site.

Appendix 3.4 Proportion of species classes (Stability Quotient) (a) bare ground, (b) ryegrass, (c) HFR grasses, (d) LFT grasses, (e) legumes and (f) other species (broadleaf weeds and dead material) at each of 400 first-hit-pin positions per treatment that did not change between measurement periods July-September and September-October.

Treatments	Species Classes					
	(a) Bare ground		(b) Ryegrass		(c) HFR grasses	
	Jul –Sep	Sep-Oct	Jul –Sep	Sep-Oct	Jul –Sep	Sep-Oct
A	0.61[ab]	0.04[b]	0.45	0.44	0.54	0.49
B	0.37[b]	0.17[ab]	0.45	0.50	0.45	0.45
C	0.38[b]	0.04[b]	0.56	0.41	0.56	0.44
D	0.54[ab]	0.19[ab]	0.27	0.46	0.16	0.32
E	0.74[a]	0.31[a]	0.54	0.58	0.30	0.46
sem	0.084	0.041	0.099	0.086	0.081	0.039
Significance	P = 0.09	*	ns	ns	ns	ns

Treatments	(d) LFT grasses		(e) Legumes		(f) Other species (weeds)	
	Jul –Sep	Sep-Oct	Jul –Sep	Sep-Oct	Jul –Sep	Sep-Oct
A	0.47	0.31	0.28	0.25	0.40	0.28
B	0.50	0.44	0.31	0.22	0.27	0.39
C	0.41	0.43	0.28	0.37	0.48	0.47
D	0.23	0.52	0.09	0.34	0.18	0.14
E	0.37	0.54	0.14	0.50	0.42	0.23
sem	0.059	0.065	0.099	0.074	0.139	0.075
Significance	ns	ns	ns	ns	ns	ns

sem = standard error of the least squares means, * = P < 0.05, ns = not significant

Data are from of each replication of the treatments shown in Appendices 3.2 and 3.3. For example: Stability Quotient of bare ground in Treatment A (July-September Appendix 3.2) - the unchanged values are (1 (track) + 12(slope))/ (3(total bare July track) + 20(Total bare July slope)) = 13/23 = 0.57 ≅ 0.61 which is the value that takes replicate data into account.

Appendix 3.5 Proportion of treatment all species or group of species at each of 400 first-hit-pin positions per treatment that did not change between measurement periods July-September and September-October.

Treat. No.	July-Sept	Sept-Oct
A	0.47[a]	0.36[b]
B	0.42[a]	0.38[b]
C	0.44[a]	0.36[b]
D	0.23[b]	0.29[c]
E	0.44[a]	0.42[a]
sem	0.049	0.008
Significance	P = 0.09	**

sem = standard error of the least squares means; ** denote $P < 0.01$ significant level

$\{(i \div j)\}$ = Stability Quotient

i = Stability value (Appendix 3.1, sum shaded values of each diagonal)

j = Total value of all rows within each treatment (shown at bottom of shaded diagonal).

Using Appendix 3.2,

For tracks, all the species on the diagonal = 1+16+2+0+30+1=50

Sept. $\Sigma = 92$

Stability quotient for Tracks = 50÷92 = 0.54

Similarly, stability quotient for Slopes = 0.44

Appendix 3.6 SAS output of the GENMOD analysis of change in species, groups of species and bare ground at specific positions between (a) July and September and (b) September and October for treatment and contour classes. Data in the highest order interaction term in the shaded areas represent the finding of interest. All earlier factors define the base model.

(a) July to September

The SAS System
The GENMOD Procedure, LR Statistics For Type 1 Analysis

Source	Deviance	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
Intercept	3203.1057						
trtno	3200.9653	4	141	0.47	0.7598	1.87	0.7600
contour	2866.5458	1	141	291.89	<.0001	291.89	<.0001
july	2529.1116	5	141	58.91	<.0001	294.53	<.0001
sept	2135.3305	5	141	68.74	<.0001	343.71	<.0001
trtno*contour	2117.6799	4	141	3.85	0.0053	15.41	0.0039
trtno*rep	2117.0815	5	141	0.10	0.9911	0.52	0.9913
trtno*july	1971.9828	20	141	6.33	<.0001	126.65	<.0001
trtno*sept	1716.4186	20	141	11.15	<.0001	223.07	<.0001
trtno*contour*rep	1705.8884	5	141	1.84	0.1091	9.19	0.1017
contour*july	1445.3301	5	141	45.49	<.0001	227.43	<.0001
contour*sept	1306.3950	5	141	24.25	<.0001	121.27	<.0001
trtno*rep*july	1213.8210	25	141	3.23	<.0001	80.80	<.0001
trtno*rep*sept	1159.6411	25	141	1.89	0.0109	47.29	0.0045
trtno*contour*july	1141.1732	20	141	0.81	0.7031	16.12	0.7092
trtno*contour*sept	1114.0334	20	141	1.18	0.2762	23.69	0.2563
july*sept	618.3089	25	141	17.31	<.0001	432.69	<.0001
trtno*july*sept	475.7407	100	141	1.24	0.1157	124.44	0.0494
contour*july*sept	456.6880	25	141	0.67	0.8828	16.63	0.8948
trtno*rep*july*sept	260.9926	125	141	1.37	0.0360	170.81	0.0041
trtn*contour*july*sept	0.0000	0	141	0.00	<.0001	0.00	<.0001

(b) September to October

Source	Deviance	Num DF	Den DF	F Value	Pr > F	Chi-Square	Pr > ChiSq
Intercept	2815.1612						
trtno	2814.5766	4	251	0.15	0.9639	0.59	0.9641
contour	2449.3475	1	251	368.98	<.0001	368.98	<.0001
sept	2054.9615	5	251	79.69	<.0001	398.44	<.0001
oct	1759.6122	5	251	59.68	<.0001	298.38	<.0001
trtno*contour	1739.9613	4	251	4.96	0.0007	19.85	0.0005
trtno*rep	1739.6995	5	251	0.05	0.9982	0.26	0.9983
trtno*sept	1484.0079	20	251	12.92	<.0001	258.32	<.0001
trtno*contour*rep	1478.2716	5	251	1.16	0.3299	5.80	0.3267
contour*sept	1339.3366	5	251	28.07	<.0001	140.36	<.0001
contour*oct	1231.7811	5	251	21.73	<.0001	108.66	<.0001
trtno*rep*sept	1177.6012	25	251	2.19	0.0013	54.74	0.0005
trtno*rep*oct	1004.9136	45	251	3.88	<.0001	174.46	<.0001
trtno*contour*sept	977.7739	20	251	1.37	0.1370	27.42	0.1239
trtno*contour*oct	957.1894	20	251	1.04	0.4158	20.80	0.4092
sept*oct	567.1520	25	251	15.76	<.0001	394.04	<.0001
trtno*sept*oct	450.8066	100	251	1.18	0.1587	117.54	0.1111
contour*sept*oct	411.5608	25	251	1.59	0.0417	39.65	0.0317
trtno*rep*sept*oct	0.0000	0	251	0.00	<.0001	0.00	<.0001
trtno*contour*sept*oct	0.0000	0	251	0.00	<.0001	0.0	<.0001