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**The Influence of Pastoral Fallow on Hill Country Pastures,
Emphasising White Clover Growth Behaviour**

**A thesis presented
in partial fulfilment of the requirements
for the degree of Doctor of Philosophy in Plant Science
at Massey University, New Zealand**

Zhongnan Nie

1997

DECLARATION

The studies presented in this thesis were completed by the author whilst a postgraduate student in the Department of Plant Science, Massey University, Palmerston North, New Zealand. This is all my own work and the views presented are mine alone. Any assistance received is acknowledged in the thesis. All references cited are included in the bibliography.

I certify that the substance of the thesis has not been already submitted for any degree and is not being currently submitted for any other degree. I certify that to the best of my knowledge any help received in preparing this thesis, and all sources used, have been acknowledged in this thesis.



Zhongnan Nie
PhD candidate



Dr. I. Valentine
Chief supervisor



Professor J. Hodgson
Co-supervisor



Dr. A. D. Mackay
Co-supervisor



Dr. D. J. Barker
Co-supervisor

June 1997

ABSTRACT

Appropriate pre-sowing methods for oversowing new plant germplasm and the presence of productive legume are of key importance to development of New Zealand hill country. A pastoral fallow, which involves not defoliating pasture for a period generally from spring to autumn, has profound influence on plant and soil, and creates a potentially favourable environment for introducing improved germplasm. A series of field and glasshouse experiments examined the response of pasture structure, soil properties and natural reseeding to pastoral fallow, and the post-fallowing effects on white clover (*Trifolium repens* L.) and pasture growth in moist North Island hill country, New Zealand.

Pastoral fallowing effectively reduced the plant population density and altered the structure of a hill sward. A seven-month (October - May) pastoral fallow dramatically decreased the densities of grass tillers by 72%, white clover growing points by 87% and other species by 87%. The decline in tiller density by pastoral fallow was enhanced on a shady, south facing aspect. Root growth and distribution was altered by pastoral fallowing and there was significantly less root biomass at 0 - 50 mm depth of soil in the fallowed than the grazed sward. Decreased plant density during pastoral fallowing was attributed to above-ground biomass accumulation which altered sward structure, leading to inter-plant competition and mortality by self-thinning and completion of the life circle of some matured plants.

Pastoral fallowing significantly improved soil physical properties. Compared with the grazed treatment, pastoral fallow increased soil air permeability at 500 mm tension by 38%, saturated hydraulic conductivity by 26%, unsaturated hydraulic conductivity at 20 mm tension by 56% and soil moisture by 10 - 15%, and reduced soil bulk density by 11% at the end of an October - May pastoral fallow. Pastoral fallow had little effect on the concentration of most

nutrients in soil both at the end of fallowing and two to three years after fallowing.

A spring - autumn pastoral fallow increased the viable grass, legume and weed seed population by 51-160%, compared with the grazed control. The variation in viable seed population during the fallow followed a predictable pattern, which could be used to manipulate natural reseeding in practice. Regression analysis revealed that the patterns of cumulative seedling appearance followed a modified negative exponential function. Partial differentiation of this function derived a germination rate curve on which a two-pool (rapidly germinable pool and base pool) model was developed to quantitatively describe the seed dynamics of soil viable seed reserves.

Short-duration (partial) pastoral fallow had a marked effect on plant population density and natural reseeding. Pastoral fallows starting from December, January and February or March with nitrogen addition and ending in June considerably reduced plant population density. Most partial pastoral fallows also considerably reduced viable seed population of all plant species, except for December to June fallow which had a higher viable grass seed population than the grazed sward.

Pastoral fallowing increased dispersion of white clover stolons by internode elongation. At the conclusion of a pastoral fallow, the clover stolons initiated branching, and grasses initiated tillering. Their growth and competition resulted in a greater grass growth rate in the first two years after fallowing, and a greater white clover yield and content with an increase in clover patch density and size 3 - 4 years post-fallowing, compared with the grazed pastures.

Key words: hill pasture, pastoral fallow, plant population density, soil physical properties, stolon, sward structure, viable seed population, white clover.

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PREFACE

Pastoral fallow - what is it? Why do you do it? How does it affect plant and soil in a hill pasture? When and how long do you do it? What are its short- and long-term effects on pasture species composition and yield? This thesis provides answers to these questions.

This thesis is based on a series of papers that have been prepared for publication, preceded by Introduction and Objectives (Chapter 1) and General Literature Review (Chapter 2), and succeeded by General Discussion and Conclusion (Chapter 8). A series of experiments were undertaken to quantify the effects of pastoral fallow on pasture plant, soil, natural reseeding and white clover growth behaviour in a naturalised hill pasture at the AgResearch Hill Country Research Station, 'Ballantrae' near Palmerston North, New Zealand.

Chapters 3 and 4 are based on a field experiment where a fallowing treatment was imposed from October 1993 to May 1994. Chapter 3 describes changes in plant population density and sward structure of a mixed-species hill pasture during the experiment, and the application of self-thinning rule to the fallowed treatments. Chapter 4 compares plant root growth and soil physical and chemical properties between fallowed and grazed swards. To describe the long-term effects of pastoral fallow on soil chemical characteristics, soil samples were taken and analysed from plots with previous fallowing history (Experiment 2 in Chapter 4).

Since the seed production by pasture plants and resultant drop in plant/tiller density by fallowing were considered as an opportunity to reseed, identification and numbers of seedlings germinating from turf plugs kept in a glasshouse were recorded to examine the effect of pastoral fallow on the potential to naturally reseed. Chapter 5 gives quantitative descriptions on 1)

the patterns of seed germination for various plant species after fallowed and grazed treatments (Experiment 1 in the chapter), and 2) variation of natural reseeding during the October 1993 to May 1994 pastoral fallow (Experiment 2 in the chapter).

Chapter 6 describes the impact of timing and duration of pastoral fallow and nitrogen fertiliser on plant density, sward structure, natural reseeding and white clover growth in a field experiment from December 1994 to September 1995. Seed germination from soil plugs held over seven-months in a glasshouse was recorded to estimate the capacity of natural reseeding in various treatments following the field experiment.

Chapter 7 describes the short- and long-term effects of pastoral fallow on herbage production and plant population density with emphasis on white clover growth and distribution. The results of the experiment examining the short-term effect of pastoral fallow, based on the experiment described in Chapter 3, are presented as Experiment 1 in this chapter. The long-term effect of pastoral fallow was investigated on plots with a series of fallowing history (Experiment 2 in the Chapter).

Since the individual papers are self-contained with their reference listing, separate reference listing is given for Chapters 1, 2 and 3 as well. The context and/or structure of individual papers have been modified to fit into chapters, which are integrated into the thesis.

Chapter 1

General Introduction and Objectives

Pasture in hill and mountain land is an important resource of agriculture in the world and its potential for improvement is substantial (Riveros, 1993). Half of New Zealand's grassland occurs on hill and high country (White, 1990). Deterioration and reduced carrying capacity are features common to the hill country pastures due to low fertility, overgrazing, weed invasion and soil erosion etc. (Madden et al., 1949; Grant et al., 1973). The improved management of pastures to achieve a sustainable and low-input hill farming system is of significant importance to New Zealand pastoral industry and economy (Hight, 1979; White, 1990; Caradus et al., 1996).

The key to pasture improvement in New Zealand hill country is the presence of productive legume (Ball et al., 1982; White, 1990). Due to the steep slopes and uneven contour of the hill country, the only feasible technique for the introduction of new plant germplasm to improve pastures is oversowing, although it is a notoriously unreliable method (Grant et al., 1973; Barker and Zhang, 1988; White, 1990). Successful establishment of the introduced germplasm with this technique necessitates the use of herbicide to reduce competition of resident vegetation and fertilizer to build soil fertility (Suckling, 1959; Cullen, 1969; Macfarlane and Bonish, 1986; Barker and Zhang, 1988). However, use of herbicide in hill country is costly and incurs social concerns about chemical use. Other pre-sowing methods such as burning and stock treading do not reduce densities of resident plant species (White, 1977) and their role in controlling competition from resident vegetation is limited.

Historically, sabbatical fallowing has been used to increase soil moisture, build soil fertility, restore soil structure and improve plant growth post-fallowing (Lamb et al., 1985; Bowen et al., 1988; Thorburn, 1992). During the past few years, pastoral fallow, which involves no defoliation of pastures for a period generally from spring to autumn, has been studied in an attempt to improve the productivity, persistence and management of New Zealand hill pasture (Mackay et al., 1991; McCallum et al., 1991; Mountfort, 1996).

Pastoral fallowing substantially changes sward structure, reducing plant density and increasing individual plant size as predicted by the self-thinning rule (Yoda et al., 1963, Weller, 1987). Moreover, Mackay et al. (1991) found that the mineralization of soil organic matter and the release of legume-fixed nitrogen is stimulated by pastoral fallowing. Both legume and pasture growth rates in the following summer were higher on the pasture left fallowed the previous year. When cattle graze accumulated herbage material at the end of a pastoral fallow, it may present a favourable environment for oversowing pasture species, taking advantage of the reduced competition from resident vegetation and improved soil conditions and nutrient supply (Barker and Dymock, 1993). However, a spring to autumn fallow can result in abundant seeds produced by resident plants (McCallum et al., 1991), which may impose strong competition on oversown species. Techniques to control natural reseeding may therefore be necessary if a pastoral fallow is used as a management tool for oversowing hill pastures.

Legume-based pastures play a key role in the sustainable and low-input system of pastoral farming (Riveros, 1993). The basis of increasing pasture yield and quality in New Zealand hill pasture is by increasing content and growth of legumes, usually white clover (*Trifolium repens* L.) (Grant et al., 1973; Ball et al., 1982; Williams et al., 1982). Since seedling regeneration of white clover is rare in moist hill country (Chapman, 1987), manipulation of vegetative spread (stolon elongation and branching) through pasture and grazing management is crucial to improving the productivity and persistence of white clover in this type of hill pasture.

This thesis reports on a series of field and glasshouse experiments designed to examine the response of a hill pasture and soil to pastoral fallow. The effects of contrasting aspects and soil fertility both during and post fallowing were also examined. The objectives were:

- 1) to quantify the changes in plant population density, sward structure, natural reseeding, and soil physical and chemical properties during an October to May fallow;
- 2) to examine how these changes are affected by varying soil fertility status, aspect, and the timing and duration of pastoral fallow;
- 3) to investigate the response of white clover and grass growth up to 4 years post pastoral fallowing.
- 4) to develop decision rules for manipulating pasture components, based on an ecological understanding of the interaction between a pastoral fallow and sward characteristics:
 - a) creating low plant density and low reseeding environment in the autumn for oversowing improved plant germplasm;
 - b) improving white clover content in a low fertility hill pasture.

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Chapter 2

Literature Review

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This chapter provides an overview of New Zealand hill country pasture improvement, with emphasis on the role and performance of white clover (*Trifolium repens* L) in hill country. More specific reviews precede each chapter.

2.1 INTRODUCTION

Hill pasture is a major resource of the New Zealand pastoral industry. Of the total 19 million ha of pasture, there are about 5 million ha surface sown on unploughable hill country (mainly in the North Island), and almost 5 million ha of hill and high country pasture in the eastern districts of the South Island (White, 1990). Hill country farming is a major enterprise and a key aspect of the New Zealand economy in terms of land area, livestock carrying numbers and the volume and export value of animal products (Hight, 1979; White, 1990).

New Zealand hill country is complex, not only in the intricate combinations of steep slopes and aspects that occur within short distances, but also in the range of climate and micro-climate present. Annual rainfall varies from 300 to over 2000 mm with most hill country in the 635 - 1500 mm range. Temperature also varies dramatically from the north to south. North-westerly winds in the drier eastern hill country of both Islands have a marked local desiccating effect on pastures, reflected in the large difference and seasonal variation in pasture composition and production between the sunny and shady aspect (White, 1977; Radcliffe, 1982). Soil patterns are complicated because of the diversity of parent materials, the effect of volcanic activity and other soil-forming factors e.g. climate, vegetation and topography.

The large variations in climatic, edaphic and topographic factors result in a great diversity of hill country pastures both regionally and on a single farm or even within a hill paddock (Chapman and Macfarlane, 1985; Scott *et al.*, 1985). Pasture production varies from about 1400 to 13000 kg dry matter (DM)/ha on dry to wet hill faces and up to 22000 kg DM/ha on stock camps (Hight, 1979).

Pastures are botanically complex. Pasture composition varies from browntop (*Agrostis capillaris* L.) dominance with some sweet vernal (*Anthoxanthum odoratum* L.), Yorkshire fog (*Holcus lanatus* L.), dogstail (*Cynosurus cristatus* L.), danthonia (*Rytidosperma* spp.), suckling clover (*T. dubium* Sibth.), white clover and *Lotus* spp. in the wetter areas, to danthonia dominance with ratstail and other minor species in drier situations (Scott, 1979; Scott *et al.*, 1985). Legume content in hill pastures is often low which further affects the total pasture production and quality (Stevens *et al.*, 1993). The average stock-carrying capacity is about 7 stock units (s.u.)/ha, with 2.5 s.u./ha on the South Island hill country and 10 s.u./ha on the easier and wetter land in the North Island (Hight, 1979).

Over the past decades considerable improvements of hill pastures have been made through oversowing, fertilizer, subdivision and increased stocking rate. For example, pasture productivity increased from 5600 to 11500 kg DM/ha on hillsides at the Te Awa hill pasture research area near Palmerston North (Suckling, 1959, 1960, 1966, 1975). The extent to which these pastures can be manipulated on a farm basis towards pastures with a higher legume content and better producing grasses is substantial (Hight, 1979).

2.2 HILL COUNTRY PASTURE IMPROVEMENT

2.2.1 History of hill country pasture improvement

The conversion of forest to grassland was one of the major activities in the early stages of pasture development in New Zealand (Levy, 1955). The forests were felled during the winter and early spring and burned before oversowing grass and legume species. Following burning and oversowing, secondary growth of fern and scrub such as gorse (*Ulex europaeus* L.) was often a problem on deforested hill country in wetter districts of North Island. The main technique of dealing with this problem involved the classical 'hoof and tooth' treatment, aided by further burning, fencing, scrub cutting and hand oversowing

(Levy, 1955; White, 1977). Grazing pressure and the use of cattle was the key to control reversion to fern and scrub. Animal species in a hill farm involved cattle or cattle and sheep, and the stocking of deforested hill country entirely with sheep could lead to disaster (Levy, 1955). In the tussock grasslands of South Island hill and high country, the development in the nineteenth century was by widespread burning and a rapid increase in stock numbers. The problem of grassland deterioration again appeared due to natural reduction in soil fertility and poor persistence of the grass sown to the hills, encouraged by regular burning, overgrazing and rabbits from 1880s to 1950 (Madden et al., 1949; O'Connor, 1987). As a result, pasture production and stock numbers have been steadily declining. Agronomic improvement of tussock lands and rabbit control started in 1950 have addressed the problem in some situation (O'Connor, 1986 and 1987).

Before the middle of this century, pasture improvement on hill country in New Zealand was mainly concerned with introduction and maintenance of species at the existing level of soil fertility, which was mostly very low (White, 1990). Limited by the topographical conditions in hill country, large scale improvement of hill pastures was not possible until the late 1940s when aerial top-dressing of fertilizer and oversowing of improved species and cultivars were adopted in New Zealand. During 1950s, light aircraft was actively used in hill country (Levy, 1955), and about 2 million ha of permanent pastures were topdressed and oversown (Robinson and Cross, 1960). This technique was developed rapidly and farmers could quickly improve pasture production and quality following the correction of soil nutrient deficiencies and introduction of new pasture species by air (White, 1990).

Meanwhile, considerable research work has been done to support the development and improvement of hill country pastures. Suckling (1959, 1960, 1964, 1975) reported the improvement from oversowing, fertilizer application, subdivision and increased stocking at the Te Awa hill pasture research station near Palmerston North. Comprehensive research on pasture species, pasture

and grazing management, soil fertility and fertiliser use, and animal nutrition were documented at Ballantrae hill country research station and Whatawhata hill country research station (Brougham et al., 1974; Gillingham, 1980, 1982; Lambert et al., 1982; Sheath, 1982, 1984; Williams et al., 1982; Chapman et al., 1985; Barker and Zhang, 1988; Mackay et al., 1991). In South Island, a considerable contribution has been made to improve the hill and high country pastures in a wide research area (Scott, 1979; Scott et al., 1985; White and Meijer, 1978; White, 1990; O'Connor, 1986). The transfer of these research achievements into practice has substantially influenced the improvement of New Zealand hill country pastures.

2.2.2 Limitations to hill pasture production

Moisture, temperature, soil fertility and pasture/grazing management are considered the four main limitations to pasture growth in the hill country of both Islands (Chapman and Macfarlane, 1985; Scott *et al.*, 1985). Soil moisture and temperature are largely affected by hill topography, i.e. aspect and slope. Soil fertility and pasture/grazing management can be manipulated in a hill farming system.

2.2.2.1 Moisture, temperature and their alteration by aspect and slope

Hill country in New Zealand can be divided by moisture conditions into two main areas: 'summer moist' where rainfall during summer is reliable and 'summer dry' where rainfall in summer is low and droughts can occur (Thomson, 1983). Topographical conditions such as aspect can greatly affect soil moisture content due to considerable difference in solar radiation and potential evapotranspiration between contrasting micro-environments, e.g. sunny and shady aspects (Radcliffe, 1967 and 1981). Even in the regions generally considered summer-moist or wet, moisture stress can occur regularly on steep, north faces (Chapman and Macfarlane, 1985). Bircham and

Gillingham (1986) found that, in hill country with high rainfall, the total effective rainfall contributing to the soil moisture storage available for plant use may be quite low and similar to many dryland regions. Soil water loss in runoff and deep drainage can be as high as 58 - 79% of annual rainfall on steep hill soils.

Temperature can also be modified by aspect and slope. Sunny (north-facing) aspects have higher soil temperature than shady (south-facing) aspects. In general, temperature together with soil moisture affect pasture growth and yield between aspects. Pasture production on shady aspects may be much higher than on sunny aspects in lower rainfall seasons or districts, but these differences disappear or even favour sunny aspects in higher rainfall and more humid seasons or districts such as the northern and western districts of the North Island. The influence of aspect on hill pastures at various regions or sites of New Zealand has been well documented (Radcliffe et al., 1968; Suckling, 1975; Lambert and Roberts, 1978; Gillingham, 1980; Luscombe, 1980; Radcliffe, 1982).

2.2.2.2 Soil fertility

Nitrogen (N) deficiency is the principal nutrient limitation to pasture growth in most hill soils of New Zealand. Deficiencies of phosphorus (P) and sulphur (S) are also common in many hill soils. The combination of these three deficiencies results in a grass, weed and moss dominated pasture with low production and poor quality. On some acid soils, deficiency of the trace element molybdenum (Mo) often occurs. Addition of lime alleviates Mo deficiency and reduces the levels of available manganese or aluminium in the soil by raising soil pH, thus improving pasture growth (White, 1990).

Correction of these deficiencies can improve the quantity and quality of hill pastures. Introduced improved grass and legume species generally have a higher nutrient requirement than resident species and give greater responses

when the nutrients are applied. In New Zealand pastoral systems, the solution to N deficiency in the low-producing swards is the introduction of legumes to fix N from the atmosphere, and transfer it to grasses through herbage death and decay, or through animal excreta. The amount of N fixed by legumes in hill pastures is dependent on the availability of P and other nutrients such as S and Mo, which are important for good legume establishment and growth. At Ballantrae, annual N fixation rose from about 30 kg/ha (Grant and Lambert, 1979) in unimproved pastures to 100 kg/ha with moderate superphosphate application, and to 200 kg/ha with high fertiliser input (Lambert, 1987). High input of fertiliser (57 kg P/ha/year) improved legume production and N fixation, which resulted in a consistent increase in winter and annual grass yield in a fertiliser experiment started in 1975 (Lambert et al., 1983 and 1986).

2.2.2.3 Pasture/grazing management

Under-grazing (too lax grazing pressure) and over-grazing (too severe grazing pressure) are two extremes of grazing management which limit pasture production. When pasture is under-grazed, dead material accumulates and plant density declines, which reduces both pasture quality and production. Where pasture is over-grazed, photosynthesis of plants is depressed and plant mortality exposes bare areas for weed invasion which eventually again reduces pasture quality and production. Thus a suitable grazing pressure is of great importance in hill pasture management. This can be achieved by subdivision and manipulation of stocking rate (Chapman and Macfarlane, 1985).

Most hill country pastures are extensively grazed with set-stocking by sheep being the most common management. Compared with rotational grazing management, a set-stocking system may give lower pasture accumulation and animal production (Hodgson, 1990), although the difference is small. Under this system, frequent grazing close to ground level is normal, which may result in the rapid ingress of low-producing species (Harris and Brougham, 1968;

Lambert et al., 1986). Continuous close defoliation also limits the dispersion of white clover stolons and reduces clover patch size, which consequently reduces clover production and content in the pasture (Edwards, 1994; Sheldrick et al., 1993). Lambert et al. (1983) reported a legume production decline at a high stocking rate (16.1 ewe/ha) even under a high fertiliser regime (57 kg P/ha/year) after an initial increase in legume production. An alternative approach to set-stocking is the “controlled grazing systems” proposed by the Ministry of Agriculture and Fishery (Lambert et al., 1985). These systems, incorporating virtually year-round rotational grazing, are becoming more important in hill pasture management (Chapman and Macfarlane, 1985).

2.2.3 Oversowing hill pasture

Methods for improving hill pastures include oversowing, fertiliser application, subdivision, mixed livestock, and grazing management (Wedderburn and Macfarlane, 1993). The introduction of high producing pasture species, particularly the legumes, is of key importance in improvement of the hill country pasture in New Zealand (White, 1990). Most hills in New Zealand are steep in slope and extremely uneven in contour, which makes oversowing the only possible method for introducing new plant germplasm, although oversowing is a notoriously unreliable method of improving hill pasture productivity.

Oversowing is defined as the broadcasting of seed, manually, by aeroplanes or by surface machines over the pasture surface with no attempt at precise placement of seed (Robinson and Cross, 1960). The aims of oversowing in hill country involve: 1) pasture development after clearance of scrub and bush; 2) pasture renovation following damage to existing pastures by pest attack, drought treading damage, or erosion; and 3) pasture improvement to increase farm productivity (Lambert et al., 1985). The species introduced by oversowing generally have improved annual or seasonal herbage production, better feeding value and better tolerance or resistance to grazing, treading, pest attack, drought or low fertility. Since no tillage is a characteristic of oversowing, good

seedbed preparation to suppress resident vegetation and improve soil conditions is crucial to successful establishment of oversown species.

2.2.3.1 Seedbed preparation methods

Successful establishment of an introduced species by oversowing depends on the seed reaching a favourable site, its ability to germinate and subsequent growth competing with neighbouring resident plants (Harper, 1977; Barker and Zhang, 1988). These are all related to the modification of the existing vegetation and soil surface before new plant species are oversown.

Competition from the resident pasture plants is a major factor limiting the survival rate of the oversown seedlings. Where herbicide is used prior to oversowing, the competition of resident plants will be suppressed, and the contact of sown seed with soil will become more likely. A number of authors have shown that application of herbicide to kill existing vegetation improves the establishment of introduced species (Blackmore, 1957; Cullen, 1969; Macfarlane and Bonish, 1986; Barker and Zhang, 1988). The advantage of herbicide application has been outlined by Thom and Barker (1993) and they recommended herbicide use especially in the no tillage pasture renovation system. However, the use of herbicide is limited in practice because of the cost of herbicides and their application in hill country, and other problems which may be caused by herbicides e.g. the risk of soil loss, invasion by undesirable plant species, and the growing environmental concerns regarding chemical use. Chapman et al. (1985) indicated that herbicide use was not essential for rapidly establishing species such as white clover and ryegrass, but was necessary for cocksfoot (*Dactylis glomerata* L.) which has a slower germination rate. Similar results were derived while a herbicide (paraquat) was applied (Table 2.1).

Stock treading is a cheap and practicable seedbed preparation and establishment method for oversowing in hill country (Charlton and Thom, 1984;

Table 2.1 Effect of paraquat on grass and clover survival in dense closely-grazed sward (From Cullen, 1969).

Species	Percentage survival	
	No paraquat	Paraquat
Cocksfoot	10	42
Ryegrass	27	54
White clover	26	29

Macfarlane and Bonish, 1986). The classical 'hoof and tooth' treatment was recommended as a means to ensure seed-soil contact (White, 1977). Pre-sowing treading also suppresses the growth of resident pasture plants, hence reducing competition to oversown species. Burning to clear above ground materials has frequently been practised before oversowing in hill country in the South Island (White, 1977; Allan et al., 1985). However, in dry hill country, burning and heavy grazing before oversowing should be avoided to alleviate soil moisture stress. A severe burn significantly reduced germination of oversown lucerne (Jason and White, 1971). Burning at a time when the base of tussock or long grass is damp, for example winter, will reduce the severity of the burn (White, 1990).

Leaving some cover on the seedbed has been demonstrated to improve seedling establishment (Cullen, 1966, 1971; Dowling et al., 1971). Cover can improve humidity and moisture relations at soil surface, protect rhizobia on inoculated legume seed from sunlight (Hely, 1965), and reduce frost effect on seedlings from winter sowings in cold districts (During et al., 1963). In the low rainfall areas or sunny faces where desiccation is a major problem, the main aim of seedbed preparation is to provide a reasonable cover for moisture conservation.

2.2.3.2 The potential of pastoral fallowing to prepare seedbed

Fallowing, i.e. resting land for a period, has been practiced since biblical times in the Near East. The evolution of agriculture up to industrial agriculture has seen a shift from long-fallows (>10 years, e.g. swiddens agriculture) down to short-fallows of 1 year (Bayliss-Smith, 1982). The purpose of the fallow was variously assumed to allow accumulation of materials, break pest and disease cycles and to improve soil properties. In semi-arid regions of USA and Australia, bare fallowing is practiced within crop systems with the additional objective of accumulating soil moisture (Sims, 1977). A fallow, incorporating

into the Rothamsted classical experiment, showed responses of 30% in subsequent crop yield (Gamer and Dyke, 1969).

Pastoral fallow involves no defoliation of pastures for a period generally from spring to autumn (Mackay et al., 1991). In recent years, studies have shown that pastoral fallow is effective in improving the productivity, persistence and management of hill pasture in New Zealand (Mackay et al., 1991; McCallum et al., 1991; Mountfort, 1996). In moist hill country where competition on oversown species from dense and vigorous resident vegetation is a major problem, pastoral fallow may be used to reduce the resident plant population density based on the self-thinning rule (Yoda et al., 1963; Barker and Dymock, 1993). It may also have to be used to provide ground cover and suitable moisture conditions for oversowing (White, 1990).

2.2.4 Other methods of hill country pasture improvement

Other methods such as topdressing, increasing stocking rate, subdivision and use of genetically superior livestock have also been proven to achieve the goals of improving farm productivity in hill country (Lambert et al., 1985). For example, a desired pasture composition can be achieved by fertiliser application, use of selective herbicides or high intensity strip-grazing with cattle (Lambert et al., 1985). On the other hand, the success rate of oversowing is usually dependent on other improvements such as a lift of soil fertility. Which method or what combination which can be effective in improving pasture and animal productivity depends on the factors such as environment, pasture species present, soil fertility, production systems and finance available (Wedderburn and Macfarlane, 1993).

The strategy for lifting soil fertility in New Zealand hill country is to apply fertiliser phosphate and sulphate to improve legume growth and stimulate symbiotic nitrogen fixation. Since the advent and acceptance of aerial topdressing in the early 1950s, most of the farmed hill country in New Zealand

has been improved to some degree through topdressing with fertilisers such as superphosphate and molybdenum. Initially application of low rates of superphosphate at 100 to 250 kg/ha/year was practised, and was further increased to 700 - 1100 kg/ha/year superphosphate (Grant et al., 1973). Jackman et al. (1962) estimated that 550 to 700 kg/ha/year superphosphate (55 to 70 kg/ha/year phosphorus) were necessary to overcome initial phosphate limitations on unimproved yellow-brown earths. Many studies demonstrated that the main elements limiting legume growth are sulphur, phosphorus and molybdenum in the tussock grasslands of the South Island (Walker et al., 1955; Lobb, 1958; Ludecke, 1960; Scott and Covacevich, 1987). Similar results were found in much of the North Island hill country (Blackmore et al., 1969).

Fencing is an effective way to control grazing animals and to ensure optimum grazing management is achieved. The pre- and post-sowing management of grazing and treading by animals is based on effective subdivision. Fencing also improves pasture utilisation. In improved tussock country of the South Island, the key to successful management is controlled utilisation by subdivision to prevent both loss of introduced species through overgrazing and loss of pasture quality through undergrazing (Allan et al., 1985).

Grazing management can influence both quantity and quality of pastures. In early stages of pasture development in hill country, grazing by animals played the most important role in controlling reversion to fern, scrub and secondary growth (Levy, 1955). Stocking rate should be carefully planned with sward conditions and seasonal variation of pasture production since appropriate stocking rate increases the productivity and persistence of pasture. Rotational grazing improves the evenness of utilisation within blocks and creates a feed bank ahead of stock, thus helps the balance of annual feed supply and demand (Allan et al., 1985). However, many studies comparing rotational grazing and set-stocking have shown that there is little difference in pasture utilisation

between the two grazing systems (Suckling, 1975; Clark et al., 1982; Lamert et al., 1983; Chapman and Clark, 1984).

2.3 PERFORMANCE OF WHITE CLOVER IN HILL PASTURES

2.3.1 Role of white clover in hill country

The key to pasture improvement in hill country is the introduction of high producing legumes following the correction of soil nutrient deficiencies, to provide symbiotic nitrogen to the system (White, 1990). This in turn will stimulate the growth of associated grasses and increase the quantity and quality of herbage produced, both from grasses and introduced legumes.

White clover is the most important legume in New Zealand pastoral industry. This is not only because of its ability to fix nitrogen, its high nutritive value and its seasonal complementarity with grasses, but also its widespread adaptability and ability to withstand grazing stress and interspecific competition better than other legumes. The annual financial contribution of white clover through nitrogen fixation and forage, seed and honey production is estimated as about three billion dollars in New Zealand (Caradus et al., 1996). Vigorous growth of white clover is essential for hill country improvement (Williams et al., 1982), especially in summer-moist areas. In dry hill country, white clover and subterranean clover (*Trifolium subterranean* L.) often occur together, i.e. white clover dominates the legume population during moist seasons followed by a shift towards subterranean clover during dry periods (Macfarlane and Sheath, 1984). The importance of good clover production to hill country pasture cannot be over-emphasised (Ball et al., 1982).

Hill pasture in New Zealand usually has low (<10%) legume content which results in poor pasture yield and quality (Stevens et al., 1993). Even where fertiliser inputs are relatively high, legume contribution to sward productivity remains low. For example, in long-term grazing trials under adequate

topdressing, legumes contributed an average of 11% of total pasture DM production on hillsides at Te Awa (Suckling, 1975). In clover based pastures of steep (12-28° slope) hill country which covers about 42% of the total (13.5 million ha) in New Zealand, estimated N-fixation is only 20 kg N/ha/year, a fraction of the nitrogen (185 N/ha/year) fixed in low slope (<12°) and flat lands (Caradus et al., 1996). The ideal legume content in swards is at least 20-25% (Suckling, 1975). Therefore, the potential to increase clover content and productivity in hill country is substantial.

2.3.2 Propagation and persistence

One important reason for low white clover content in hill country is the poor propagation and persistence of this species due to climate and management of soil fertility and grazing pressure. White clover has a stoloniferous growth habit and its basic structural unit is the stolon (Thomas, 1987). The stolon consists of a series of nodes separated by internodes where leaves and adventitious roots are produced. Each node has an axillary bud which may remain dormant for a period or develop into either a lateral stolon or an inflorescence. Therefore, white clover may spread vegetatively (through stolon growth and branching) or by seed produced from the resident clover plants (seedling regeneration). The relative importance of seedling regeneration and vegetative spread in the demography of white clover is a key issue to improve the persistence of this species in hill country.

2.3.2.1 Seedling regeneration

Early study (Chippindale and Milton, 1934) showed that there were large amounts of white clover seed present in the soil beneath pasture. Hyde and Suckling (1953) found that, although low compared with low land pasture, buried seed populations within hill swards in the North Island of New Zealand were sometimes very high. This led to their suggestion that regeneration from

such seed could be important in the persistence of this species in permanent pasture. Similar results of 217-395 buried seeds/m² of white clover were observed by Charlton (1977).

To quantify the contribution of these buried seeds to the persistence of white clover in hill pastures, Chapman (1987) investigated white clover seedling appearance and survival influenced by a number of factors such as grazing management, fertiliser, aspect and slope in summer moist hill pastures for three years. He found that an average of only 4.4% of seedlings survived to form established, stolon-bearing plants which means a recruitment rate of one seedling per 5.5 m² per year (Table 2.2). Compared with the background stolon population and rapid stolon turnover (Chapman, 1983; Chapman and Anderson, 1987), this rate of establishment of white clover plants from seedling regeneration was negligible (Chapman, 1987). Thus, seedling regeneration plays a minor role in the persistence of white clover in summer moist hill country.

However, there has been little detailed information about the contribution of seedling regeneration to clover persistence in dry hill country. Chapman (1987) reported higher (10%) survival rates of seedlings on drier, steep north-west facing hill sites. White clover genotypes in summer dry hill country typically flower earlier and more intensely than the commonly used cultivars such as Huia, Pitau or Tahora (Macfarlane and Sheath, 1984). Macfarlane et al. (1990) evaluated eleven cultivars or selections of white clover in summer dry hill country and found that lines that set high levels of seed did re-establish greater numbers of seedlings each autumn. This mechanism may contribute to sward stability where disturbance is frequent, particularly where white clover populations are depleted by severe drought or insect attack (Macfarlane et al., 1990).

Table 2.2 Seedling appearance and survival (total area = 64 m²) of white clover in summer moist hill country (From Chapman, 1987).

year	Number of seedlings appearing	Number of seedlings surviving	% Survival	Number of seedlings surviving per m ² per year
1982-83	312	13	4.2	0.20
1983-84	213	8	3.8	0.13
1984-85	263	14	5.3	0.22
<i>Mean</i>	<i>263</i>	<i>12</i>	<i>4.4</i>	<i>0.18</i>

2.3.2.2 Vegetative spread

The capacity to spread horizontally by growth of stolons is an important characteristic for the competitiveness and persistence of white clover in mixed swards (Harris, 1987). This characteristic compensates the lower seed rate of white clover, which makes the variation in seeding rate only has a short-term effect after sowing on the clover content of swards. Harberd (1963) measured the stolon spread in mixed plant communities and found that most of the stolons could spread into patches 2 m across. Under rotational cattle grazing in hill pasture, stolon elongation rate can be as high as 32 to 35 mm/week during summer periods, and Chapman (1983), using these maximum elongation rates, estimated that stolons have the potential to explore a distance of 700 mm per year within the sward. Survival of residual stolons during drought and their subsequent recovery played a large role in re-establishing white clover populations in dry hill country (Chapman and Williams, 1990). Cultivars that have low propensity to produce stolons and are vulnerable to stolon damage by grazing have lower persistence levels in hill country (Macfarlane et al., 1990).

The growth and dispersion of white clover stolons are not only influenced by climatic and environmental factors such as seasons, topography and soil conditions, but also by grazing management (Brougham, et al., 1978; Hay and Chapman, 1984; Hay, 1983; Harris, 1987). The frequency, intensity and timing of defoliation can determine the relative contribution of white clover in mixtures (Harris, 1987). Hay (1985) described the vertical distribution (aerial, surface and buried) of white clover stolons under two contrasting grazing systems, rotational grazing by cattle and set-stocking by sheep. Rotational grazing by cattle resulted in higher aerial and surface stolon dry weight and clover content in the sward compared with set-stocking by sheep, but the latter favoured stolon growing point numbers, branches per unit length of stolon and buried stolon weight. This implies that set-stocking by sheep, though stimulating branching of stolons, probably restricts the dispersion of clover stolons in the sward and causes stolon burying,

and, consequently, reduces the productivity and persistence of white clover. It is evident that there is lower clover content under set-stocking by sheep in hill pastures (Williams et al., 1982; Lambert et al., 1986). However, the effects of defoliation on white clover content in mixtures are complicated since one defoliation strategy may favour some aspects of stolon growth, but exert adverse effects on others (Thomas, 1972; Sheldrick et al., 1993).

2.3.3 Genotypes of white clover in hill country

White clover populations in hill country are dominated by small-leaved genotypes (Suckling and Forde, 1978; Macfarlane and Sheath, 1984). This is attributed to an adaptation to greater persistence under sheep grazing (Williams and Caradus, 1979; Williams et al., 1982). Williams and Caradus (1979), having compared 95 white clover lines from overseas and New Zealand hill country, found that, in the first year after establishment, large-leaved genotypes generally performed better than the small-leaved ones in hill country. However, with time and increased grazing pressure, the large-leaved forms declined in relative performance while some small-leaved forms improved. The inability of large-leaved forms to withstand harsh conditions, including grazing pressure, are well documented (Davies and Levy, 1931; Davis and Cooper, 1951; Brock, 1974). Chapman (1983) also indicated that genotypes with a high frequency of branch and root formation at the same node will have greater persistence and productivity than others in intensively-grazed hill pastures.

Since large-scale hill country pasture improvement started by aerial oversowing and topdressing in 1940s, 'Grassland Huia', a general purpose cultivar, has been widely sown in hill country of New Zealand (Charlton, 1984). However, this intermediate-leaved cultivar was originally bred for use in high-fertility lowland pastures (Williams, 1983). Studies demonstrated that small-leaved types were more prevalent on poorer land grazed mainly by sheep (Davies and Levy, 1931), and Huia failed to persist at regular fertiliser input and good grazing management (Forde and Suckling, 1977). In 1982, 'Grassland

Tahora”, selected for improved agronomic performance in moist hill country was released (Williams, 1983). It is the only white clover cultivar bred for, and selected in, hill country (Chapman and Macfarlane, 1985), although there are other seed lines such as Whatawhata Early Flowering which was selected from a dryland collection for early flowering (Macfarlane and Sheath, 1984). A number of authors (Williams et al., 1982; Charlton, 1984; Brock, 1988) have shown that these types of white clover are better adapted in hill country than Huia. The small-leafed and strongly stoloniferous cultivars such as Tahora should replace Huia on all wetter hills of low to moderate fertility under sheep grazing (Chapman and Macfarlane, 1985), but Huia should continue to be used on moderate to high fertility sites under cattle grazing (White, 1990).

2.4 SUMMARY

Hill country pasture is an important resource for New Zealand agriculture and economy. The large variation of climatic, edaphic and biotic factors has caused a great diversity of pastures on New Zealand hill country both within and between regions.

The improvement of hill country pastures has experienced a history from simple development methods such as burning and introducing new grass species, to advanced improvement techniques such as aerial topdressing and oversowing. Temperature, soil moisture, soil fertility and pasture/grazing management are four main limitations to hill pasture growth. Amongst many hill country pasture improvement techniques such as topdressing, increasing stocking rate and subdivision etc., the introduction of high producing pasture species, particularly the legumes, is the key to improve hill country pasture.

However, because of the topography of most hills in New Zealand, oversowing, though unreliable in success rate, becomes the only possible method for the introduction of new plant germplasm. The procedure of oversowing involves seedbed preparation, sowing techniques and post-sowing management.

Herbicide use, burning, seedbed cover and stock treading as seedbed preparation methods have all been shown to have significant but variable roles in improving establishment from oversowing. An alternative method such as pastoral fallow may overcome the shortcomings of some of these methods.

White clover is the most important legume in the New Zealand pastoral industry, because of many advantages of this species in the pasture and grazing management system. However, the content of white clover in hill pastures is low, even with regular fertiliser input and good pasture management. Since regeneration of seed from resident clover plants contributes little to the clover population in moist hill swards, vegetative spread by stolons plays a major role in the persistence of white clover in mixtures. Stolon growth and dispersion are determined by the frequency, intensity and timing of defoliation of swards and clover genotypes.

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Chapter 3

Changes in Plant Population Density, Composition and Sward Structure of a Hill Pasture During a Pastoral Fallow

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This chapter is based on a paper of the same title (Nie, Z. N.; Mackay, A. D.; Barker, D. J.; Valentine I.; Hodgson, J.; 1997) published in *Grass and Forage Science* 52: 190-198.

Abstract

Appropriate pre-sowing methods for the introduction of improved forage legume and grass germplasm are an important issue for hill pasture improvement in New Zealand. A pastoral fallow, which involves not defoliating pasture for a period generally from late spring/early summer to autumn, could create a potentially favourable environment for introducing improved germplasm. A field study was conducted on two aspects (shady and sunny) of moist, low fertility hill country with or without added fertiliser (phosphorus and sulphur) in the southern North Island of New Zealand, to investigate the changes in plant population density and sward structure during a full or partial pastoral fallow, compared to a rotationally grazed pasture. A seven-month (October - May) pastoral fallow dramatically decreased the densities of grass tillers by 72% ($P < 0.01$), white clover (*Trifolium repens* L.) growing points by 87% ($P < 0.01$) and other species by 87% ($P < 0.05$). The decline in tiller density by pastoral fallow was enhanced on the shady aspect. Fertiliser application increased white clover growing point density on the shady aspect ($P < 0.05$) and grass tiller density on the sunny aspect ($P < 0.05$). Decreased plant density during pastoral fallowing was attributed to above-ground biomass accumulation which altered sward structure, leading to inter-plant competition and mortality by self-thinning and completion of the life cycle of some matured plants. The plant size/density relationship during pastoral fallowing in this mixed species sward followed the self-thinning rule, particularly when the calculation was based on all plant species rather than grass alone. There was no significant ($P > 0.05$) difference in final plant population density between the seven-month pastoral fallow and a shorter-term (October - December) pastoral fallow. It is concluded that pastoral fallowing effectively reduced the plant population density and altered sward structure of a hill pasture. Such changes create a more favourable environment for the introduction of improved forage species.

Key words: pastoral fallow; plant population density; sward structure; self-thinning

3.1 INTRODUCTION

The introduction of improved forage legume and grass germplasm is one tool for improving the pattern of forage supply of a typically-dense hill pasture low in legume content and dominated by low-fertility grasses. Although herbicide defoliation is not essential for successful oversowing of rapidly germinating species, such as perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.) (Chapman et al., 1985; Johnson et al., 1993), it is essential for successful establishment of slow establishing and growing species, such as cocksfoot (*Dactylis glomerata* L.), tall fescue (*Festuca arundinacea* L.) and phalaris (*Phalaris aquatica* L.) (Chapman et al., 1985; Barker and Dymock, 1993). However, the use of herbicide as a tool for reducing competition from the resident species is limited, because of the cost of defoliant and their application in hill country and, to a lesser degree, the risk of soil loss, invasion by undesirable plant species, and the growing environmental concerns regarding chemical use. McCallum et al. (1991) showed that pastoral fallowing (or deferred grazing) improved perennial ryegrass contribution to yield by enhancing natural reseeding of this species, and increased pasture growth by 15 - 19% in the year following the fallow. Barker and Dymock (1993), reported on the management requirements for the successful establishment of one of the slow establishing species, cocksfoot, and suggested that a pastoral fallow, rather than herbicide spraying, might bare the soil surface sufficiently, to allow germination and establishment of this slow growing species.

A pastoral fallow involves no defoliation from late spring/early summer through to autumn. Studies (Mackay et al., 1991) showed that pastoral fallowing stimulated mineralisation of soil organic matter and the release of nitrogen (N) fixed by legumes. The accumulation of above-ground biomass during pastoral fallowing causes increased inter-plant competition and self-thinning (Westoby, 1984). After the pastoral fallow period, intensive grazing by stock creates an open canopy with a low plant density per unit area and this presents a

potentially favourable environment for introducing improved germplasm. While the competition with established plants on seedlings of introduced species is reduced by pastoral fallow, competition with seedlings, derived from seed shed by the established plants during the pastoral fallow is intense (Nie *et al.*, unpublished data). To optimise the use of inter-plant competition and self-thinning to reduce competition from resident plants and minimise the shedding of viable seed by established plant species following a pastoral fallow, a detailed understanding of the changes in total and reproductive tillers over the duration of a pastoral fallow is required.

The self-thinning rule, also known as the $-3/2$ law, was first proposed as an empirical relationship describing plant mortality due to competition in crowded even-aged stands (Tadaki and Shidei, 1959; Yoda *et al.*, 1963). The rule was found to be applicable to many plant species, including mixed-species stands (Westoby, 1984). A number of authors found that grass/legume stands generally follow the $-3/2$ law (Kays and Harper, 1974; Lonsdale and Watkinson, 1982; Bircham and Hodgson, 1983; Morris and Myerscough, 1985; Lambert *et al.*, 1986; Matthew *et al.*, 1996). Applying this law in hill pastures (Lambert *et al.*, 1986) might satisfactorily explain changes in sward density during a pastoral fallow.

The objective of this study was to examine the changes in plant population density and sward structure of a low fertility hill pasture sward on two aspects with or without the addition of fertiliser over the duration of a full (November 1993 - May 1994) or partial (October - December 1993 and February - May 1994) pastoral fallow. The applicability of the self-thinning rule in this temperate hill pasture is also examined.

3.2 MATERIALS AND METHODS

3.2.1 Site

The field study was carried out at AgResearch Hill Country Research Station, 'Ballantrae' (40°19' S, 175° 50' E). The field site (Plate 3.1) covered 2.2 ha of hill country (slope 5° - 25°), split on a south (shady) and north (sunny) face. The soil was a yellow-grey earth/yellow-brown earth intergrade (Typic Dystrochrept) of sedimentary origin, with pH 5.4 and Olsen P 10 µg P/g dry soil. No fertiliser had been applied in the 10 years before 1989. The pasture consisted of predominantly low fertility-tolerant grasses such as browntop (*Agrostis capillaris* L.) and sweet vernal (*Anthoxanthum odoratum* L.) with small quantities of perennial ryegrass and white clover.

3.2.2 Design and treatments

Main plots of 500 - 800 m² had previously been either (a) rotationally grazed and fertilised with 35 kg P/ha/year of North Carolina reactive rock phosphate and 14 kg S/ha/year of elemental sulphur in August annually since 1989 or (b) rotationally grazed without added fertiliser. In October 1993 these were split (sub-plots), with one half fallowed from 19 October 1993 until 31 May 1994 (full pastoral fallow) and the other half rotationally grazed by sheep with herbage dry matter (DM) mass not exceeding 3000 kg/ha. Two additional treatments, examined the effect of partial pastoral fallowing. An early pastoral fallow was imposed from 19 October to 31 December 1993 on plots with a previous history of pastoral fallowing 1989/90. A late partial pastoral fallow was imposed from 17 February to 31 May 1994 on plots that had been fallowed in 1990/91. Both supplementary treatments received the same rate of fertiliser as the fertilised main plots and were rotationally grazed by sheep during the non-fallowing periods. The main plots and partial pastoral fallow plots were replicated three times on the shady aspect and twice on the sunny aspect.



Plate 3.1 An overview of the experiment site showing fallowed and grazed plots.

3.2.3 Measurements

Monthly measurement of plant population density commenced in October 1993 until May 1994, based on twenty 50 mm diameter turf plugs from each plot (Mitchell and Glenday, 1958). The number of turf plugs was determined by comparing the means and variances of randomly sampled 5, 10, 15 and 20 turf plugs prior to the start of the experiment, fewer than 20 plugs resulting in high sampling variation. The number (No.) of grass tillers, white clover growing points, other legume plants and weeds were counted to estimate plant density (No./m²). Moss cover was scored as 0 (none), 1 (< 50% of surface covered by moss), 2 (> 50% cover) and 3 (100% cover).

At each sampling, five 0.1 m² quadrats were also cut to approximately 10 mm above ground to measure pasture phytomass. Subsamples, taken from each herbage sample, were dissected into vegetative and reproductive tillers of grasses, white clover, other legumes, weeds and dead matter to calculate botanical composition and phytomass of each sward component. Reproductive tillers were distinguished from vegetative tillers by observing the node development of stem to obtain an estimate of potential for seed production. The ratio of vegetative to reproductive tillers was determined to monitor the tiller mortality due to either competition or reproductive development or combination of both.

After pasture phytomass sampling, two of the five quadrats were further cut to ground level, washed and dried to measure phytomass below 10 mm. Total pasture phytomass was calculated as the sum of these two measurements.

3.2.4 Statistical analysis

Data were analysed by Analysis of Variance (ANOVA) using a pooled split-plot model, with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, 1990). A split-plot design over time (repeated

measures) was used to analyse general effects of pastoral fallowing, fertiliser and aspect, with sampling times treated as split-split-plots. A randomised complete block design was used to compare the effects of full and partial pastoral fallows on final plant population density and biomass accumulation.

The relation of self-thinning was given by Yoda et al. (1963) as:

$$w = k d^{3/2}$$

$$\text{or } \text{Log}_{10} w = \text{Log}_{10} k - 3/2 \text{Log}_{10} d$$

where: w = the mean shoot weight per plant

d = the density of plants

k = a constant, the value of which depends on growth form and environment.

The data matrices of plant density and mean plant shoot weight were derived at sub-plot level of the full pastoral fallowing treatment and mean shoot weight was calculated by dividing total biomass by plant density. The self-thinning line was estimated by Principal Component Analysis (PCA), slope was calculated by obtaining the ratio of the two coefficients of the first principal component. The intercept values presented were those for a line of slope as determined by PCA analysis and passing through the center point (\bar{x}, \bar{y}) of the data set (C. Matthew, personal communication).

3.3 RESULTS

3.3.1 Climate

Mean monthly rainfall during September - October 1993 was 62.1 mm, 56% of the 23-year average, and during February - April 1994 was 48.8 mm, 73% of the 24-year average. Mean air temperature (14.0 °C) during October 1993 - May 1994 was identical to the 23-year average.

3.3.2 Plant population density

Pastoral fallow substantially decreased densities of grass tillers ($P < 0.01$), white clover growing points ($P < 0.01$) and weeds ($P < 0.05$), but did not alter the moss cover (Table 3.1) or the density of other legumes which contributed less than 2% to the total plant population density. There were significant ($P < 0.05$) interactions between pastoral fallow and aspect in grass tiller density, and between fertiliser and aspect in grass tiller density and white clover growing point density. The decline in tiller density by a pastoral fallow was greater on the shady aspect than the sunny aspect (Table 3.1). A significant fertiliser by aspect interaction was the result of fertiliser application reducing tiller density on the sunny aspect, but not on the shady aspect (Table 3.1). This interaction was also significant for white clover growing point density, but was the result of increased growing point density for fertiliser application on the shady aspect and no fertiliser effect on the sunny aspect. Only the main effect of aspect affected moss cover, which was higher ($P < 0.01$) on the shady than on the sunny aspect, reflecting the contrast of soil moisture in the two aspects.

Compared with grazed swards, the tiller density of grasses under a pastoral fallow declined significantly ($P < 0.05$) four weeks after the pastoral fallow was imposed (Figure 3.1). This difference became steadily greater during the pastoral fallow period. At the end of the pastoral fallow period, the mean tiller density of fallowed plots (6370 tillers/m²) was only 23% of the grazed plots and 28% of the initial tiller density.

White clover growing point density of both fallowed and grazed treatments declined in the first two months of the study (Figure 3.1). A significant difference ($P < 0.05$) between fallowed and grazed treatments did not occur until January, continuing to the end of May 1994. The weed population responded in a similar manner, but weed densities declined in both treatments from late summer to autumn. A significant difference in weed density between fallowed and grazed sward was found from February to May.

Table 3.1 Mean plant density (19 October 1993 - 31 May 1994) of grass (tillers/m²), white clover (growing points/m²) and weeds (plants/m²) and moss cover (0, 1 (< 50%), 2 (> 50%), 3 (100%)) under different treatments of pastoral fallow, fertiliser (Fert + and Fert -) and aspect and some significant interactions.

Treatment	Grass	Clover	Weed	Moss	Interaction	Grass	Interaction	Grass	Clove
Graze	23900	2560	697	1.4	Graze/Shad	24300	Fert	17800	2713
Fallow	11100	1329	530	1.4	Graze/Sunn	23100	Fert	15500	1483
<i>F-ratio</i>	<i>1701.9</i>	<i>49.8</i>	<i>10.1</i>	<i>0.0</i>	Fallow/Shad	11000	Fert -/Shady	17500	1543
<i>Significance</i>	**	**	*	<i>ns</i>	Fallow/Sunn	11300	Fert -/Sunny	19000	1601
Fert +	16900	2320	560	1.3	<i>F-ratio</i>	<i>9.2</i>		<i>10.5</i>	<i>26.6</i>
Fert -	18100	1570	667	1.6	<i>Significance</i>	*	*	*	*
<i>F-ratio</i>	<i>1.6</i>	<i>31.4</i>	<i>1.1</i>	<i>3.5</i>	<i>Mean s.e.m.</i>	<i>315</i>		<i>706</i>	<i>123</i>
<i>Significance</i>	<i>ns</i>	**	<i>ns</i>	<i>ns</i>					
Shady	17700	2130	790	1.6					
Sunny	17300	1670	348	1.2					
<i>F-ratio</i>	<i>0.5</i>	<i>4.2</i>	<i>2.7</i>	<i>35.8</i>					
<i>Significance</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	**					

*, ** and *ns* denote <5% and <1% significant levels and not significant, respectively

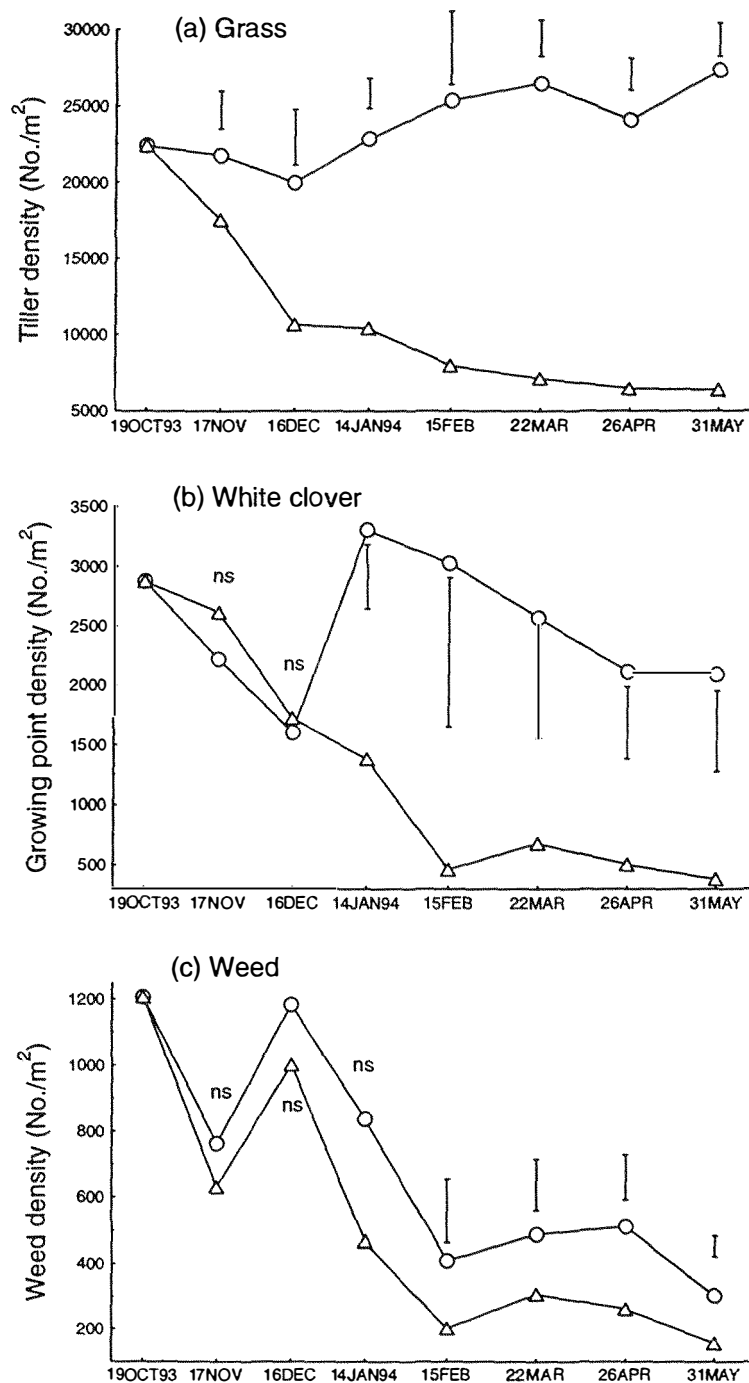


Figure 3.1 Plant population density of grass, white clover and weed under pastoral fallow (Δ) and grazing (O) regimes (vertical bars show $LSD_{0.05}$; ns represents not significant).

3.3.3 Thinning lines

Since grass dominated the sward plant population density (approximately 90% of total plant density), self-thinning lines were calculated based on the fallowed treatments for grass alone (Figure 3.2b), as well as total plant population (Figure 3.2a).

The relationship between total plant density (D) and plant unit size (W , division of total shoot biomass by total density) calculated by PCA followed the $-3/2$ power law with the slope slightly higher than $-3/2$ as follows:

$$\text{Log } W = 8.42 - 1.65 \log D, \text{ percentage eigenvalue} = 97.6\%.$$

The percentage eigenvalue (%EV) is a measure of the variation accounted for by the first principal component.

For grass alone, the equation was:

$$\text{Log } Wg = 7.81 - 1.57 \log Dg, \text{ \%EV} = 90.8\%,$$

where Wg was grass tiller weight and Dg tiller density.

The application of fertiliser had no effect on the self-thinning slope (-1.65 vs -1.66 for fertilised and non-fertilised treatments, %EV = 97.5% and 97.9% respectively) and the intercept (8.39 vs 8.50) for total plant population. The slope (-1.71 , %EV = 97.9%) and intercept (8.66) of the thinning line for the shady aspect were higher than that (-1.54 and 7.97, respectively, %EV = 97.3%) for the sunny aspect.

3.3.4 Sward structure

During pastoral fallowing, the pasture phytomass above 1 cm increased from 1400 kg/ha to 6600 kg/ha (Figure 3.3a). This increase initially resulted from the development of grass tillers (both vegetative and reproductive) and subsequently, dead matter. Reproductive tillers developed most rapidly in the early stage of pastoral fallowing and reached a maximum (2310 kg/ha) in mid-

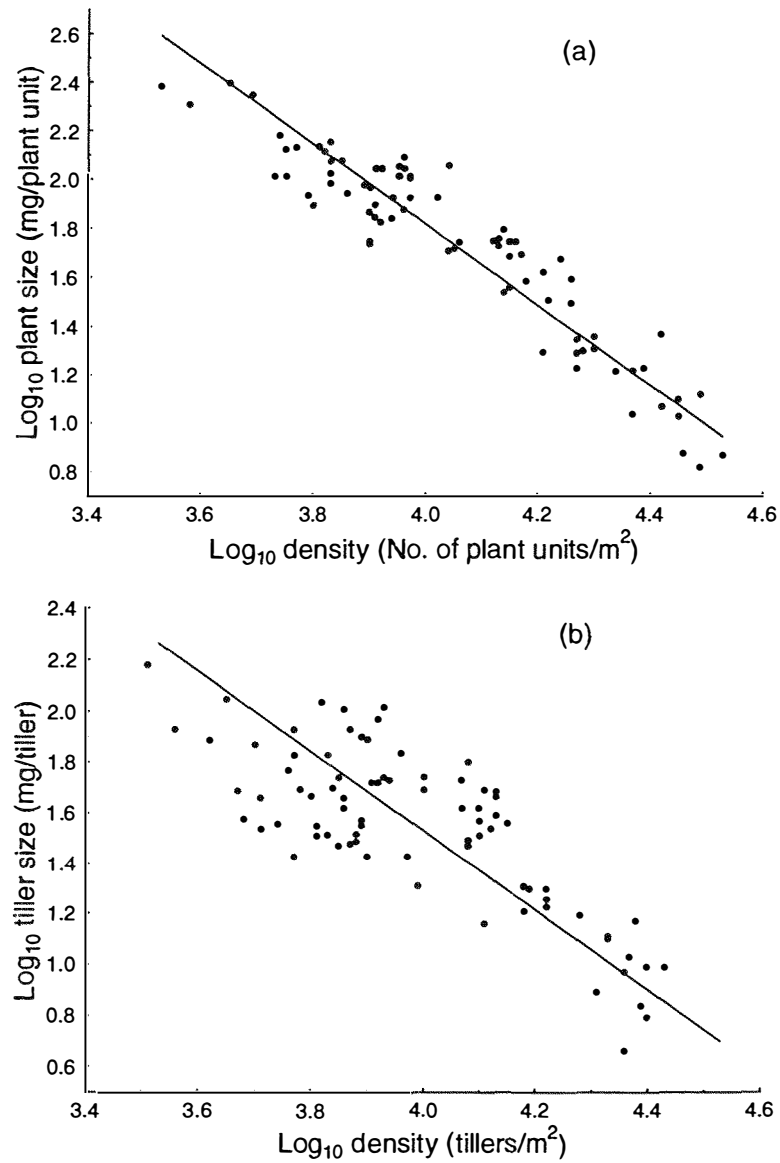


Figure 3.2 Scatter plots and self-thinning lines calculated by Principal Components Analysis: (a) mean plant unit size plotted against total density of all plant species; (b) mean tiller size of grasses plotted against grass tiller density.

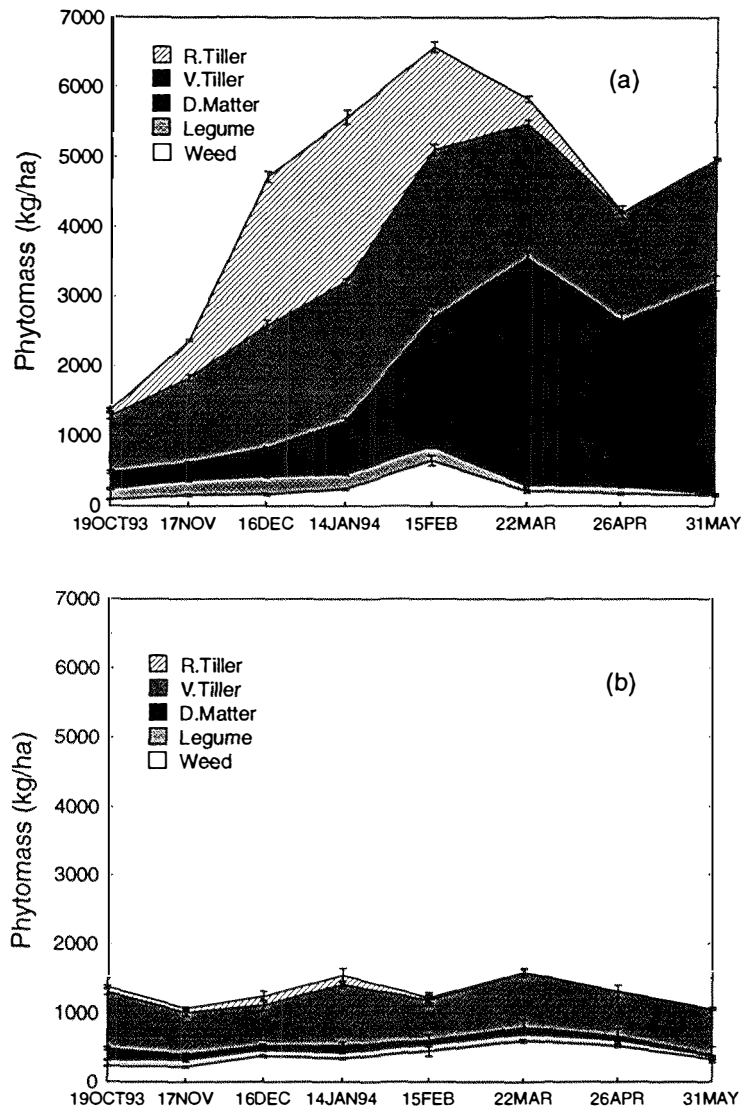


Figure 3.3 Change of sward phytomass of reproductive tillers (R.Tiller), vegetative tillers (V.Tiller), dead matter (D.Matter), legumes and weeds under (a) pastoral following, and (b) grazing (vertical bars show s.e.).

January. There was an increase in phytomass of vegetative tillers from October to January, but this remained relatively constant, subsequently. Initially legumes and weeds accounted for 12% and 7% of the total phytomass, respectively. However, their contribution to pasture phytomass decreased substantially at the conclusion of pastoral fallowing. White clover was the major legume species. The reduction of legume phytomass during pastoral fallowing probably reflected the shift of white clover from growing point growth to stolon growth in response to shading and competition, i.e. branching was restrained and stolon elongation was enhanced (Nie et al., 1996). Dead phytomass increased slowly from October to mid-January, and then rapidly from mid-January to March, when reproductive tillers were senescent.

In contrast with the pastoral fallowing treatment, the components of sward phytomass above 10 mm in the grazing treatment remained relatively stable (Figure 3.3b). Reproductive tillers accounted for only a low proportion (< 10%) of the grazed sward phytomass. The phytomass (2140 kg/ha) of the fallowed sward in the first 10 mm above ground level was significantly ($P < 0.05$) greater than that (1910 kg/ha) of the grazed sward, indicating more phytomass accumulation in this layer during pastoral fallowing.

3.3.5 Comparison of the effects of partial and full pastoral fallows on final plant population densities

There was no significant difference in total initial plant density between treatments (Table 3.2). Significant differences were found between fallowed treatments in grass tiller density ($P < 0.01$) and white clover growing point density ($P < 0.05$), but not in weed density at the end of each pastoral fallow. The late fallowed sward had significantly more tillers and clover growing points, compared with both fertilised and non-fertilised full-fallowed swards, and the early fallowed sward. However, the early fallowed sward was not significantly different from the full-fallowed swards in grass tiller and clover growing point

Table 3.2 Total initial plant density (IPD, plant units/m²), plant density of grass (tillers/m²), white clover (growing points/m²) and weed (plants/m²) and total dry matter (DM) accumulation (kg/ha) under full and partial pastoral fallowing treatments.

Treatment	Total IPD	Grass	Clover	Weed	Total DM
Early fallow	33700	10900	1120	220	9600
Late fallow	30300	23800	2270	310	2900
Full fallow + fertiliser	26800	6350	360	110	6700
Full fallow - fertiliser	26500	6400	410	200	7800
<i>s.e.d.</i>	<i>2533</i>	<i>1636</i>	<i>345</i>	<i>70</i>	<i>1710</i>
<i>Significance</i>	<i>ns</i>	<i>**</i>	<i>*</i>	<i>ns</i>	<i>†</i>

****, ***, *†* and *ns* denote $P < 1\%$, $P < 5\%$, $P < 10\%$ and not significant, respectively.

densities. The DM accumulation (2900 kg/ha) of late fallowed sward was low, compared with either the early or full pastoral fallows ($P < 0.1$).

3.4 DISCUSSION

3.4.1 Treatment effects and mechanisms of tiller population change

The decline of plant population density occurred rapidly after the pastoral fallow started (Figure 3.1 and 3.2). This was due to the high initial total pasture mass (3120 kg DM/ha), which was much greater than the 700 kg DM/ha of pasture mass at which Bircham and Hodgson (1983) observed declines in tiller and stolon densities through self-thinning. The decline in white clover growing point and weed density in the grazed sward in the early stages was probably attributed to the low rainfall during September and October in 1993. Since grass dominated (approximately 90%) the sward population, only the dynamics of grass tiller population during pastoral fallowing are illustrated (Figure 3.4). Loss of grasses tillers was attributed partly to competition and partly to the death of reproductive tillers once they matured. The loss of tillers prior to the January sampling was mainly due to inter-plant competition and subsequently was a combination of tiller mortality due to both competition and maturity. Tiller mortality was calculated by multiplying tiller loss at various stages and the vegetative : reproductive tiller ratio. The initial tiller population density was 22 400 tillers/m², 12% of which entered into reproductive development and died after maturity, 61% died through competition (self-thinning) or other causes such as pests. Only 28% remained at the end of pastoral fallowing. Of the vegetative tillers lost, the majority (89%) died before January, and only 11% died in the period after January. It should be indicated that the tiller loss through competition illustrated in Figure 3.4 was a net change. Daughter tiller production during pastoral fallowing could be reduced by reproductive development and was not taken into account.

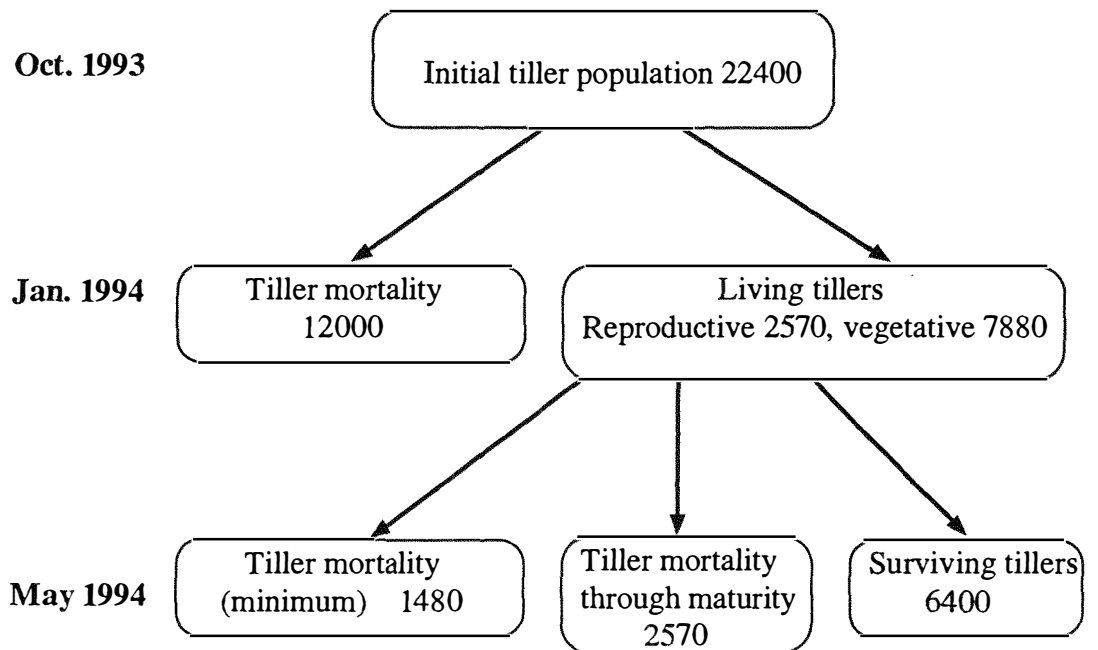


Figure 3.4 Quantitative description of net tiller survival and mortality due to competition and reproduction during an October - May pastoral fallow (unit of tiller density: tillers/m²).

Increases in white clover growing point density appeared to be related to soil moisture availability. Mackay et al. (1991) found that the addition of P and S considerably increased summer legume growth and nitrogen fixation on a shady aspect, but no comparison of aspect effects was made. Fertiliser increased grass tiller density on the sunny aspect. The effect of mass/density compensation was seen, to some extent, in the lower densities of grass and weeds on the fertilised treatment (Table 3.1). The absence of a significant difference in moss abundance between fertiliser treatments was in contrast to the findings of Lambert et al. (1986) who found that high superphosphate application (plus lime) significantly decreased moss incidence. The difference in this result may have been due to a lower fertiliser rate than in the study of Lambert et al. (35 vs 57 kg P/ha) and the use of a water insoluble (phosphate rock) rather than soluble (superphosphate) P fertiliser. The main effect of aspect on plant density was not significant, but the interactions between aspect and fallowing/grazing on tiller density, and aspect and fertiliser on tiller and clover growing point density were significant, which demonstrated that both pastoral fallowing and fertiliser should be used with aspect in consideration.

3.4.2 Self-thinning response

Pastoral fallow significantly reduced the density of all plant species as predicted by the self-thinning rule (Yoda et al., 1963; Westoby, 1984). There are various regression algorithms to calculate the self-thinning line (Sackville Hamilton et al., 1995). Although the Ordinary Least Squares (OLS) regression method was initially used to determine the self-thinning rule (Yoda et al., 1963), it was subsequently recognised as inappropriate because the regression assumes zero error variance in one variable (Mohler et al., 1978; Weller, 1985), which results in extreme estimates (lowest or highest) of slope depending on which variable (density or size) is used as the non-error independent variable. Most analyses are now based on PCA (Weller, 1985, 1987a, b; Morris and Myerscough, 1985; Lonsdale, 1990). The slope of the self-thinning line based

on total plant density (number of plant units/m²) and plant unit size (mg plant/unit) were close to -3/2 with a higher %EV (Figure 3.2a). However, most studies of pastures used grass alone to quantify the tiller size/density relationship (Bircham and Hodgson, 1983; Davies, 1988; Matthew *et al.*, 1996). Lambert *et al.* (1986) used total species in a grazed hill sward, but they only plotted the data with the standard self-thinning to show their fit. When the self-thinning line was calculated on grass alone in this experiment, the slope (-1.57) was close to -3/2 (Figure 3.2b), but the %EV was lower than that based on the total plant population (90.8% vs 97.6%). The deviation of scatter points from the thinning line (Figure 3.2) was greater for grass alone than for total species estimate ($R^2 = 62.0\%$ and 88.4% , respectively based on OLS regression). The use of data from all plant species was probably more appropriate to estimate the self-thinning line of mixed-species swards.

3.4.3 Implications for resowing improved forage germplasm

Since both herbicide spraying and pre-sowing defoliant techniques present problems for oversowing, more appropriate techniques are sought for hill pasture improvement (Barker and Dymock, 1993). A pastoral fallow was expected to reduce plant density and create a favourable environment for oversowing. The accumulation of above-ground biomass during pastoral fallow allowed sufficient inter-plant competition and reproductive development (Figure 3.3a), resulting in a 72% plant loss at the end of the full pastoral fallow. Most decline (93%) in plant density occurred before mid-February. After February the decline was small and occurred at a much slower rate (Figure 3.1a). Thus it is suggested that, in practice, the completion date of a pastoral fallow can be flexibly chosen from February onwards from a plant density point of view, depending on the requirement of other environment conditions for oversowing, such as moisture. In fact, the early pastoral fallow (October - December) treatment was concluded in late December and resulted in final tiller and clover growing point densities which were not significantly different to those of the full pastoral fallows. The decline in plant densities in the late pastoral fallow

(February-May) was not as substantial as the full or early pastoral fallows due to lower pasture accumulation in the autumn, than in the late spring and summer, which was driven in part by low rainfall during February - April 1994. Sufficient pasture growth is necessary for an autumn pastoral fallow to achieve a satisfactory decline of plant population density. This can be obtained by either extending the fallowing period or growth promoting methods such as addition of nitrogen. Decomposition of plant litter which accumulated during pastoral fallowing, especially from January to March (Figure 3.2a), might provide additional nutrients to meet the needs of the seedlings of oversown pasture species. This can be important in the post-appearance survival and initial growth of seedlings (Barker and Zhang, 1988). Significant decline in root mass at 0 - 50 mm soil depth during pastoral fallow (Nie *et al.*, unpublished data) should reduce root competition from remaining plants on the seedlings of oversown species.

A detailed discussion of the effect of pastoral fallow duration was given by Mackay *et al.* (1991). A spring-late autumn pastoral fallow allowed reproductive growth of all species, resulting in considerable natural re-seeding (Nie *et al.*, unpublished data). This may impose strong competition if pasture seeds are oversown. An early-concluded or late-commenced pastoral fallow to avoid seed maturity or seed development may considerably suppress reproduction while retaining the benefit of substantially reducing plant density for oversowing, as long as a sufficient growth is achieved during pastoral fallowing.

In conclusion, pastoral fallowing substantially altered sward structure and decreased plant population density, as predicted by the self-thinning rule, in a hill pasture, which may present a favourable environment for introducing improved forage species (Plate 3.2). A shorter-term partial pastoral fallow will also reduce plant population density and competition from natural reseeding and might offer a more practical method for preparing a pasture for sowing new species. The success rate of sown species following a pastoral fallow needs further study.



Plate 3.2 A close view of the open sward when plant materials have been grazed off by cattle.

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Chapter 4

Influence of Pastoral Fallow on Plant Root Growth and Soil Physical and Chemical Characteristics in a Hill Pasture

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This chapter is based on a paper of the same title (Nie, Z. N.; Mackay, A. D.; Valentine I.; Barker, D. J.; Hodgson, J.; 1997) accepted by *Plant and Soil*.

Abstract

Pastoral fallowing over a growing season (October - May) has a profound effect on standing biomass and sward structure, and this should have an impact on below ground plant growth and soil biological activities. Two field studies were conducted to compare the effects of pastoral fallow with rotational grazing on root growth and soil physical and chemical properties. Root growth and distribution was altered by pastoral fallowing and there was significantly ($P < 0.01$) less root biomass at 0 - 50 mm depth of soil in the fallowed sward than the grazed sward. Compared with the grazed treatment, pastoral fallow increased soil air permeability at 500 mm tension by 38%, saturated hydraulic conductivity by 26%, unsaturated hydraulic conductivity at 20 mm tension by 56% and soil moisture by 10 - 15%, and reduced soil bulk density by 11%. Fallowing had little effect on soil nutrients both at the end of fallowing and two to three years after fallowing, except for small reductions in K and mineral N levels at 0 - 75 mm soil depth.

Key words: air permeability, hydraulic conductivity, pastoral fallow, root biomass, soil moisture, soil nutrient.

4.1 INTRODUCTION

A pastoral fallow, which involves no defoliation of pasture for a period generally from spring to autumn, has been suggested as a management tool to reduce plant population density of hill pasture in preparation for oversowing improved germplasm (Chapter 3; Nie et al., 1997a). While decline in above ground competition on introduced species during a pastoral fallow has been quantified (Chapter 3; Nie et al., 1997a), the impact of pastoral fallow on below ground root density has not been reported. Seager (1987) indicated that below ground competition is a major factor influencing the growth and development of ryegrass (*Lolium perenne* L.) seedlings in a hill pasture. Sangakkara (1983) concluded that root competition between grass species began earlier and had a

greater impact on the overall competitive relationships between the species than shoot competition. The capacity of below ground competition of a plant species is predominantly determined by root density and distribution in the soil.

Studies have also shown that a pastoral fallow stimulates mineralisation of soil organic matter and the release of nitrogen (N) fixed by legumes, and improves white clover (*Trifolium repens* L.) growth and content in a hill pasture for up to four years post-fallowing (Mackay et al., 1991; Nie et al., 1996; Chapter 7). However, the impact of these changes on the soil resource during a pastoral fallow has received little attention.

Stock treading can cause leaf crushing and bruising, plant displacement and burial, and root damage as a result of direct hoof impact (Edmond, 1963). Animal traffic and treading pressures also exert considerable forces on the soil. Soil pressures from sheep and cattle hooves may reach 200 to 350 kPa, considerably higher than those exerted by a tractor which range from 30 to 150 kPa (Proffitt et al., 1993). As a result, the increase in bulk density and decrease in macroporosity which occurs during compaction can restrict root development, inhibit air and water movement, and hence decrease plant growth (Watkin and Clements, 1978; Climo and Richardson, 1984; Naeth et al., 1990). Thus, the development of farm management practices which aim to restore the structural condition of soil is of great importance for sustainable agricultural production, especially in a system where grazing often occurs on wet soil (Edmond, 1974; Willatt and Pullar, 1983). During a pastoral fallow, the impacts of animal traffic and treading are ameliorated, providing an opportunity for a soil to restore physical structure.

This chapter describes changes in root biomass and distribution and a range of soil physical and chemical properties (air permeability, hydraulic conductivity, soil moisture and nutrients) between fallowed and grazed hill pastures.

4.2 MATERIALS AND METHODS

4.2.1 Site

Two experiments were carried out at the AgResearch Hill Country Research Station, Ballantrae (40° 19' S, 175° 50' E), 20 km east of Palmerston North. The trial site was split between a south (shady) and north (sunny) face. The soil was a yellow-grey earth/yellow-brown earth intergrade (Typic Dystrochrept) of sedimentary origin, with average pH 5.4 and Olsen P 10 µg P/g soil. No fertiliser had been applied in the 10 years before 1989. Mean monthly rainfall during the experimental period (October 1993 - May 1994) was 83.3 mm, 86% of the 24-year average. Full details of trial site are described by Nie et al. (1997a; Chapter 3).

4.2.2 Design and treatments

Experiment 1 was a split-plot design with three replicates on the shady and two on the sunny aspect. Individual main plot size was 500 - 800 m², split in half as split-plots (sub-plots). The main plots involved two treatments: 1) fertilised treatment which received 35 kg P/ha/year as North Carolina reactive phosphate rock, and 14 kg S/ha/year of elemental sulphur from 1989 to 1993; 2) non-fertilised treatment. The sub-plots involved two treatments: 1) fallowed treatment which was not defoliated from 19 October, 1993 until 31 May, 1994; 2) non-fallowed treatment which was rotationally grazed by sheep with herbage mass not exceeding 3000 kg dry matter (DM)/ha.

To monitor long-term effects of pastoral fallow on soil chemical characteristics, soil samples were taken and analysed in Experiment 2 which was a randomised complete block (RCB) design with four treatments replicated three times on the shady and two times on the sunny aspect. The four treatments were: 1) and 2) the same treatments of the above main plot treatments (fertilised and non-fertilised), sampled before the fallowing treatments were

imposed; 3) previously fallowed from September 1989 until May 1990 (PF89); 4) previously fallowed from September 1990 until April 1991 (PF90).

4.2.3 Measurements

4.2.3.1 Root biomass

On 8 June 1994 five, 50-mm diameter cores were sampled in each plot of the fertilised fallowed and fertilised grazed treatments on the shady aspect to measure root biomass from Experiment 1. Cores were trimmed to remove above ground plant material, divided into 0-50, 50-100, 100-200, 200-400 and 400-600 mm depths, and the five cores from each plot were combined and evenly mixed within each depth. Soil was washed from a 450 - 500 g sub-sample from each depth using water and fine (200 μm) mesh nylon bags. Roots were further cleaned by hand picking stones and particles that could not pass through the 200 μm mesh nylon bags before being dried at 65 °C for 48 hours.

4.2.3.2 Soil moisture

Time-Domain-Reflectometry (TDR) (Trase - Model 6050X1, Soil Moisture Equipment Corp, California, USA) was used to measure volumetric soil moisture along a 150-mm length of wave guide on 27 April 1994 (Topp and Davis, 1985). The manufacturer's calibration were confirmed as being sufficiently close to manual determinations of volumetric soil water content using 100 mm diameter rings to 75 mm depth. The wave guides were installed perpendicular to the soil surface. Ten readings were recorded in each of twelve sub-plots from the shady aspect of Experiment 1. Gravimetric soil moisture was measured by collecting twenty soil cores of 25 mm diameter and 50 mm depth in each plot on 28 April 1994. Fresh soil samples were weighed and oven-dried at 105 °C for 24 hours.

4.2.3.3 Soil hydraulic conductivity, air permeability and bulk density

Along with the measurement of root biomass, ten soil cores of 100 mm diameter and 77 mm depth were collected using stainless steel tubes in the same plots to measure hydraulic conductivity, air permeability and bulk density. The base of each core was trimmed off level with the stainless steel edge, then treated with plaster of Paris to allow the soil to fracture across its natural weakness. This treatment removed loose fragments of soil, roots and any smearing as a result of cutting. Washed and graded sand was added to the base to bring it up to a smooth level surface and a nylon cloth with a hole size of 90 μm was placed on to the base and held tightly in position with large rubber bands. The cores were then saturated in a stainless steel tray for four days, and saturated hydraulic conductivity was measured by obtaining, at a minimum, three consistent recordings of water flow rate through the cores. Unsaturated hydraulic conductivity was measured with tensions of 20, 40 and 100 mm applied to the permeameter. Air permeability was measured at 100, 200 and 500 mm of tension using flow gauges and a graduated U-shape tube filled with water. Bulk density was determined following oven-drying of the cores at 105 °C.

4.2.3.4 Soil nutrient analysis

On 22 October 1993, twenty-five, 75 mm deep and 25 mm diameter soil cores were taken from each plot of Experiment 2, then air-dried and analysed for Ca, K, P, Mg, Na, S, anion storage capacity and organic sulphur.

At the conclusion (31 May 1994) of the 1993/94 pastoral fallow, twenty, 75 mm deep and 25 mm diameter soil cores were taken from each of twelve sub-plots from the shady aspect and analysed for soil pH and exchangeable Ca and K and extractable P and S, Mg, Na, organic carbon and organic sulphur in the soil. On the same day, ten, 25 mm diameter soil cores were sampled from each of the six fertilised subplots to analyse ammonium nitrogen ($\text{NH}_4^+\text{-N}$) and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) on a field moist soil sample. These soil cores were divided into 0-75, 75-150 and 150-300 mm depths. Mineral nitrogen was

calculated by summing NH_4^+ -N and NO_3^- -N. The soil analytical methods are described in Blakemore et al. (1987).

4.2.4 Statistical analysis

Data were analysed by Analysis of Variance (ANOVA) using a pooled split-plot model, with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS Institute, 1990). A randomised complete block (RCB) design was used to compare air permeability, bulk density, root biomass and soil nitrogen content between fallowed and grazed treatments. A pooled RCB design was used to analyse the soil nutrient content of fertilised, non-fertilised and previously fallowed treatments.

4.3 RESULTS

4.3.1 Root biomass and distribution

Root biomass declined with sampling depth, with the 0-50 mm soil depth accounting for 74% and 62% of the total root biomass (0-600 mm soil depth) for the fertilised grazed and fertilised fallowed swards, respectively (Figure 4.1). There was significantly ($P < 0.01$) lower root biomass under the fallowed sward than the grazed sward at 0-50 mm soil depth. However, there were no significant ($P > 0.1$) differences in root biomass between fallowed and grazed plots at other soil depths.

4.3.2 Soil moisture

Soil moisture of 0-50 mm depth was significantly ($P < 0.05$) higher in the fallowed than in the grazed sward (Table 4.1). The soil moisture of the fallowed treatment at 0-150 mm depth was also higher ($P < 0.1$) than the grazed treatment.

Soil moisture on the sunny aspect was significantly ($P < 0.01$) lower than on the shady aspect at all soil depths. The difference in soil moisture between fertilised and non-fertilised treatments was not significant ($P > 0.1$) for 0-50

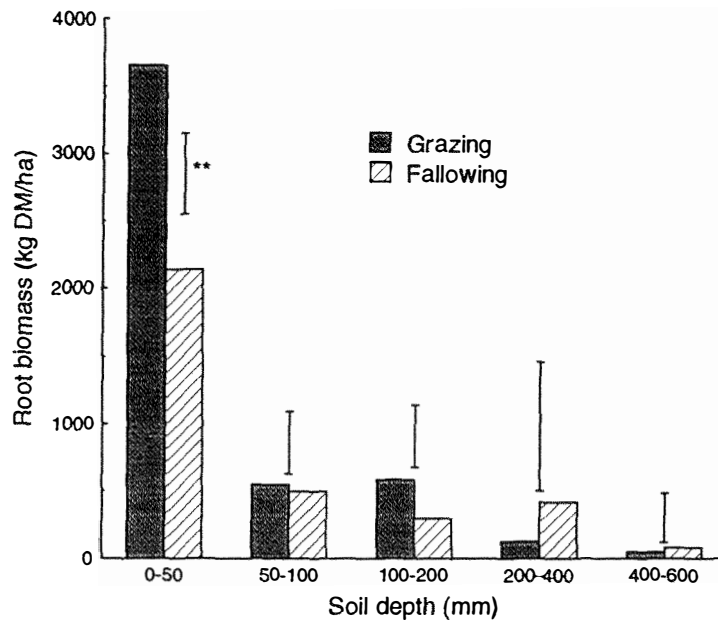


Figure 4.1 Root biomass of a range of soil depths under fallowing and grazing (bars indicate $LSD_{0.05}$; ** represents $P < 0.05$).

Table 4.1 Effects of pastoral fallow, fertiliser and aspect on gravimetric (0-50 mm depth) and volumetric (0-150 mm depth, TDR tested) soil moisture (%) at the late stage (27-28 April 1994) of a spring - autumn fallow.

Treatment	Soil depth (mm)	
	0-50	0-150
Fallow	28.2	25.4
Grazing	25.6	22.1
<i>s.e.m.</i>	0.66*	0.99†
Shady aspect	32.6	29.1
Sunny aspect	18.4	15.8
<i>s.e.m.</i>	0.74**	1.52**
Fertiliser added	27.9	24.8
No fertiliser	25.9	22.7
<i>s.e.m.</i>	1.14	0.82†

** , * and † represent $P < 0.01$, $P < 0.05$ and $P < 0.1$, respectively.

depth, but significant ($P < 0.1$) for 0-150 mm depth with an increased soil moisture by fertiliser application.

4.3.3 Air permeability, bulk density and hydraulic conductivity

Air flow was greater through the cores collected from fallowed plots at all tensions of 100, 200 and 500 mm, with the difference between the fallowed and grazed treatments reaching the significance ($P < 0.05$) at a tension of 500 mm (Table 4.2). The bulk density (0.65 Mg/m^3) of fallowed soil was lower ($P < 0.1$) than that (0.72 Mg/m^3) of the grazed soil.

The saturated hydraulic conductivity (483 mm/hr) of fallowed soil was significantly ($P < 0.05$) higher than that (383 mm/hr) of the grazed soil (Figure 4.2). The unsaturated hydraulic conductivity (152 mm/hr) of fallowed soil at 20 mm of tension was 67% higher, though not significant, than the grazed soil (91 mm/hr). There were minor differences in unsaturated hydraulic conductivity at 40 and 100 mm of tension between fallowed and grazed soils.

4.3.4 Soil nutrients

At the end of the October - May pastoral fallow, the two detectable differences in nutrient content were K and mineral N level at 0-75 mm soil depth, which were significantly ($P < 0.01$ and 0.05 , respectively) higher on the grazed than the fallowed plot (Table 4.3 and 4.4). There was no significant difference in either $\text{NH}_4^+\text{-N}$ or $\text{NO}_3^-\text{-N}$ at all soil depths between the two treatments (Table 4.4). There was also no significant ($P > 0.05$) difference in other nutrient levels including P, S, Ca and Mg, pH, organic carbon and organic sulphur levels.

Soil pH of both previously fallowed treatments (PF89 and PF90) was significantly ($P < 0.01$) higher than that of the fertilised treatment which was significantly higher than that of the non-fertilised treatment (Table 4.5). There were lower ($P < 0.1 - 0.01$) Ca, P and Na levels in the non-fertilised treatment

Table 4.2 Air permeability ($\times 10^{-12} \text{ m}^2$) and bulk density (Mg/m^3) of fallowed and grazed sward at the conclusion (31 May 1994) of a spring - autumn fallow.

Treatment	Tension (mm)			Bulk density
	100	200	500	
Fallow	4.3	5.5	43.0	0.65
Grazing	2.8	4.5	31.2	0.72
<i>s.e.m.</i>	1.3	0.3	1.3*	0.02†

* and † represent $P < 0.05$ and $P < 0.1$, respectively.

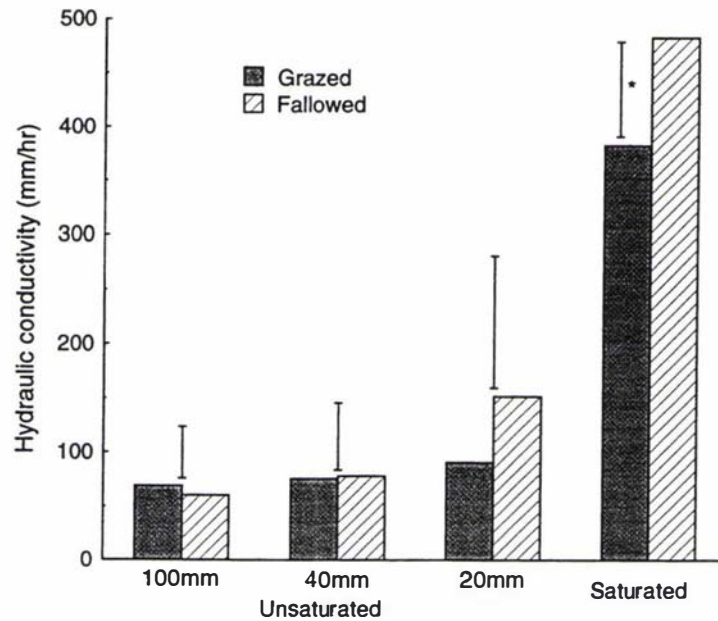


Figure 4.2 Saturated and unsaturated hydraulic conductivity at tensions of 100, 40 and 20 mm in grazed and fallowed soils (bars indicate $LSD_{0.05}$; * represents $P < 0.05$).

Table 4.3 Soil nutrients of fallowed and grazed treatments at the conclusion (31 May 1994) of a spring - autumn fallow (OC and OS are organic carbon and organic sulphur, respectively).

Treatment	pH	Ca	Mg	K	Na	Olsen-P	SO ₄ -S	OS	OC
		—cmol(charge)/kg soil ^a —				—mg/kg soil—			%
Fallow	5.3	3.5	1.3	0.4	0.3	14.4	12.2	11.3	5.4
Grazing	5.3	3.6	1.3	0.5	0.3	13.5	8.9	11.0	5.8
<i>s.e.m.</i>	<i>0.03</i>	<i>0.11</i>	<i>0.02</i>	<i>0.01</i> **	<i>0.01</i>	<i>0.74</i>	<i>2.21</i>	<i>0.66</i>	<i>0.19</i>

** represents $P < 0.01$; ^a meq%.

Table 4.4 Ammonium-nitrogen (N as NH_4^+), nitrate-nitrogen (N as NO_3^-) and their total (mineral-N) content of soil at three soil depths (mm) for fallowed and grazed treatments (31 May 1994).

Soil depth	Treatment	N as NH_4^+	N as NO_3^-	Mineral N
		-----mg/kg soil-----		
0 - 75	Fallow	23.7	11.8	35.5
	Grazing	30.9	11.5	42.4
	<i>s.e.m.</i>	4.04	3.90	1.17*
75 - 150	Fallow	16.9	9.5	26.4
	Grazing	22.5	9.0	31.5
	<i>s.e.m.</i>	3.04	1.18	3.10
150 - 300	Fallow	14.9	9.2	24.1
	Grazing	18.0	9.0	27.0
	<i>s.e.m.</i>	2.35	0.15	2.31

* represents $P < 0.05$.

Table 4.5 pH and soil minerals (mg/kg soil) of fertilised (Fert+), non-fertilised (Fert-), 89/90 fallowed (PF89) and 90/91 fallowed (PF90) treatments tested on 19 October 1993 (PR and OS represent phosphorus retention (%) and organic sulphur, respectively).

Treatment	pH	Ca	K	P	Mg	Na	S	PR	OS
Fert+	5.36b	5.2a	6.2	11.2a	28.2	8.6ab	5.8	31.6	5.4
Fert-	5.3c	4.6b	7.2	7.6b	30.0	8.2b	6.8	33.6	5.2
PF89	5.4a	5.4a	6.6	10.6a	29.2	9.4a	6.0	30.6	5.6
PF90	5.4a	5.0ab	6.2	12.0a	26.4	9.2a	6.6	32.8	6.4
<i>s.e.m.</i>	0.004**	0.11*	0.27	0.53*	1.79	0.22†	0.46	1.39	0.32

** , * and † represent $P < 0.01$, $P < 0.05$ and $P < 0.1$, respectively; means with different superscripts are significantly different.

compared with the fertilised treatments. There were no significant ($P > 0.1$) differences in other soil nutrient content between treatments.

4.4 DISCUSSION

4.4.1 Root biomass

The reduction in plant number on the fallowed plots was accompanied by a decline in root biomass compared with the grazed plots in the top soil (0 - 50 mm depth). At the end of the pastoral fallow, Nie et al. (1997a) reported that the total plant population density (29700 plants and tillers/m²) of the grazed sward was 4.3 times that (6910 plants and tillers/m²) of the fallowed. If each plant or tiller of grass has its own root system, then substantially more plants/tillers in the grazed sward resulted in a significantly higher root biomass at 0-50 mm deep soil than the fallowed sward. Similar results were observed with increasing grazing pressure (Deinum, 1985; Barker et al., 1988). Low root biomass at 0 - 50 mm depth under the fallowed sward should favour the practice of using pastoral fallow as a tool to reduce plant shoot and root competition and oversow new plant germplasm (Nie et al., 1997a). Studies have shown that seedling survival is influenced by competition from existing vegetation while oversowing hill country pastures (Seager, 1987), and below ground competition occurred before, and was more severe than, above ground competition (Sangakkara, 1983). Reduced root biomass at 0 - 50 mm below ground as well as reduced plant population density above ground (Nie et al., 1997a) may present a favourable environment for seedling survival while oversowing in hill country.

Root biomass decreased with increasing soil depth for both fallowed and grazed treatments, the proportion of root biomass at depths >50 mm in the soil profile was similar for the two treatments (Figure 4.1). This indicates that pastoral fallowing encouraged the growth of fewer, larger plants with more, deeper roots per plant than the grazed sward. The smaller plants in the grazed

sward could result in a shallower root system, and compaction by grazing may also decrease rooting depth (Shierlaw and Alston, 1984).

Mackay et al. (1991) also found a higher root biomass below 200 mm soil depth in the fallowed swards than the grazed swards, but unlike the present study, root biomass in the fallowed swards was also higher in the upper (0-200 mm) soil profile. Interestingly, in the study of Mackay et al. (1991), root biomass was sampled in early May, four weeks earlier than in the present study. The higher absolute root density reported in that study on both the fallowed and grazed swards, is consistent with a pattern of declining root biomass from the peak root biomass in early summer till the autumn/winter period measured by Matthew et al. (1991), and supported by the data for a hill pasture environment (D.J. Barker, personal communication). In late spring with above ground biomass in excess of 5000 kg DM/ha on the fallowed plots compared with only 2000 kg DM/ha on the grazed pasture, root density would probably be higher at all soil depths on the fallowed plots. Associated with the subsequent dramatic loss in plant number from >20000 to <7000 plants/m² on the fallowed plots from spring till late autumn (Nie et al., 1997a), would be the accelerated loss of plant root biomass, resulting in lower root biomass on fallowed compared to grazed plots by the end of the fallow. Seasonal variation of root biomass and quantity of plant loss during fallowing may affect the results of root biomass comparing fallowed and grazed swards.

4.4.2 Soil physical properties

The effect of grazing wet soils has been recognised as a potential problem in New Zealand, the U.S.A., and the U.K. since 1930s (Sears, 1956; Proffitt et al., 1993). Stock treading has been shown to increase soil bulk density and decrease water infiltration and/or hydraulic conductivity (Edmond, 1974; Willatt and Pullar, 1983; Burch et al., 1986). Compared with the grazed treatment, removing stock grazing and treading through a spring - autumn pastoral fallow resulted in an 11% reduction in soil bulk density ($P < 0.1$), a 38% increase in air

permeability at 500 mm tension ($P < 0.05$), a 26% increase in saturated hydraulic conductivity ($P < 0.05$), and a 67% increase in unsaturated hydraulic conductivity at 20 mm tension. Similar pastoral fallow effects on soil infiltration rate were observed by Proffitt et al. (1993). Although reduction in bulk density indicates an increase in soil porosity, it provides little information on pore size distribution and function. The measurement of unsaturated hydraulic conductivity at 20, 40 and 100 mm tensions presents an indication of the flow rate of water through pores $>1500 \mu\text{m}$, $>750 \mu\text{m}$ and $>300 \mu\text{m}$, respectively. In the present study, the increase in both saturated, and unsaturated hydraulic conductivity at 20 mm tension on fallowed soil showed improved water flow rates as a result of an increase in large pores ($>1500 \mu\text{m}$) compared with the grazed soil. The mechanisms that reduced bulk density and improved hydraulic conductivity during pastoral fallowing were probably the release of soil from compression by stock treading, the growth and subsequent decay of plant root systems and the activity of soil fauna, such as earthworms, which increase soil porosity. These results demonstrate that pastoral fallow can be an effective management option to reduce soil structural deterioration caused by stock treading. However, in this situation the soil physical properties of the grazed sward were unlikely to inhibit pasture growth.

The fallowed sward had higher moisture content at 0 - 50 mm depth of soil than the grazed sward (Table 4.1). This was probably attributed to 1) the accumulation of plant litter at the base of the sward and dead standing plants following the completion of life cycle (after reproduction) in February/March, which formed a layer of "mulch" on the soil; 2) a lower transpiration rate due to the smaller area of green leaves at the late stage of fallowing (Nie et al., 1997a). A number of authors (Kamara, 1986; Hulugalle and Palada, 1990; Yunusa et al., 1994) have shown that mulching can restrain soil evaporation, and hence increase the availability of soil moisture. It would be an advantage of pastoral fallow to increase soil water conservation as well as to reduce soil compaction, because mechanical methods to reduce soil bulk density and increase soil porosity can result in a significant drier soil profile (0 - 700 mm)

(Harrison et al., 1994). Furthermore, soil moisture content is the most dominant factor affecting seed germination and seedling establishment (Harper and Benton, 1966; McWilliam and Dowling, 1970) if pastoral fallow is used to reduce resident plant population density for oversowing improved germplasm.

Soil moisture on the south aspect was significantly higher than on north aspect, primarily due to considerably greater solar radiation and potential evapotranspiration on the north aspect, which is similar to Radcliffe's findings (1967 and 1981). Plots receiving fertiliser had higher soil moisture content (0 - 150 mm soil depth) than non-fertilised plots, probably due to more organic matter accumulation in the fertilised sward by a long-term (1989 - 1993) fertiliser use. It was reported that as organic matter levels increase, a soil could hold more water (Wind and Schothorst, 1964; Climo and Richardson, 1984; Sheath and Boom, 1985). Indirect evidence was that higher soil water content was found on animal camps and tracks (Radcliffe, 1967).

4.4.3 Soil chemical properties

In general, pastoral fallow had no significant ($P > 0.1$) effects on the content of most nutrients in soil both during the fallowing period and in the post-fallow period (2 - 3 years), compared with the grazed treatment (Table 4.3 and 4.5). The significant difference in Ca, P and Na levels between previously fallowed treatments with added fertiliser and the non-fallowed treatments with or without added fertiliser appeared to be a fertiliser effect in that only the non-fertilised treatment had significantly lower Ca, P and Na levels (Table 4.5).

Pastoral fallow resulted in a slightly lower K content, and mineral N content at 0 - 75 mm soil depth at the end of fallow, compared with the grazed sward (Table 4.3 and 4.4). There are two possible reasons for this. Firstly, exclusion of grazing animals in the fallowed sward eliminated input of dung and urine which mostly contains the nitrogen and potassium in rapidly available form (Sears, 1956). Secondly, the high pasture growth rate during pastoral fallowing

(Mackay et al., 1991) may lead to nutrient depletion. It is well known that, in pastoral systems, grass and clover may compete actively for N, P, K and S (Donald, 1963). Because soil P and S levels had been raised in the fertilised plots of this experiment, it is, therefore, not surprising that N and K were deficient in the fallowed sward. Another possible factor reducing mineral N content in the fallowed sward was less N fixation (Mackay et al., 1991), the herbage mass of legumes declining by 83.7% during the fallowing period (Nie et al., 1997a).

Both grass tiller population and pasture production were markedly increased in the fallowed sward one to two years after fallowing (Nie et al., 1996 and 1997b). This may result from: 1) the improvements of soil physical properties by fallowing; 2) the mineralisation of plant residues and soil organic N being stimulated shortly after the conclusion of pastoral fallowing (Mackay et al., 1991).

Soil pH was not affected at the end of a pastoral fallow, but was slightly increased two years after fallowing. Because acid and moderately acid soils (pH 5 - 6) are wide-spread in farmed areas of New Zealand (Carran, 1992), the use of pastoral fallow to raise soil pH may be of benefit. However, the mechanism for this soil pH increase needs further investigation.

In conclusion, pastoral fallow reduced the root biomass at top soil, improved soil physical properties, e.g. soil porosity, air permeability, hydraulic conductivity and moisture, but had little effect on soil chemical properties.

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Chapter 5

Influence of Pastoral Fallow on Natural Reseeding in a Hill Pasture

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This chapter is based on a paper of the same title (Nie, Z. N.; Barker, D. J.; Valentine I.; Mackay, A. D.; Hodgson, J.; 1997) submitted to *Journal of Applied Ecology*.

Abstract

1. A pastoral fallow is a management tool that either encourages natural reseeding for increasing sward persistence and productivity, or reduces plant population density through self-thinning for oversowing improved plant germplasm. Two field experiments were carried out in a hill pasture, (i) to identify patterns of cumulative seedling appearance of grasses, legumes and weeds in fallowed and grazed swards through glasshouse germination measurement, and (ii) to investigate the change of viable seed population of these species during a spring - autumn pastoral fallow.

2. Regression analysis revealed that the patterns of cumulative seedling appearance followed a modified negative exponential function. Partial differentiation of this function derived a germination rate curve on which a two-pool (rapidly germinable pool and base pool) model was developed to quantitatively describe the seed dynamics of soil viable seed reserves.

3. A spring - autumn pastoral fallow increased the viable grass, legume, weed and the total seed population by 51-160%, compared with the grazed control. Fertilizer application reduced the viable grass seed population by 26%. The viable legume seed population was higher on a shady than on a sunny aspect.

4. Short duration (2 - 3 months) pastoral fallows resulted in significantly lower viable grass seed population than the full (spring - autumn) fallows.

5. The variation in soil viable seed population during a spring - autumn pastoral fallow followed a predictable pattern, which provides useful information for either utilising or restricting natural reseeding in practice.

Key words: hill pasture, natural reseeding, pastoral fallow, viable seed population.

5.1 INTRODUCTION

Natural reseeding is the process of plant regeneration from seeds produced by resident parent plants. It has been recommended as a means to rehabilitate rangeland (Sampson, 1952) and to rejuvenate a declining content of desirable pasture species (Langer, 1973; East et al., 1980; Yang et al., 1988). The importance of natural reseeding for new plant recruitment to maintain sward persistence of prairie grass (*Bromus willdenowii* Kunth) (Boom and Sheath, 1990; Hume et al., 1990) and perennial ryegrass (*Lolium perenne* L.) (L'Huillier and Aislabie, 1988) has been demonstrated in New Zealand. In a North Island dairy system, natural reseeding doubled the tiller density of perennial ryegrass and increased pasture growth by 15 - 19% in the year following a spring - summer deferred grazing, which allowed the resident ryegrass to set seed (McCallum et al., 1991).

The potential of natural reseeding is determined by the viable seed population beneath a pasture, which further depends on the balance between seed gains and losses (Harper, 1977; Howe and Chancellor, 1983). Since seed gains result largely from the amount of seed shed from matured plants (Howe and Chancellor, 1983), allowing reproductive development of a sward is essential to increase buried seed reserves. Studies showed that a pastoral fallow (otherwise called deferred grazing or summer spelling), where pasture is not defoliated for a period from summer - autumn, is effective in encouraging seedhead numbers and natural reseeding (Sheath and Boom, 1985; Boom and Sheath, 1990; Hume and Barker, 1991; McCallum et al., 1991). However, the success rate of natural reseeding is greatly related to the *in situ* climate, edaphic conditions, seed germination and seed dormancy of plant species (Howe and Chancellor, 1983; Hume and Barker, 1991). This was reflected in large variation in natural reseeding in dry hill country among sites and years (Hume and Barker, 1991). Therefore, an estimate of germination patterns of viable seeds of different plant species beneath pastures, the change in viable

seed population during pastoral fallow and its relation to climate and soil conditions is needed to improve our understanding of the natural reseeding ability of pastures.

Knowledge of the natural reseeding characteristics of a hill pasture would also prove useful for reducing the competition to improved germplasm introduced by oversowing. A pastoral fallow provides an effective tool for reducing plant population density, through inter-plant competition and self-thinning, in order to present a potentially favourable environment for oversowing improved pasture species (Nie et al., 1997). Despite the reduction in competition from established plants as a result of the pastoral fallow, the competition from seeds shed from the resident plant species during a spring - autumn pastoral fallow would be intense. To reduce this competition, information on how the viable seed population of pasture responds to various timing and duration of pastoral fallows is required.

Understanding the dynamics of viable seed populations of fallowed and grazed pasture is important for making management recommendations either to encourage natural reseeding for increasing the persistence and productivity of desirable species, or to minimise natural reseeding to lessen the competition to improved germplasm introduced by oversowing.

This paper describes two studies designed to (a) measure the patterns of cumulative seed germination under fallowed, previously fallowed and grazed swards, and (b) investigate the change of reseeding potential of grasses, legumes and weeds due to pastoral fallow, fertility and aspect.

5.2 MATERIALS AND METHODS

5.2.1 Site and treatments

Two experiments were conducted at the same site at the AgResearch Hill Country Research Station, 'Ballantrae' (40° 19' S, 175° 50' E, 250 m altitude) near Palmerston North, New Zealand. The pasture consisted of predominantly low fertility-tolerant grasses such as browntop (*Agrostis capillaris* L.) and sweet vernal (*Anthoxanthum odoratum* L.) with small quantities of perennial ryegrass and white clover (*Trifolium repens* L.). The proportions of grasses, legumes and weeds at the field site were 79, 13 and 8% of plant density, respectively, at the commencement of the experiment. Full details of the site are outlined by Nie et al. (1997; Chapter 3).

Experiment 1 had three treatments randomised in three blocks on a south (shady) aspect and two blocks on a north (sunny) aspect. The area of individual plots ranged from 500 - 800 m². The three treatments were:

- (1) Fallowed September 1990 - April 1991 (F90/91);
- (2) Fallowed September 1991 - May 1992 (F91/92);
- (3) Not fallowed (grazed).

Apart from the two fallow periods, all plots were continuously grazed by sheep to prevent herbage mass exceeding 3000 kg DM/ha. All plots received 35 kg P/ha/year as North Carolina reactive phosphate rock and 14 kg S/ha/year as elemental sulphur, from 1989 to 1992.

Experiment 2 was a split-plot design with fertilizer/non-fertilizer treatments as main plots and fallowing/grazing treatments as sub-plots, replicated three times on the shady aspect and twice on the sunny aspect. The fertilised plots received the same fertilizers at the same rates as Experiment 1. The fallow period was from 19 October 1993 to 31 May 1994. Two additional treatments were designed to examine the effect of partial fallowing, one fallowed from 19

October to 31 December 1993, and the other fallowed from 17 February to 31 May 1994. Full details of the treatments and grazing management were given by Nie et al. (1997; Chapter 3).

5.2.2 Measurements

5.2.2.1 Experiment 1

At the completion of F91/92 on 26 May 1992, twenty 50 mm turf plugs were collected from each plot of all treatments and put in a glasshouse at a temperature of 20 °C for 7.5 months. Grass, legume and weed seedlings were counted and removed at two to four week intervals in the first ten weeks after harvest (26 May 1992), and at six to ten week intervals for the rest of the measurement period. Turf plugs were trimmed to soil surface at each seedling counting and watered to keep moisture for seed germination. Viable seed population was the germinable seed number during the experimental period and did not include the dormant seeds.

5.2.2.2 Experiment 2

At the start (19 October 1993), middle (15 February 1994) and end (31 May 1994) of the experiment for all treatments, and on 29 December 1993 and 22 March 1994 for fallowed swards, twenty 50 mm soil plugs were collected from each plot to test the reseeding potential of grasses, legumes and weeds. Difficulties in identifying seedlings amongst growing tillers in Experiment 1 led to modifying the technique in Experiment 2. The soil plugs were sprayed with glyphosate, which was assumed to have no detrimental effect on seed viability, to eliminate the resident vegetation, then put in a glasshouse with an automatic watering system at 20 °C for seven months. One week after the spray, plugs were trimmed to the soil surface, and grass, legume and weed seedlings were counted and removed at four to eight week intervals depending on seedling density.

5.2.3 Statistical analysis

Data were analysed by Analysis of Variance using a pooled randomised complete block (RCB) or split-plot model, with the General Linear Model procedure of the Statistical Analysis System (SAS Institute, 1990). A RCB model was used to analyse the data of Experiment 1, and to compare the effects of fallowing treatments during the middle stages of the experiment, and the final effects of full and partial fallows on natural reseeding in Experiment 2. A pooled split-plot model was used to analyse general effects of fallowing, fertilizer and aspect in Experiment 2. The equations of cumulative seedling density and germination time for Experiment 1 were calculated by the NLIN (non-linear regression) procedure of the Statistical Analysis System using the Marquardt option.

5.3 RESULTS

5.3.1 Rainfall and temperature

While mean monthly rainfall during Experiment 1 (115.8 mm/month) and Experiment 2 (83.3 mm/month) was similar to the 26-year average (differences = +8% and -14%, respectively), monthly rainfall for Experiment 2 during November 1993 was 168.9 mm, 84% over the 23-year average (91.8 mm), and from January to March 1994 was only 57.5 mm in average, 66% of the 24-year average (87.5 mm). Mean monthly air temperature (12.2 °C and 13.8 °C) during the experimental period of both years was similar to the 26-year average (mean 13.8 °C).

5.3.2 Experiment 1

5.3.2.1 Viable seed population

Grasses comprised 77% of the total viable seed population that germinated over the 7.5 month test period, while weeds and legumes were only 18% and 4%, respectively (Table 5.1). There were significant differences ($P < 0.05$) between treatments in grass viable seed population and in the total viable seed population of grasses, legumes and weeds, which were the result of considerably higher grass and total seedling population (21480 and 26310 seedlings/m², respectively) for F91/92, than F90/91 and the grazed sward (means 5450 and 7790 seedlings/m², respectively). The effects of treatments on the viable seed population of legumes and weeds were marginal ($P < 0.1$) but with trends similar to those for total and grass viable seed population.

5.3.2.2 Pattern of cumulative seedling population

The germination rate of grasses in the F91/92 treatment was much higher in the early than late stages of the test period (Figure 5.1a). Of the total germinated grass seedlings for F91/92, 72% appeared in the first 40 days of incubation. In contrast, there was a uniform rate of seedling accumulation in grass in the F90/91 and grazed treatments. There were significant ($P < 0.05$) differences in grass seedling density between F91/92 and the other two treatments from 112 days of incubation onwards.

Legume seedling accumulation was more evenly distributed throughout the germination period for all treatments compared with the grasses, although the curvature of F91/92 response was greater than the other two treatments (Figure 5.1a and b). With time, the cumulative legume seedling density of F91/92 became progressively higher than that of F90/91 and the grazed sward ($P = 0.06$ for the last count, Figure 5.1b). The accumulation of weed seedling

Table 5.1 Viable seed population (seedlings/m²) of grasses, legumes, weeds and the total in 1991/92 fallowed sward (F91/92), 1990/91 fallowed sward (F90/91) and the grazed sward (sampled on 26 May 1992).

Treatment	Grass	Legume	Weed	Total
F91/92	21500 ^a	983	3850	26300 ^a
F90/91	6860 ^b	535	1600	9000 ^b
Grazed	4040 ^b	336	2210	6590 ^b
<i>s.e.m.</i>	1970 [*]	89 [†]	378 [†]	2151 [*]

* and † denote $P < 0.05$ and 0.1 , respectively; means with different superscripts are significantly different.

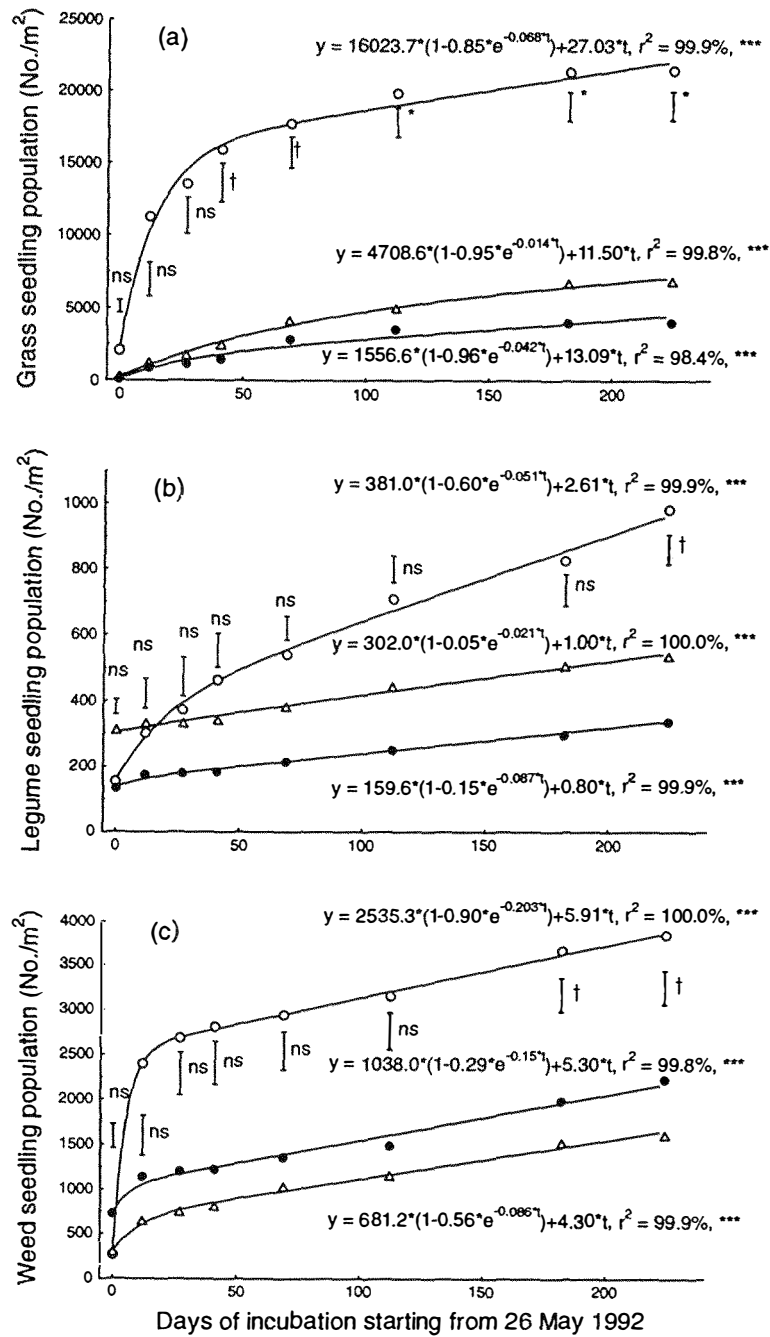


Figure 5.1 Cumulative (a) grass, (b) legume and (c) weed seedling populations and their curve patterns with incubation time under treatments fallowed September 1991 - May 1992 (o), fallowed September 1990 - April 1991 (Δ) and grazed (\bullet) (vertical bars show s.e.m.; ***, *, \dagger and ns represent $P < 0.001$, $P < 0.05$, $P < 0.1$ and not significant, respectively).

density responded in a similar trend to grass species (Figure 5.1c). The treatment effects on cumulative weed seedling density were marginal ($P < 0.1$) for the last counts.

The relationship of cumulative seedling population and germination time for all species in all treatments was well described ($r^2 = 98 - 100\%$, $P < 0.001$, $n = 8$) by a modified negative exponential equation (Figure 5.1) as:

$$y = a(1 - be^{-ct}) + dt \quad (1)$$

where:

y = cumulative viable seed population,

t = days of glasshouse incubation, since sampling on 26 May 1992,

a, b, c and d = coefficients.

5.3.3 Experiment 2

5.3.3.1 Effects of fallowing, fertilizer and aspect.

Compared with the grazed sward, there were substantial ($P < 0.01$) increases in grasses, weeds and the total viable seed population, but not legumes ($P > 0.05$), in the fallowed treatment (Table 5.2). The application of fertilizer significantly ($P < 0.05$) reduced the viable seed population of grasses, but did not significantly change that of legumes and weeds. There was significantly greater viable seed population of legumes ($P < 0.05$) on the shady than on the sunny aspect, but the viable seed populations of grasses and weeds were statistically not different between aspects.

5.3.3.2 Effects of full and partial fallow

Early completion or late start to the fallow reduced the grass and total viable seed population ($P < 0.05$), but not legume and weed viable seed population compared with full fallowed swards with or without added fertilizer (Table 5.3).

Table 5.2 General effects of pastoral fallow, fertilizer application and aspect on the viable seed population (seedlings/m²) of grasses, legumes, weeds and the total sampled at the completion (31 May 1994) of an October 1993 - May 1994 fallow with seven months of germination.

Treatment	Grass	Legume	Weed	Total
Fallow	6360	323	675	7360
Grazing	2440	214	425	3080
<i>LSD</i> _{0.05}	1314	284	121	1420
<i>Significance</i>	**	<i>ns</i>	**	**
Fertilizer +	3740	196	677	4620
Fertilizer -	5050	341	423	5820
<i>LSD</i> _{0.05}	1010	265	676	1300
<i>Significance</i>	*	<i>ns</i>	<i>ns</i>	†
Shady	4320	371	636	5350
Sunny	4510	115	395	5020
<i>LSD</i> _{0.05}	1514	247	853	2050
<i>Significance</i>	<i>ns</i>	*	<i>ns</i>	<i>ns</i>

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

Table 5.3 Viable seed population (seedlings/m²) of grasses, legumes, weeds and the total under early fallow, late fallow and full fallow with (Fallow + F) and without (Fallow - F) added fertilizer at the end of each fallow during Experiment 2 (October 1993 - May 1994).

Treatment	Fallowing term	Grass	Legume	Weed	Total
Fallow - F	Oct.93 - May94	7070 ^a	402	550	8030 ^a
Fallow + F	Oct.93 - May94	5640 ^a	245	800	6690 ^{ab}
Early fallow	Oct.93 - Dec.93	2220 ^b	76	362	2650 ^{bc}
Late fallow	Feb.94 - May94	2750 ^b	402	520	3670 ^c
<i>s.e.m.</i>		619*	136	134	794*

* denotes $P < 0.05$; means with different superscripts are significantly different.

There was no significant ($P > 0.05$) difference in grass, legume, weed and total viable seed population between partial fallow and grazed treatments.

5.3.3.3 Variation of viable seed population during pastoral fallowing

The viable seed population of grass species was dominant and far greater than that of legumes and weeds in the fallowed swards after late December 1993 (Figure 5.2a). It increased slightly from October to December 1993, and considerably from December 1993 to March 1994, then declined for the rest of the fallowing period. There was very little variation in the viable seed population of legumes during the fallowing period. The increase in the weed seed population was later than grass, starting from February, rather than October.

There was a much lower viable seed population of grasses in the grazed sward (Figure 5.2b) than in the fallowed sward, although the grass viable seed population was still higher than legume and weed. The grass viable seed population seemed to increase linearly with a low slope in the grazed sward, and the changes in legume and weed viable seed population were minor.

5.4 DISCUSSION

5.4.1 Methodology for testing viable seed reserves in soil

There are a variety of techniques for quantitatively describing natural reseeding in a plant community depending on the requirements of the experimental study (Harper, 1977). Extremely laborious techniques which provide accurate estimation of the number of seeds in a soil sample were proposed by Kropáč (1966) and Major and Pyott (1966). These techniques were considered impractical for large-scale studies, especially those involving small-seeded species (Thompson and Grime, 1979). The technique of Thompson and Grime

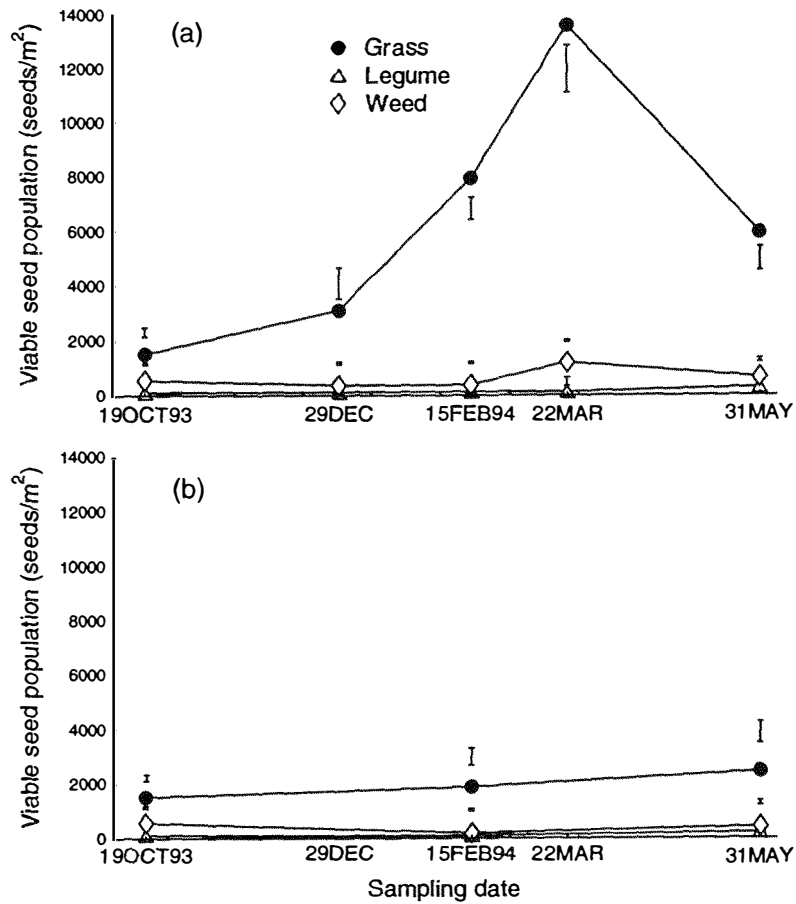


Figure 5.2 Change of viable seed population of grasses, legumes and weeds under (a) pastoral fallowing and (b) grazing (vertical bars show s.e.).

(1979) consists essentially of the collection of surface soil (30 mm in depth), soil preparation (air-dry and sieving) and seed germination in a favourably germinable environment. Similar methods were adopted by Howe and Chancellor (1983) and Wedderburn et al. (1993). More recently, Hume and Barker (1991) used fixed quadrats in the field to estimate the seedling appearance and fate from natural reseeding following different summer grazing managements. This technique measures actual seedling appearance and the survival of these seedlings as plants, but not potential viable seed population. Moreover, it is difficult to estimate the change in natural reseeding capacity during a pastoral fallow using this technique.

The technique in this study involved incubating “undisturbed” soil plugs in a glasshouse and sequentially removing seedlings as they appeared. This method measures the potential germinable seed population and may be a better representation of the natural reseeding capacity than the method of Thompson and Grime (1979), because it causes less soil disturbance and the viable seed population measured is not greatly affected by sampling depth. The technique probably provides higher estimates of viable seed population than the fixed quadrat technique (Hume and Barker, 1991) since the glasshouse conditions are optimum for germination. It is practically impossible to give an accurate estimation of maximum viable seed population for all plant species because some of them have high and long-term dormancy (Chapman and Anderson, 1987). This was the case particularly for legumes which showed linear seedling appearance with time (Figure 5.1b).

5.4.2 Germination rate curve and soil viable seed reserve

The germination rate of pasture species can be estimated from the equation describing the relationship between cumulative seedling population and germination time. Differentiating equation (1),

$$\begin{aligned}\frac{dy}{dt} &= \frac{d(a - abe^{-ct} + dt)}{dt} \\ &= abc e^{-ct} + d\end{aligned}\quad (2)$$

shows the rate of germination is determined by the time of incubation (t) and some coefficients (a , b , c and d). For a given species and treatment, the coefficients are constants and the germination rate varies only with the incubation time (Figure 5.3). The germination rate is highest at the start of germination (maximum germination rate = $abc + d$), and decreases towards an asymptote, d , as the days of incubation increases. This pattern was most pronounced following a pastoral fallow, but also applied in the year after a fallow and in grazed pasture (Figure 5.1). The pattern should favour the practice of using pastoral fallow to increase the persistence of pasture through natural reseeding, because most seeds might germinate in a relatively short time before new tillers produced from the resident plants impose a strong competition on the seedlings. On the other hand, where a pastoral fallow might be used to reduce plant density for introducing new pasture species, limiting natural reseeding to a minimum level is very important for a successful establishment of introduced species.

In a pastoral system, seed input to the soil seed reserve is predominantly from the reproduction of the resident plants. Freshly-shed seeds during the reproductive season of pastures may remain close to the soil surface and could germinate rapidly (rapidly germinable pool, RGP) if conditions for germination allow, and the seeds are not dormant. Alternatively seed could be buried in the soil and germinate slowly (base pool, BP) as the result of either enforced or innate dormancy (Howe and Chancellor, 1983). The soil seed reserve is the total of these two pools which change in size through seed gains and losses in each pool. Figure 5.3 illustrates the two pools based on the germination curve, the shaded and dark areas being the size (viable seeds/m²) of RGP and BP, respectively.

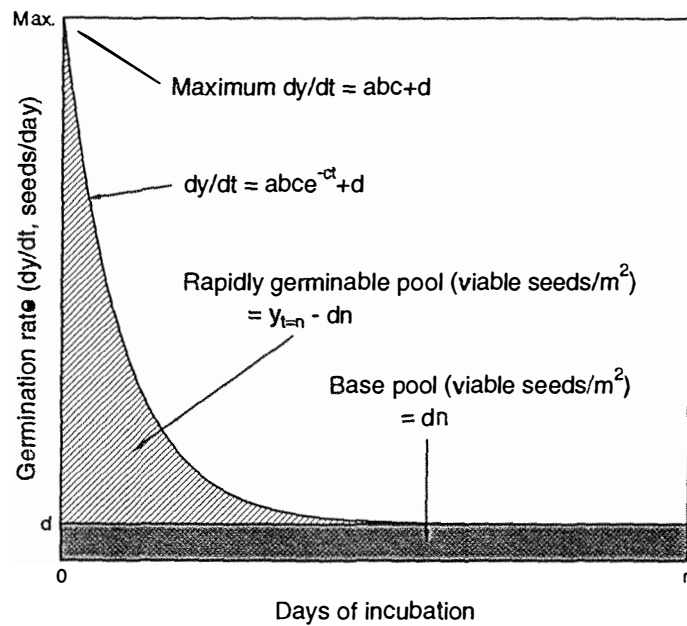


Figure 5.3 Germination rate curve (the partial derivative (dy/dt) of the seedling cumulative model, $y=a(1-be^{-ct})+dt$) and the two pools (rapidly germinable pool and the base pool) of the soil seed reserves.

The size of RGP and BP is largely influenced by the amount of seed produced by natural reseeding and the seed characteristics of various plant species. Table 5.4 shows the total viable seed reserve and the two pools for different species and treatments. Compared with the grazed treatment, pastoral fallow increased not only the total viable seed reserve, but also the size of both RGP and BP for all species. The difference between the viable seed population of the fallowed treatment and the grazed treatment (F-G, Table 5.4) measures the seed contribution to the soil reserve produced by the fallow treatment. Of the grass seeds (17590 viable seeds/m²) produced by the fallow, 82% went into RGP and only 18% went into BP. Weeds had a similar trend to grasses. Of the legume seeds (628 viable seeds/m²) purely produced by the fallow, however, most seeds (65%) went into BP and only 35% went into RGP. This difference reflected the generally higher dormancy of legume seeds (Suckling and Charlton, 1978; Langer, 1990).

5.4.3 Effects of pastoral fallow

The gains in seed number of a species result largely from the amount of seed shed in the field, and losses are determined largely by death, predation and germination (Harper, 1977; Howe and Chancellor, 1983). McCallum et al. (1991) showed that a spring - summer/autumn pastoral fallow (or deferred grazing) enhanced natural reseeding of perennial ryegrass, which doubled the tiller density of this species and increased pasture growth by 15 - 19% in the season following pastoral fallow. In both experiments of this study, the total viable seed population of all species in the swards immediately after pastoral fallowing was 4.0 ($P < 0.05$) and 2.4 ($P < 0.01$) times that of the grazed swards, respectively (Table 5.1 and 5.2). However, the total viable seed population in the sward fallowed one year earlier (F90/91) in Experiment 1 was not significantly ($P > 0.05$) higher than that of the grazed sward (Table 5.1), indicating loss of a large amount of viable seeds, probably mostly through germination and seedling death, during the one-year period after the pastoral

Table 5.4 Total viable seed reserve (VSR, seeds/m²) calculated for 224 days of incubation and the size (seeds/m²) of the rapidly germinable pool (RGP) and the base pool (BP) for grasses, legumes and weeds under fallowed and grazed treatments; F-G is the viable seed population (seeds/m²) of the fallowed subtracting that of the grazed and % VSR_{F-G} is the percentage to VSR in row F-G.

Species	Treatment	VSR	RGP	BP
Grass	Fallowed	22080	16020	6060
	Grazed	4490	1560	2930
	F-G	17590	14470	3120
	% VSR _{F-G}	100	82	18
Legume	Fallowed	966	381	585
	Grazed	338	160	178
	F-G	628	221	407
	% VSR _{F-G}	100	35	65
Weed	Fallowed	3860	2540	1320
	Grazed	2170	1040	1130
	F-G	1690	1490	198
	% VSR _{F-G}	100	88	12

fallowing was completed. The large difference in viable seed population between the newly-fallowed sward in Experiment 1 and 2 was probably attributed to: 1) difference in seed production between years - much higher rainfall (168.9 mm/month) occurred during the flowering period of most plant species in November 1993, which might considerably reduce seed production for Experiment 2; 2) technical difference - Experimental 1 included any seedlings which had already been resident in the soil plugs for the first counting of seedlings, whereas in Experiment 2 all green vegetation and seedlings were killed by herbicide prior to the germination test to allow easier distinction of seedlings from resident vegetation.

Pastoral fallow appears to have considerably favoured the viable seed population of grasses in comparison with the grazed treatment (Table 5.1 and 5.2). This is attributed to the high proportion of grasses in the sward, where they were the dominant species. Many studies have emphasised the importance of natural reseeding on the persistence and productivity of grass species such as perennial ryegrass (L'Huillier and Aislabie, 1988; McCallum et al., 1991), prairie grass (Boom and Sheath, 1990; Hume et al., 1990; Jung et al., 1994), and cocksfoot (*Dactylis glomerata* L.) (Yang et al., 1988), but little emphasis has been put on that of legume species (Lowther et al., 1992). Chapman (1987) showed that seedling regeneration of white clover played a minor role in its persistence in a grazed hill pasture. However, prevalence of annual legume species such as suckling clover (*T. dubium* Sibth.) shows that reseeding processes do occur in hill pasture (Chapman, 1987). The viable legume seed populations in the newly-fallowed swards in both experiments (Table 5.1 and 5.2) were, to some extent ($P < 0.1$ or $P > 0.1$), higher than in the grazed sward. Higher dormancy of some legume species such as white clover (Harrington, 1972) and lotus (*Lotus pedunculatus* Cav) (Lowther et al., 1992), and slower germination rate, may have affected the significance of natural reseeding of these species in a relatively short term (seven months in this study).

5.4.4 Effects of fertilizer and aspect

There is little information on the influence of fertilizer and aspect on natural reseeding in moist hill pasture. The results of this study (Table 5.2) demonstrated that the application of fertilizer considerably reduced viable grass seed population, but had no significant effect on legumes or weeds. The reason for this was probably because the long-term (1989 - 1993) history of fertilizer application in the fertilised plots may have restrained the growth of low-fertility species such as browntop, which generally produce small, but abundant seeds (Charlton, 1991). This was supported by the finding of Lambert et al., (1986) that high fertility hill pastures had a greater content of perennial ryegrass and a smaller content of low fertility grasses such as browntop and sweet vernal. Hume and Barker (1991) reported on natural reseeding of five grass species in summer dry hill country and suggested that the effects of fertilizer were generally minor for each species.

Aspect only had an effect on the viable seed population of legumes, which was significantly higher on the shady than on the sunny aspect. This was probably related to the population of white clover, a main legume species at the experimental site, which generally grew better on the moist, shady aspect than on the drier, sunny aspect (Nie et al., 1997).

5.4.5 Practical implications

Two of the objectives of pastoral fallow are: 1) to increase the natural reseeding ability of a sward by encouraging seed production during summer/autumn (L'Huillier and Aislabie, 1988; Boom and Sheath, 1990; Hume et al., 1990; McCallum et al., 1991); and 2) to reduce plant population density through inter-plant competition and self-thinning for oversowing new plant germplasm (Nie et al., 1997). The first objective requires maximal natural reseeding, but the second objective requires minimal natural reseeding in order that the

competition with seedlings from natural reseeding on introduced species is minimised (Nie et al., 1997).

The viable seed population of grasses reached a peak in March (Figure 5.2a). This was because the maturity of seeds for most species occurred after December, and seeds shed from the matured plants accumulated beneath the pasture from late December to March. Seed loss from germination during January - March should be low because of the low rainfall (mean 57.5 mm/month) in this period. The viable seed population of grasses declined sharply from March to late May, reflecting high loss of seeds by germination during this period. The viable seed population of legumes and weeds was very low, in comparison to the viable grass seed population (Figure 5.2a). Therefore, the best completion time of a pastoral fallow should be in March to achieve a maximum reseeding ability for Objective 1, if rainfall before the completion date is not high.

For Objective 2, a detailed discussion on partial pastoral fallow has been given by Nie et al. (1997). Partial pastoral fallows involve either completing a pastoral fallow earlier (early fallow), for example in late December, or starting a pastoral fallow later (late fallow), for example in January or February. The early and late fallow treatments in Experiment 2 reduced the total viable seed population of all plant species by 64% and 50%, compared with the mean (7360 seedlings/m²) of full fallow treatments (Table 5.3), but the partial fallow treatments were similar in total viable seed population (2650 and 3670 seedlings/m² respectively) compared with the grazed sward (3080 seedlings/m²). Therefore partial pastoral fallow was an effective method of minimising natural reseeding.

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Chapter 6

Influence of the Timing and Duration of Pastoral Fallowing and Nitrogen Fertiliser on Pasture and White Clover (*Trifolium repens* L.) Growth in Hill Country

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Abstract

One of the objectives of a pastoral fallow is to reduce plant/tiller density for the introduction of improved germplasm. Short-duration pastoral fallow may achieve this objective, and be better suited with hill country pasture management than a long-duration fallow. A field study was conducted to examine the effects of the timing and duration of pastoral fallowing and nitrogen fertiliser addition on plant population density, natural reseeding and white clover (*Trifolium repens* L.) growth behaviour in a hill pasture. Pastoral fallows starting from December, January and February and terminating in June significantly ($P < 0.01$) reduced the tiller density of grasses, the dominant species in the sward. At the conclusion of these fallows, the plant population (grass + legume + weed) density was only 29 to 49% of the grazed control. Fallows from December and January to June significantly ($P < 0.01$ and 0.05) increased the internode length of white clover. Only the December fallow significantly ($P < 0.05$) increased the viable seed population of grasses, while for other treatments and other species in the December fallow, there was no significant difference between the fallowed and grazed swards. The addition of fertiliser nitrogen significantly ($P < 0.05$) enhanced the decline in tiller density for the March to June fallow from the time of application. It did not impact negatively on the legume component of the sward and in fact improved the specific stolon weight of white clover and reduced the viable seed population of weeds and rushes ($P < 0.05$). It is concluded that pastoral fallows starting from December, January and February or March with nitrogen addition and ending in June considerably reduced plant population density for oversowing new plant species. However, attention to natural reseeding from grass species should be given when the December to June fallow is used. The increased dispersion of white clover stolons by internode elongation in the fallowed swards, especially in the December and January to June fallows, may improve the distribution and content of white clover.

Key words: nitrogen, pastoral fallow, plant density, viable seed population, red:far red ratio, sward structure, stolon.

6.1 INTRODUCTION

A pastoral fallow, which involves not defoliating pasture for a period generally from spring to autumn, is a technique to raise soil fertility (Mackay et al., 1991) and to reduce plant/tiller population density (Nie et al., 1997a) in preparation for introducing new germplasm. Previous studies (Nie et al., 1997a; Chapter 3) showed that at the end of a spring to autumn (October 1993 - May 1994) pastoral fallow, the reduced plant/tiller density provided a potentially favourable environment for resowing new plant species or cultivars. However, autumn competition between self-sown grasses that seeded during the earlier pastoral fallowing period (natural reseeding) and the sown germplasm can be intense. Nie et al. (unpublished data) found that seed production from the resident grass population could be as high as 26300 seeds/m². While perennial ryegrass (*Lolium perenne* L.) or cocksfoot (*Dactylis glomerata* L.) would usually be applied in an oversowing programme, the seeding rate of 400 - 1000 seeds/m² for either species would only be a fraction of that from natural reseeding in a hill pasture. Shifting the timing and duration of a pastoral fallow to avoid natural seed production might overcome the problem of competition on sown species while retaining the benefits to sown species from reduced resident plant/tiller populations.

Self-thinning is a plant biomass accumulation-driven process causing plant or tiller mortality through competition (Yoda et al., 1963; Westoby, 1984). Herbage accumulation rates in the post-flowering period, particularly in autumn or winter are much slower than those in the spring or early summer. This is likely to reduce the effectiveness of self-thinning as a tool for reducing plant density. The addition of nitrogen (N) can considerably increase plant growth rate, especially in grass species. Zhou et al. (1993) found that N fertiliser increased herbage mass of a North Island hill pasture by up to 41 kg dry

matter/kg N applied. Tactical use of N may therefore offer a tool for increasing herbage accumulation in a fallow commenced in either summer or autumn.

Addition of N fertiliser, however, has been shown to have a large negative effect on legume growth and N-fixation in a pasture under continuous grazing (Ball and Crush, 1985). Nie et al. (1996) found that the dispersion of white clover (*Trifolium repens* L.) stolons in a sward through internode elongation during a fallow, and subsequent initiation of branching of the stolons following the conclusion of the fallow, resulted in an increase in white clover content in the four years post-fallowing. Whether the clover response would be influenced by the addition of N is uncertain.

A previous study showed that release of white clover from intense defoliation increased its internode elongation while decreasing branching (Nie et al., 1996). As pasture mass accumulates, insolation of stolons is increasingly from light transmission through leaves. The light has a low red:far red (R:FR) ratio which has been shown to increase stem extension rate (Lechamy and Jacques, 1979; Morgan et al., 1980).

The objective of this study was to examine the effects of the timing and duration of pastoral fallow and nitrogen fertiliser addition in the shorter fallowed treatments, emphasising effects on white clover growth behaviour during fallowing and its response to light quality.

6.2 MATERIALS AND METHODS

6.2.1 Site

The experiment was conducted at the AgResearch Hill Country Research Station, Ballantrae (40° 19' S, 175° 50' E), 20 km east of Palmerston North, on an area with a south face of relatively uniform and moderate slope. The soil was a yellow-grey earth/yellow-brown earth intergrade (Typic Dystrochrept) of

sedimentary origin. Little fertiliser had been applied to the area and the soil fertility was low with pH 5.4 and Olsen P $10 \mu\text{g P g}^{-1}$ dry soil. The pasture consisted of predominantly low fertility-tolerant grasses such as browntop (*Agrostis capillaris* L.) and sweet vernal (*Anthoxanthum odoratum* L.) with smaller quantities of perennial ryegrass, cocksfoot, white clover and suckling clover (*T. dubium* Sibth.). The weed species were mainly flatweeds such as catsear (*Hypochoeris radicata* L.) and hawkbit (*Leontodon taraxacoides* [Vill.] Merat) (Lambert et al., 1986).

Treatments

The experiment was a randomised complete block (RCB) design with eight treatments replicated in four blocks. The initiation and completion date of each fallow treatment was:

- (1) Dec. fallow, 5 December 1994 - 20 June 1995;
- (2) Jan. fallow, 17 January 1994 - 20 June 1995;
- (3) Feb. fallow, 16 February 1994 - 20 June 1995;
- (4) Mar. fallow, 16 March 1994 - 20 June 1995;
- (5) Mar.-Sep. fallow, 16 March 1994 - 28 September 1995;
- (6) Grazed control, non-fallowed;
- (7) as for (3) + N;
- (8) as for (4) + N.

N was applied at 50 kg N/ha twice at a two-week interval from the beginning of each fallow. The plot size varied, with the earlier fallowed treatments (Dec. and Jan. fallow) being larger than the rest of the treatments (2*2 m vs 2*1 m). The trial site was grazed by sheep from 2 - 5 December 1994, and the Dec. fallow was fenced immediately after grazing. Plots were fenced at the start of the appropriate fallowing treatment. The grazed control and the fallowing treatments in the non-fallowed periods were rotationally grazed by sheep.

6.2.3 Measurements

Plant population density was measured at the start, six weeks after the start and the end of each fallow treatment, in ten 50 mm-diameter turf plugs from each plot. The grazed control was sampled whenever a fallow treatment was measured. The number (No.) of grass tillers, white clover growing points, other legumes and weeds were counted to estimate plant population density (No./m²). Plugs were then dissected to obtain all surface and buried stolons of white clover. The stolons were washed, dried with absorbent paper, and trimmed of leaves to determine total stolon length (m/m²) and average internode length (mm), then dried in an oven at 65 °C for at least 48 hours to measure total stolon dry weight (g/m²) and calculate specific stolon weight (g/m).

Pasture biomass was measured monthly, by cutting a 0.1 m² quadrat to 10 mm above ground. Subsamples were dissected into vegetative and reproductive tillers of grasses, white clover, other legumes, weeds and dead matter to calculate botanical composition in terms of biomass of each component. Reproductive tillers were distinguished from vegetative tillers by observing the node development of the stem.

Photosynthetically active radiation (PAR) and light quality (R:FR ratio) were measured using a Skye light meter (SKR 116 & SKP 2155) between 11:00 am and 3:00 pm during a day. On 17 May 1995, five readings of the red (R, 660 nm) to far-red (FR, 730 nm) ratio were recorded at 10 mm above ground level and on the surface of the sward canopy of each plot, respectively, on a fine day. PAR was monitored 50 mm above the sward canopy simultaneously when both layers of R:FR ratio were measured. All measurements were made with the sensor surface parallel to the slope. The light measurements were repeated on 18 May 1995 during similar weather. On 15 June 1995, light quality was measured again by taking ten measures in each plot during cloudy weather.

On 5 December 1994 (the start of fallow treatment 1), 16 March 1995 (the start of fallow treatment 4) and 20 June 1995 (the end of fallowing), ten 50 mm diameter plugs were collected from each plot to determine the per-unit-area seedling establishment from natural reseeding. The plugs were sprayed with glyphosate to eliminate the resident vegetation, then put in a glasshouse at 20 °C. About one week after the spray, plugs were trimmed to the soil surface, and seedlings of grass, legume, weed and rush were counted and removed at one- or two-month intervals depending on seedling density for seven months.

6.2.4 Statistical analysis

Data were analysed by Analysis of Variance using the General Linear Model procedure of the Statistical Analysis System (SAS Institute, 1990). A RCB model was used to analyse treatments 1 - 6. A 2*2 factorial model was used to analyse treatments 3, 4, 7 and 8 for a N effect. Comparisons of means were made using Duncan's New Multiple-Range Test (Steel and Torrie, 1981). The PAR and R:FR ratio were averaged over the three measurements since there was no significant difference between sampling times.

6.3 RESULTS

6.3.1 Rainfall and temperature

Mean monthly rainfall during December 1994 - January 1995 was 45.4 mm, 48% of the 24-year average; during February - June 1995 was 117.0 mm, 21% higher than the 25-year average; and during July - September was 137.4 mm, 27% higher than the 25-year average. Mean air temperature (12.7 °C) during December 1994 - September 1995 with no distinctly warmer or colder month was similar to the 23-year average (12.4 °C).

6.3.2 Plant population density

There was seasonal variation in tiller density in the grazed sward, with little change from December 1994 to February 1995, and an increase through to September (Figure 6.1a). There was no significant difference between the initial tiller densities of the grazed swards at the commencement of the four following treatments (Dec. to Mar.). Six weeks after each following, the Dec. and Jan. fallow had significantly lower grass tiller density, and the Mar. fallow had significantly higher tiller density, compared with the initial mean tiller density (24490 tillers/m²). The Feb. fallow was not significantly different from the mean. The final tiller densities on 20 June 1994 for the Dec., Jan. and Feb. fallows were all significantly ($P < 0.01$) lower than that of the grazed control. On this date the Mar. fallow was not significantly ($P > 0.05$) different from the grazed control (Figure 6.1a).

There was no significant ($P > 0.05$) difference between treatments both for the initial white clover growing point density of each following treatment, and for the growing point density at six weeks after following, although there was a fast decline in clover growing point density from December 1994 to February 1995, then an increase from February to March 1995 for the initial clover growing point density (Figure 6.1b). At the conclusion of following on 20 June 1996, however, a significant difference ($P < 0.05$) was detected between treatments. Dec. fallow had a significantly lower white clover growing point density than the grazed control, while other following treatments were not significantly different from the control, although the effect of Jan. fallow was significant at $P = 0.1$ level.

The weed density was not significantly different ($P > 0.05$) between treatments for the initial measurements, six weeks after following or the final measurement on 20 June 1995 (Figure 6.1c). The plant density of other legumes which accounted for less than 1% of the total plant population density was never significantly different between treatments.

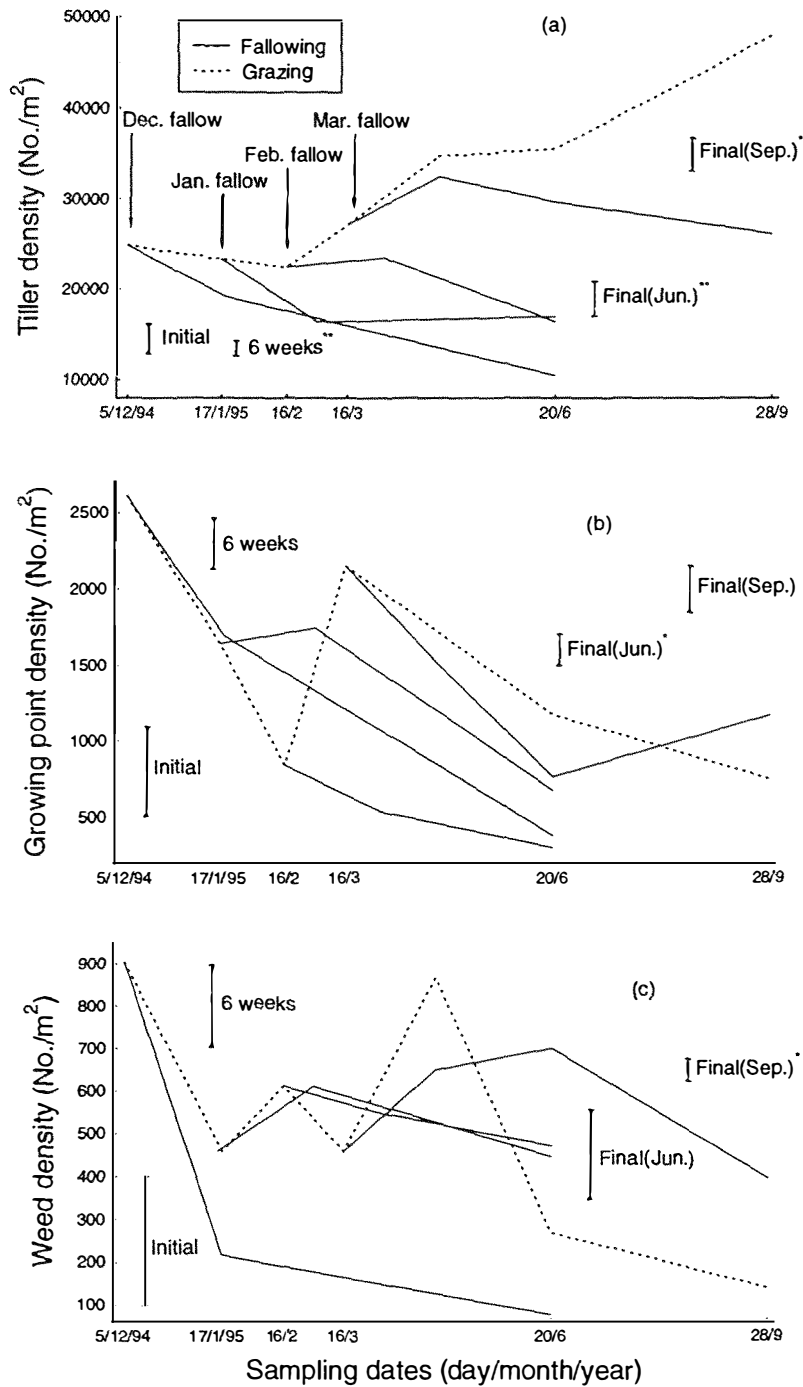


Figure 6.1 Mean plant population density of (a) grass tillers, (b) white clover growing points, (c) weeds under various fallowing treatments at the initial, 6 weeks and final stage (June and September 1995) of fallowing (vertical bars show s.e.; * and ** represent $P < 0.05$ and $P < 0.01$, respectively).

The Mar.-Sep. fallow significantly ($P < 0.05$) decreased grass tiller density and weed density compared with the grazed control on 29 September 1994 (Figure 6.1a & c), but the tiller density of this treatment was still higher than the average of the earlier initialised (December - February) fallowing treatments (26200 vs 14600 tillers/m²).

6.3.3 Nitrogen effects

The addition of nitrogen had little impact on tiller density in the Feb. fallow, but greatly reduced tiller density in the Mar. fallow during the first six weeks of fallowing (Table 6.1). This resulted in a significant interaction ($P < 0.01$) between N addition and fallow dates. The interaction did not remain up to the conclusion of fallowing in June, although the tiller density (17470 tillers/m²) of Mar. fallow with N added was only 59% of that (29630 tillers/m²) without N. N application had no significant effects on the plant population density of white clover growing points, other legumes and weeds ($P > 0.05$) both in the first six weeks and at the end of fallowing.

There was a significant ($P < 0.05$) increase in specific stolon weight of white clover by N application (Table 6.1), but there were no significant ($P > 0.05$) effects of N on stolon density (14.2 vs 11.3 m/m²) and internode length (3.5 vs 2.8 mm). The N application reduced the viable seed population of weeds and rush ($P < 0.05$), but had no significant influence on that of grasses and legumes.

The application of nitrogen in February and March increased the biomass accumulation by 27% and 44%, respectively, compared with the treatments without N addition, but did not change the botanical composition (Figure 6.2).

Table 6.1 The interaction of N addition and late-commenced (February and March) fallows on grass tiller density (TD) at six weeks after pastoral fallowing was imposed, and the effects of N on the specific stolon weight (SSW) of white clover and viable seed population (VSP) of weeds and rush.

Interaction	TD (Tillers/m ²)	Treatment	SSW (g/m ²)	VSP (seeds/m ²)	
				Weed	Rush
Feb. fallow/N	25890	N +	0.42	885	446
Feb. fallow/N	23500	N -	0.36	1133	732
Mar. fallow/N	18300	s.e.	0.027*	228*	277*
Mar. fallow/N	32430				
s.e.	1540**				

* and ** represent $P < 0.05$ and $P < 0.01$, respectively.

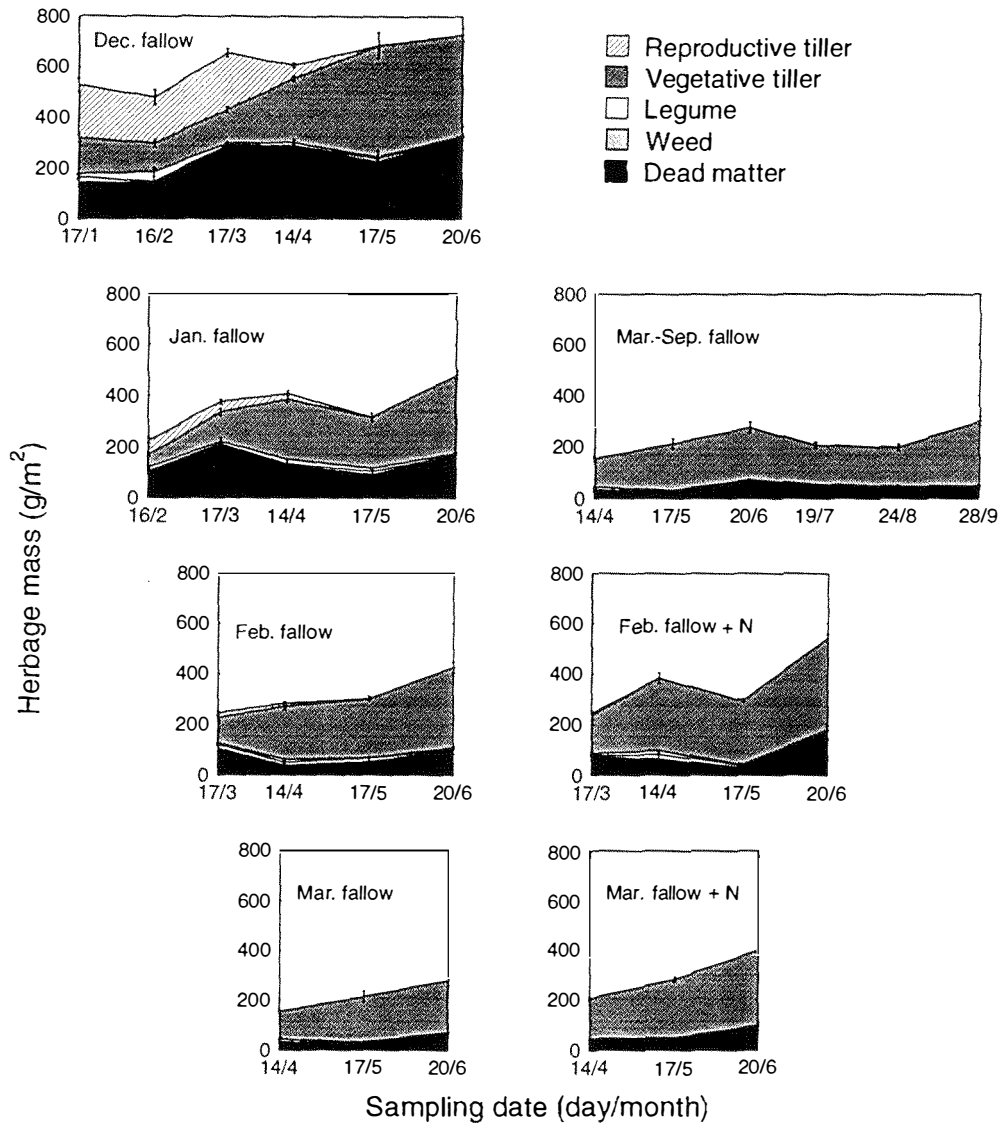


Figure 6.2 Change of sward biomass of reproductive tillers, vegetative tillers, legume and dead matter under treatments with various following durations and initial dates (initial measurements were made one month after following started from each treatment; vertical bars show s.e.).

6.3.4 Sward structure

The swards of all treatments were dominated by grasses, with legumes and weeds only contributing a small proportion of above ground biomass (Figure 6.2). The total above-ground biomass accumulation was highly dependent on the timing and duration of fallowing. In general the earlier-commenced and longer-fallowed treatments produced more above-ground biomass than the later-commenced and shorter-fallowed treatments (Figure 6.2). However, the Mar.-Sep. fallow did not greatly increase biomass accumulation although it had the longest duration of fallowing.

There was a high proportion (34%) of reproductive tillers in Dec. fallow, with fewer in the Jan. fallow (25%) and few reproductive tillers on other treatments.

6.3.5 The stolon characteristics of white clover

The seasonal variation of white clover stolon density in the grazed sward (Figure 6.3a) was similar to that of white clover growing point density (Figure 6.1b). There were significant ($P < 0.05$) differences in initial white clover stolon density between Dec. to Mar. fallows (Figure 6.3a). This was attributed to a fast decline in the stolon density from December 1994 to mid-February 1996 under grazing, which resulted in the significant ($P < 0.05$) difference between Dec. fallow and those commencing at later dates. There were no significant differences in stolon density between treatments at either six weeks or the end of fallowing.

In contrast to stolon density, the initial internode lengths (2.5 to 3.0 mm) of white clover changed very little for all fallowing treatments (Figure 6.3b). The internode lengths increased after six weeks of fallowing at all four starting dates, with the increase in the Dec. fallow (4.5 mm) significantly ($P < 0.05$) greater than the later fallows (mean = 2.9 mm). At the conclusion of fallowing, the internode lengths of all fallowing treatments (2.6 - 4.5 mm) were greater

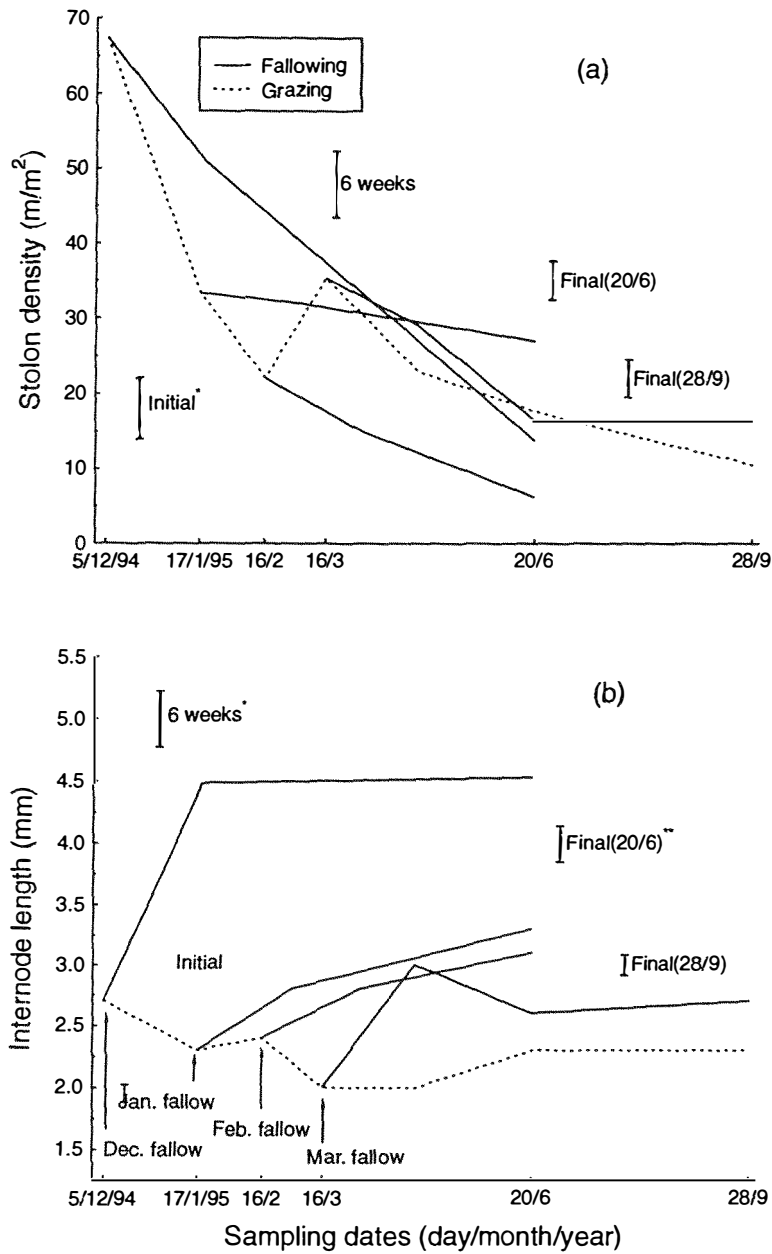


Figure 6.3 Change of (a) stolon density and, (b) internode length of white clover under treatments with various following durations and initial dates (vertical bars show s.e.; * and ** represent $P < 0.05$ and $P < 0.01$, respectively).



Plate 6.1 A close view of white clover stolon elongation in fallowed sward.

than that (2.3 mm) of the grazed control (Plate 6.1). The internode length (4.5 mm) of Dec. fallow was significantly higher than that (3.3 mm) of Jan. fallow ($P < 0.05$), both of which were significantly higher than the grazed control ($P < 0.01$ and $P < 0.05$, respectively).

There were no significant differences ($P > 0.05$) between treatments in the total stolon weight and specific stolon weight at the end of fallowing.

6.3.6 Viable seed population

Fallowing had only a significant ($P < 0.05$) effect on the viable seed population of the grass component of the sward (Table 6.2). This significance resulted primarily from the substantially higher viable seed population in Dec. fallow compared with the Mar. fallow and the grazed control. The viable seed population of legumes, weeds, rush and the total of all species was not influenced by the four fallowing treatments either at six weeks or the end of fallowing (Table 6.2).

6.3.7 Light quality

The PAR did not differ significantly between treatments when light measurements were made either at the surface or at 10 mm above ground (Table 6.3). R:FR ratio (0.9 and 0.93) at the base of the sward canopy (10 mm above ground) of Dec. and Feb. fallows, respectively, were significantly ($P < 0.05$) lower than the grazed control, while that of Jan. and Mar. fallows were not significantly different from the grazed control. There was no significant difference in R:FR ratio between treatments on the surface of the sward canopy.

Table 6.2 Viable seed population (seeds/m²) of grasses, legumes, weeds, rush and the total at the conclusion of fallowing on 30 June 1995.

Treatment	Grass	Legume	Weed	Rush	Total
Dec. fallow	1121 ^a	51	777	535	2483
Jan. fallow	700 ^{ab}	51	955	662	2368
Feb. Fallow	789 ^{ab}	13	930	662	2394
Mar. fallow	446 ^b	13	1337	802	2597
grazing	522 ^b	0	955	535	2012
s.e.	152.1 [*]	16.9	127.9	189.7	273.8

* represents $P < 0.05$; means with different superscripts are significantly different.

Table 6.3 Red:far-red (R:FR) ratio at the canopy surface and 10 mm above ground-level and mean photosynthetically active radiation (PAR) monitored while surface and 10 mm above ground-level R:FR ratio were measured at the late stage (May - June 1995) of pastoral fallowing.

Treatment	R:FR ratio		Mean PAR ($\mu\text{mol}/\text{m}^2/\text{s}$)
	Surface	10 mm	
Dec. fallow	1.00	0.90 ^a	261.6
Jan. fallow	1.13	1.25 ^{abc}	262.3
Feb. Fallow	1.28	0.93 ^{ab}	271.5
Mar. fallow	1.30	1.28 ^{bc}	288.1
grazing	1.40	1.50 ^c	257.4
s.e.	0.11	0.11 [*]	13.9

* represents $P < 0.05$; means with different superscripts are significantly different.

6.4 DISCUSSION

6.4.1 Plant population density, sward structure and self-thinning

6.4.1.1 Pattern of change in plant population density

Pastoral fallow can be used as a tool to reduce plant/tiller density and open the sward prior to oversowing with more desired and improved species. The three earlier (December, January and February) fallowing treatments significantly ($P < 0.01$) reduced the tiller density of grasses by 71, 52 and 54%, respectively, in comparison with the grazed control (Figure 6.1a). A spring - autumn (seven months) pastoral fallow reduced plant population density of grasses, white clover and weeds in a densely vegetated hill pasture by 72 - 87% (Nie et al., 1997a).

The Mar. fallow was not as effective as the early pastoral fallows in reducing plant density, indicating that a pastoral fallow either starting too late or being too short in duration and not allowing sufficient pasture growth, is not effective in achieving the goal of decreasing plant density (Figure 6.4a). However adding nitrogen produced enough growth to significantly reduce tiller/plant population. Extending the Mar. fallow through to September did significantly decrease grass tiller density compared with the grazed control at the end of fallowing (28 September 1994, Figure 6.1a), but this was due to a faster increase in tiller density of the grazed sward, rather than a faster decline of tiller density in the fallowing treatment. The final tiller density (26180 tillers/m²) of the Mar.-Sep. fallow treatment was substantially higher than that (mean = 14580 tillers/m²) of the December - February fallow treatments. An autumn - winter fallow did not reduce tiller density as effectively as the summer - autumn fallow, due to insufficient pasture growth even if the duration of fallowing was prolonged up to seven months, and to the pattern of tiller accumulation during autumn - winter period (Fig 4a & 1a).

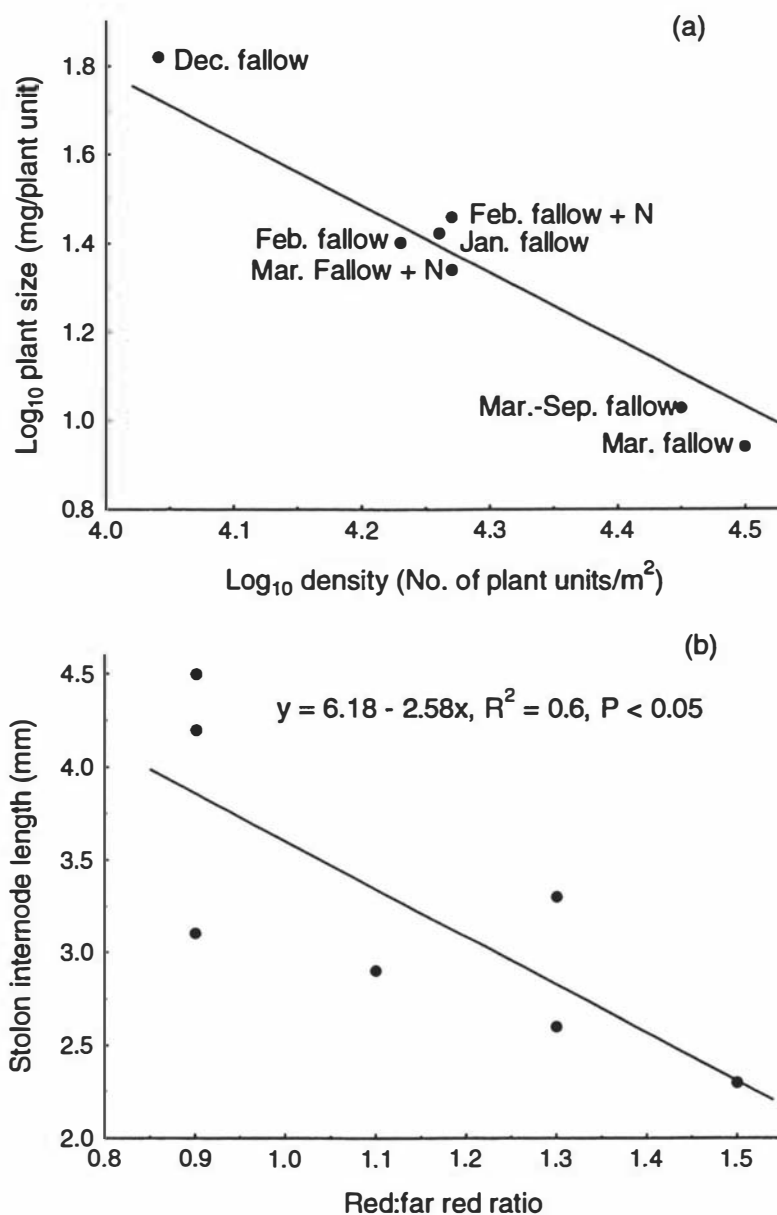


Figure 6.4 Relationship between: (a) Plant size and plant density - self-thinning line (slope = $-3/2$) and scatter plots of plant unit size against total plant density of all fallowing treatments at the end of each fallow; (b) Red:far red ratio and white clover internode length for both fallowed and grazed treatments.

The patterns of change in tiller density during fallowing varied among treatments (Fig 6.1a). In comparison with the grazed swards, all fallowed treatments showed at least some reduction in tiller density. The Dec. fallow had an immediate impact on tiller density, with a rapid decline in the first six weeks of fallowing, followed by a decline slowing for the rest of the fallowing period. This pattern of decline is similar to a spring - autumn fallow from a previous study (Nie et al., 1997a). However, the tiller densities of Feb. and Mar. fallow increased in the first six weeks, then declined. This was probably due to the difference of pasture growth rate between summer and early-autumn. Gillingham and During (1973) found a peak growth rate in late spring/early summer which then declined through to winter in a hill pasture. That is the lower growth rate in February and March, resulting in a slower above-ground biomass accumulation, had probably allowed some new tillers to be produced in the Feb. and Mar. fallow swards before the total above-ground biomass approached the self-thinning line (Westoby, 1984). The tiller density change in the Jan. fallow, where tiller populations quickly dropped in the first six weeks, then slowly increased for the rest of the fallowing period, was probably attributed to low rainfall (45.4 mm/month) during December 1994 - January 1995. The fast decline in tiller density of this treatment in the first six weeks was largely due to loss of tillers subjected to the moisture stress in mid-January. This can be seen in the dead matter : live biomass ratio (Figure 6.2) which was 51 : 49% for Jan. fallow at six weeks of fallowing, while the other three fallowing treatments had much lower dead matter proportions (mean 24 : 76%). The relatively low above ground live biomass and low tiller density of Jan. fallow at six weeks of fallowing resulted in some tiller recruitment rather than self-thinning in the following fallowed period (Figure 6.1a).

There was a general decline in white clover growing point density from summer through to winter in the grazed sward (Figure 6.1b). The steep decline of clover growing point density in the grazed sward from December 1994 to February 1995 was possibly due to the low rainfall of December 1994 - January

1995 period. The Dec. and Feb. fallow significantly ($P < 0.05$) decreased clover growing point density compared with the grazed control at the end of fallowing (20 June 1995), which was a similar pattern to a spring - autumn fallow (Nie et al., 1997a). The other fallowing treatments did not have a significant effect in reducing clover growing point density. Compared with the grazed control, the Mar.-Sep. fallow even increased the white clover growing point density and the weed density during the winter period. All June-completed fallows had no significant influence on the densities of both weeds (Figure 6.1c) and other legumes, which were less than 4% of the total plant population density. These results suggested that later (autumn) fallows do not significantly reduce the densities of clover and weeds, and fallowing during winter even increased clover and weed density.

6.4.1.2 Self-thinning during pastoral fallowing

The self-thinning relationship (Yoda et al., 1963; Westoby, 1984) predicts that biomass accumulation by plant growth causes thinning in a plant community along a self-thinning trajectory with a slope of $-1/2$ (or $-3/2$ if individual plant size rather than total plant biomass per unit area is used). The relationship between plant size and plant population density followed the self-thinning rule in a spring - autumn (seven month) fallow (Nie et al., 1997a). When final plant density was plotted against plant size for all fallowing treatments of this experiment, the relationship also fitted well along a self-thinning trajectory with a slope of $-3/2$ (Figure 6.4a). The sequence of total above-ground biomass at the end of each fallow in this experiment was Dec. fallow > Jan. fallow > Feb. fallow > Mar. fallow, which stressed the importance of biomass accumulation for self-thinning. The reverse order of final tiller density for each treatment reflected that earlier and longer fallows allowed more biomass accumulation and reduced tiller density more substantially. However, the Mar.-Sep. fallow, although fallowed about three months longer than the Mar. fallow, had similar

total biomass to the latter treatment at the end of fallowing, which explained the poor fallowing result of plant density decline of this treatment (Figure 6.4a).

6.4.2 Stolon growth behaviour and light quality

The survival of a vigorous stolon network, which supports the growth of new growing points, leaves and stolons, ensures the persistence of white clover in grazed swards (Marriott and Smith, 1992). There is a general acceptance that closer defoliation increases white clover stolon density (clover stolon m/m^2) and reduces the internode length (Thomas, 1972; Frame and Boyd, 1987; Wilman and Acuna P., 1993). When a grass-clover sward is released from close defoliation, white clover changes its growth behaviour so that the internode elongation is stimulated while stolon branching is restrained. However, the increase in main stolon growth by internode elongation cannot compensate for the loss of secondary stolons, resulting in lower total stolon density (Nie et al., 1996). Alternating clover stolon growth behaviour and increasing stolon dispersion through pasture management such as fallowing or rotational grazing with a long recovery interval resulted in improved production and content of white clover in grass - white clover swards (Sheldrick et al., 1993; Nie et al., 1996 and 1997b). In this experiment, there was a trend for stolon density to decline in all fallowed treatments, but these treatments did not differ significantly from the grazed control at the end of fallowing (Figure 6.3a). There seemed to be a seasonal pattern in the grazed sward that the clover stolon density declined from early December through to late September, and this decline was fastest during December 1994 to February 1995 when the summer drought occurred. Thus, the non-significance of stolon density between fallowed treatments and the grazed sward might have been due to the confounding effects of: 1) fallowing and seasonal variation of stolon growth; 2) fallowing and the summer drought. Brock and Kim (1994) showed that shading from accompanying grasses could improve the survival of white clover stolons during a drought. The shading effect of accompanying grasses was clearly shown in the two early-commenced treatments which declined in stolon density

at slower rates than the grazed sward during the December 1994- January 1995 drought period (Figure 6.3a).

Although all following treatments increased the internode length of white clover, the following durations and timing had a clear influence on the extent of internode elongation (Figure 6.3b). In general, the earlier and longer the following treatment, the greater internode elongation that resulted. The effect of Dec. fallow on internode elongation was the greatest, substantially higher than the later-commenced treatments, among which the internode length varied in the order of Jan. fallow > Feb. fallow > Mar. fallow. However, the internode length was not further increased during the late autumn - winter period in the Mar. and Mar.-Sep. fallow due to lack of sufficient above ground biomass accumulation.

The response of white clover growth behaviour to following was probably attributed to the change of sward structure during following, which further altered light quality (R:FR ratio) at the base of the sward (Table 6.3). Many studies indicated that the morphological changes of plants induced by the presence of taller neighbours were triggered by alterations in R:FR ratio (Siegelman and Hendricks, 1964; Kasperbauer, 1971; Smith, 1982). Lower R:FR ratio increased the stem extension rate and the elongation of other above ground organs of plants such as petioles and leaves (Lechamy and Jacques, 1979; Morgan et al., 1980; Robin et al., 1992 & 1994), and reduced branching of clover and tillering of grass (Solangaarachchi and Harper, 1987; Deregibus et al., 1983). At a condition of similar PAR ($P > 0.3$) between treatments when light quality was measured both on the surface of the sward canopy and at 10 mm above ground, R:FR ratio was not significantly different between treatments on the surface of the canopy, but significantly different ($P < 0.05$) at 10 mm above ground (Table 6.3). R:FR ratio at 10 mm was negatively ($P < 0.05$) correlated to the internode length of white clover ($r = 0.77$, Figure 6.4b). This indicated that the change of white clover growth behaviour during following was related in part to alterations in R:FR ratio at the base of the sward.

6.4.3 Practical implications

A detailed discussion on duration of a pastoral fallow was given by Mackay et al. (1991) who suggested that a shorter duration, rather than spring - autumn pastoral fallow (either starting later or finishing earlier) may fit in more closely with the forage supply pattern and with grazing management practices of a hill pasture. One option given by Nie et al. (1997a) for oversowing was to terminate a spring fallow in early summer (late December) rather than May. Although the plant density is substantially decreased with a October - December fallow (Nie et al., 1997a), there are difficulties in successfully oversowing species at this time due to the risk of low summer rainfall (or drought) which reduces the survival rate of oversown species following the conclusion of fallowing. A fallow initiated in December-February in this experiment reduced plant population (grass + legume + weed) density by 51~71%, and may provide a favourable environment without moisture stress for oversowing in late autumn.

The self-thinning relationship implies that the rate of biomass accumulation determines the rate of self-thinning, and factors promoting plant growth enhance self-thinning. This is supported by the evidence that the N addition, which stimulates plant growth, significantly decreased grass tiller density of Mar. fallow + N compared with the non-fertilised treatment (Mar. fallow) at six weeks after fallowing was imposed and N applied (Table 6.1). However, this significance did not last to the end of fallowing, reflecting the short-term effects of N fertiliser. N addition in Feb. fallow + N had no effect on plant population density probably due to the summer drought when N was being applied. This demonstrated that use of N to enhance self-thinning during pastoral fallow should allow a longer period of growth promotion and avoid moisture deficit. N addition also improved the specific stolon weight of white clover and reduced the viable seed population of weeds and rush (Table 6.1), which may benefit

both post-fallowing white clover growth and the oversown new species subject to less competition from the natural reseeding of weeds and rush.

A spring - autumn fallow allowed reproductive growth of all species, resulting in considerable natural reseeding, especially for grass species (Nie et al., unpublished data). This may impose strong competition with the oversown pasture germplasm. One goal of a late fallow is to control the reproductive development of the pasture by grazing, especially in the grass species. The fallows initiated in January onwards had low proportions (< 25%) of reproductive tillers in the swards. The Dec. fallow had a reproductive tiller proportion of 40%, which was close to that (42%) of a spring - Autumn fallow (Nie et al., 1997a). These results were well linked with natural reseeding. The December to March fallows did not significantly increase the viable seed population of legumes, weeds, rush and the total of all species (Table 6.2). The only significant difference was detected in grass viable seed population between Dec. fallow and the grazed control ($P < 0.05$). This suggested that the fallows started from January onwards were effective in controlling natural reseeding during fallowing. The Dec. fallow should be carefully used if the resident grass species are undesirable.

In conclusion, pastoral fallows starting from December, January and February or March + N and ending in June considerably reduced plant population density for oversowing new plant species. Natural reseeding of grasses was significant when a December fallow is used. The increased dispersion of white clover stolons by internode elongation in the fallowed swards, especially in the Dec. and Jan. fallow may improve the distribution and content of white clover in hill pastures.

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Chapter 7

Short- and Long-Term Effects of Pastoral Fallowing on White Clover (*Trifolium repens* L.) and Pasture Growth

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This chapter is based on the following two papers: 1) Long-term effects of pastoral fallowing on the distribution and performance of white clover (*Trifolium repens* L.) in a hill country pasture (Nie, Z. N.; Valentine I.; Mackay, A. D.; Barker, D. J.; Hodgson, J.; 1996). In D. R. Woodfield (ed.), *White Clover: New Zealand's Competitive Edge*. pp 75-78. 2) Impact of a pastoral fallow on the morphology and growth of white clover (*Trifolium repens* L.) in a New Zealand hill pasture (Nie, Z. N.; Valentine I.; Barker, D. J.; Mackay, A. D.; Hodgson, J.; 1997). *Proceedings of the XVIII International Grassland Congress*. pp 109-110 (Session 22).

7.1 INTRODUCTION

Previous work (Chapter 3) found that white clover (*Trifolium repens* L.) yield decreased during pastoral fallowing, but subsequently increased following a pastoral fallow. Two experiments were carried out to quantify the response in herbage production and stolon characteristics of white clover for a short term (1 - 2 years) and long term (up to 4 years) after spring to autumn pastoral fallowing. In Experiment 1 (short-term), herbage mass and white clover stolon characteristics were measured over two growing seasons following the conclusion (May 1994) of a 7-month pastoral fallow. In Experiment 2 (long-term), the effects of a spring to autumn fallow on white clover growth behaviour and production were examined for up to 4 years after the fallow.

7.2 LITERATURE REVIEW

Low legume content (<10%) is a common feature of most hill country pasture in New Zealand. Lifting the content and improving the distribution of perennial legumes such as white clover of hill pastures is a major objective of a pasture improvement programme. Due to the steep slopes and uneven contour of hill country in New Zealand, oversowing is the only feasible practice to increase its proportion in the sward (White, 1990). However, the success rate of oversowing for legumes is low in hill country due to unpredictable weather and limitations of the technique (Awan, 1995).

The fact that white clover has patchy distribution in a mixed sward has been well recognised, although little attention has been paid to patch analysis of white clover (Edwards, 1994). Production of white clover is determined by the patch density, patch size and clover mass per patch. Environmental and management factors such as season, cutting or grazing and fertilizer alter the two later factors rather than patch density (Edwards, 1994).

The capacity of stolons to spread horizontally is an important characteristic for the competitive ability of white clover. The extent of stolon dispersion is determined by internode elongation which can be markedly decreased by defoliation (Thomas, 1972; Wilman and Acuna-P, 1993), but compensated by an increase in both branching and total stolon length per unit area. Wilman and Acuna-P (1993) have shown that swards should be cut or grazed closely and regularly to promote branch development in order to encourage white clover competition with grass and raise the content of white clover in the pasture. By contrast, however, other studies of the effects of alternating grazing and/or cutting management on improving the growth and content of white clover in mixed swards found that, when longer recovery intervals (over six weeks) between defoliations was imposed in white clover-depleted swards, the clover content was raised without the expense of either reseeding or oversowing (Curl and Wilkins, 1985; Sheldrick et al., 1993). These conflicting conclusions may reflect the varying roles of different growth components, i.e. branches, active growing points or internode length.

Pastoral fallow is a technique originally used to improve soil fertility and post-fallowing pasture production (Mackay et al., 1991). It can be considered as a prolonged rest period or interval between defoliations. During fallowing, standing herbage increases, leading to increased plant competition altering sward structure and white clover growth behaviour (Chapter 6).

7.3 MATERIALS AND METHODS

7.3.1 Trial site and design

Two experiments were conducted at AgResearch Hill Country Station, Ballantrae near Palmerston North. The trial site was on a south (shady) aspect of moderate slope where the dominant species were low fertility-tolerant grasses such as browntop (*Agrostis capillaris* L.) and sweet vernal (*Anthoxanthum odoratum* L.). White clover constituted <10% of total annual production. The soil was a YGE/YBE

intergrade (Typic Dystrochrept) of sedimentary origin. The average soil Olsen P was 12 mg/kg soil.

7.3.1.1 Experiment 1

In 1989, six areas of 500 - 800 m² each were fenced in three blocks. One plot was randomly chosen from each block to receive 35 kg phosphorus (P)/ha/year of North Carolina reactive phosphate rock and 14 kg sulphur (S)/ha/year of elemental sulphur added in August annually from 1989 to 1993. In October 1993 all plots (main plot) were split into sub-plots (split plot design) with one half fallowed from 19 October 1993 until 31 May 1994 and the other half rotationally grazed by sheep to maintain a herbage mass not exceeding 3,000 kg DM/ha.

7.3.1.2 Experiment 2

Twelve areas (175 - 750 m²) were fenced in a randomised complete block design of 4 treatments and 3 replicates. The four treatments were: fallowed 1990/91 (F4), fallowed 1991/92 (F3), fallowed 1993/94 (F1) and non-fallowed, grazed (F0). The fallowing period was from September or October until the following May. At the conclusion of a fallow period plots were grazed twice by cattle. Outside the fallow period, in non-fallow years, and in the F0 treatment, plots were continuously grazed by sheep to prevent herbage mass exceeding 3000 kg DM/ha. All plots received reactive phosphate rock (35 kg P/ha) and elemental sulphur (14 kg S/ha) annually from 1989 to 1992, with little or no fertilizer applied in the 20 years preceding that time.

7.3.2 Measurements

7.3.2.1 Experiment 1

Measurements of pasture growth were made by cutting one 0.5 m² quadrat to 1 cm above ground-level in each sub-plot, three times during 15 December 1994 - 18 May 1995 for the first year (Year 1) post-fallowing, and 28 September 1995 - 5 February 1996 for the second year (Year 2) post-fallowing. Sub-samples of pasture were dissected into grass, white clover, other legume, weed and dead matter, to estimate the dry matter of each component. White clover stolon characteristics were measured on twenty 50 mm diameter tiller plugs from each sub-plot on 5 December 1994 and 30 November 1995, for Year 1 and 2, respectively. Tiller plugs were dissected to obtain all surface and buried clover stolons which were washed, dried and then trimmed to determine total stolon length, internode length and stolon dry matter.

7.3.2.2 Experiment 2

Herbage mass and white clover stolon characteristics were measured on the same dates using the same methods as in Year 1 of Experiment 1. Along with the measurement of clover stolon characteristics in Year 1 of Experiment 1, the numbers of grass tillers, white clover growing points, other legume plants and weeds in the tiller plugs were counted to estimate plant population density. Moss cover was scored as 0 (none), 1 (less than half of plug surface covered by moss), 2 (more than half) and 3 (full). On 16/3/1995, a 3 m transect was trimmed to ground level by electric shears in each plot. One week later, occurrence (1) or absence (0) of active growing points and young leaves in 1 cm² contiguous quadrats were recorded along each transect to estimate white clover stolon distribution pattern.

7.3.3 Statistical analysis

Data were analysed by Analysis of Variance with the General Linear Model procedure of the Statistical Analysis System (SAS Institute 1990). A split-plot model with repeated measures (Year 1 and 2) was used to analyse the data of Experiment 1. A randomised complete block model was used to analyse the data of Experiment 2.

White clover stolon distribution pattern in Experiment 2 was analysed by the Two Term Local Quadrat Variance (TTLQV) method (Dale and Maclsaac, 1989). The squared difference between adjacent block totals was plotted against an increasing block size. The x-axis of local maxima showed the scale of pattern, i.e. average distance between the centre of a patch of white clover and the centre of a gap. The smaller peaks may reflect smaller patches of branches or irregular shape of patches. The sizes of patches and gaps was estimated by multiplying the scales of pattern with the average proportions of blocks with and without active white clover growing points.

7.4 RESULTS

7.4.1 Experiment 1

7.4.1.1 The morphological characteristics of white clover

There were clear interactions in white clover stolon length ($P < 0.1$), weight ($P < 0.05$) and internode length ($P < 0.05$) between fallow and post-fallowing time (Figure 7.1). The white clover stolon length and weight on the fallowed plots increased from 17.6 m/m² and 5.8 g/m² in Year 1 to 28.6 m/m² and 8.9 g/m² in Year 2, respectively. On the grazed plots, however, both stolon length and weight of white clover decreased from Year 1 to Year 2. The internode length

declined from 2.9 to 2.1 mm on the fallowed plots, but remained consistent on the grazed plot.

7.4.1.2 Pasture growth rate

Fallow significantly ($P < 0.05$) increased grass growth rate (926 kg DM/ha/month) compared with grazing (710 kg DM/ha/month) (Table 7.1). Fallow did not significantly influence white clover and weed growth rate, though clover growth rate (36 kg DM/ha/month) on the fallowed plot appeared to be higher, and weed growth rate (89 kg DM/ha/month) lower, than the grazed plot (27 and 134 kg DM/ha/month for clover and weed growth rate, respectively). Significantly greater grass and weed growth rate ($P < 0.01$) were found in Year 2 compared with Year 1 (Table 7.1). The increased white clover growth rate from Year 1 (24 kg DM/ha/month) to Year 2 (40 kg DM/ha/month) was again not statistically significant ($P > 0.05$). There was a significantly higher white clover growth rate (data not shown) in the fertilised than the non-fertilised treatment.

7.4.2 Experiment 2

7.4.2.1 Herbage mass, botanical composition and pasture density

A significant difference in white clover yield was found among treatments (Table 7.2). The treatment F4 produced highest yield of white clover, three times that of the grazed control ($P < 0.05$). Although white clover yield for F3 was increased by 76% compared with F0, the difference was not significant ($P > 0.05$).

There were no significant differences for the dry matter yield of grasses, other legumes and weeds between fallow treatments. There was a trend (non-significant) of reduced dead material content with increasing years after fallowing.

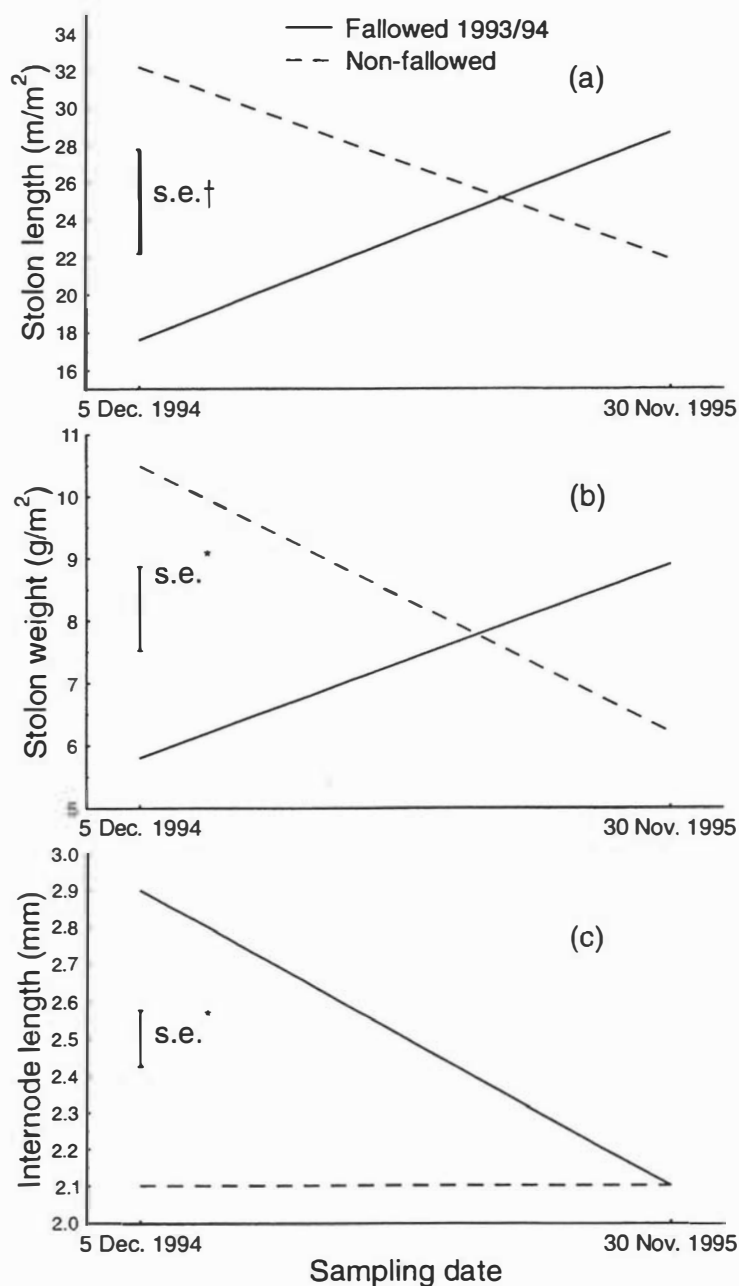


Figure 7.1 Response of (a) white clover stolon length, (b) stolon weight and (c) internode length to fallowed and non-fallowed (grazed) treatment in the first and second year post-fallowing (* and † represent interaction significance $P < 0.05$ and $P < 0.1$, respectively).

Table 7.1 Effects of fallowing and the time post-fallowing on the growth rate (kg DM/ha/month) of grass, white clover and weed in the periods of 15 December 1994 - 18 May 1995 (Year 1) and 28 September 1995 - 5 February 1996 (Year 2).

Treatment	Grass	Clover	Weed
Fallowed	925.8	36.3	89.1
Grazed	710.4	27.2	134.4
<i>SEM</i>	<i>54.8</i>	<i>3.5</i>	<i>17.0</i>
<i>Significance</i>	*	<i>ns</i>	<i>ns</i>
Year 1	641.1	23.5	50.3
Year 2	955.3	40.0	173.3
<i>SEM</i>	<i>42.2</i>	<i>5.7</i>	<i>13.2</i>
<i>Significance</i>	**	<i>ns</i>	**

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

As with yield, white clover growing point density declined in F1 (1520 points/m²) from F0 and increased subsequently to over 6500 points/m² in F4 (Table 7.2). Weed density and the cover of moss showed similar trends. There was an increase in grass and other legumes in F1 from F0, but both declined subsequently. There was an inverse relationship between grass tiller density and white clover growing point density, indicating probable competition between these two components of the sward.

7.4.2.2 Stolon characters

Significant differences ($P < 0.05$) in total stolon length were found among treatments, the sequence being F4 > F3 > F0 > F1 (Figure 7.2). Total stolon weight, not shown, followed the same trend. Fallowing decreased total stolon length and the F1 treatment had only 21 m/m² of stolons. However, internode length changed in a reverse manner to total stolon length and weight, with fallowing increasing internode length for up to 6 months after the cessation of the fallow, then gradually declined thereafter. The stolon dry matter per unit length was not statistically different between treatments, indicating stolon thickness was not altered by fallowing.

7.4.2.3 Distribution pattern

Figure 7.3 shows an example of distribution pattern of white clover from one replicate. There were clear patterns for F4, F3 and F0, but no clear pattern for F1 probably due to a recent substantial reduction in growing points and branches by fallowing. The ratio of gap diameter to white clover patch diameter had significant difference ($P < 0.01$) between treatments, with F3 and F4 being approximately 46% lower than F0 (Table 7.3). This reflected that the gap size in F0 was significantly greater than patch size in comparison with F3 and F4. Previous fallowing increased white clover patch diameter by 25-35% and decreased the gap diameter

Table 7.2 Effects of post fallowing duration on pasture yield (kg DM/ha) from 15 December 1994 to 18 May 1995 (means of three harvests) and grass tiller and white clover growing point density (No./m²) on 5 December 1994.

Treatment	Yield			Density	
	Total	Grass	White clover	Grass	White clover
F4	1796	1289	153 a	26,000	6520 a
F3	1550	1178	90 ab	28,000	2800 b
F1	1546	1168	48 b	36,000	1520 b
F0	1728	1254	51 b	27,000	3010 b

Note: Data with different letters indicate significant difference ($P < 0.05$).

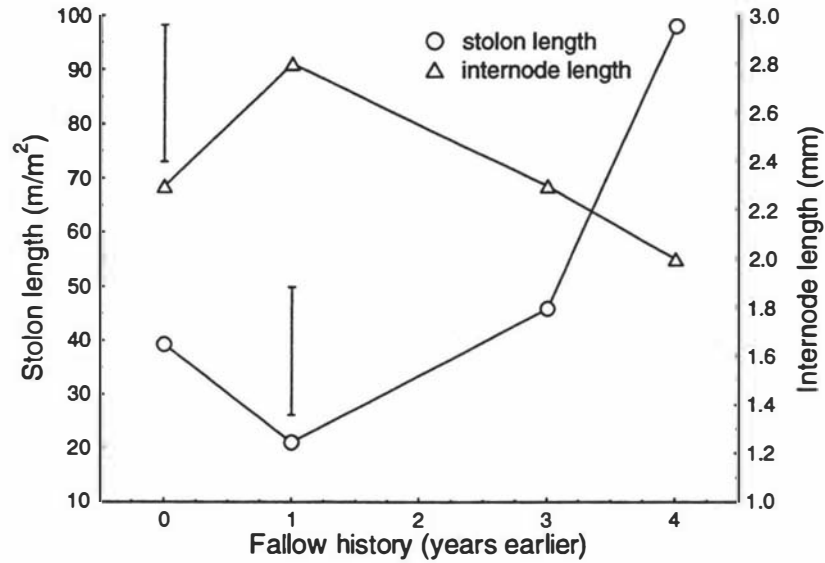


Figure 7.2 Total stolon and average internode length of white clover with various fallow history (Vertical bars show LSD_{0.05}).

by 19-30%. There was no significant difference for pattern scales between treatments.

7.5 DISCUSSION

7.5.1 Short-term post-fallowing effects

The widely spread clover stolons during pastoral fallowing (Chapter 6, Figure 7.2) initiated branching at the end of fallowing, resulted in a cumulative increase of stolon length and weight and a decline of average internode length in the two subsequent years post-fallowing (Figure 7.1). The decline of both stolon length and weight of grazed pastures was probably due to less protection by dense grasses over a dry period. The rainfall of January - March 1995 was only 57 mm/month, which was 65% of the 24 year average over the same period. Brock and Kim (1994) indicated that high pasture (grass) density that was capable of providing shelter from direct solar radiation to clover stolon gave superior survival of white clover during drought stress. The increase of stolon length and weight from Year 1 to Year 2 in the fallowed sward was the combination of both the formation of new clover patches (Table 7.3) and a higher survival rate of clover during the dry period.

Although there was a clear increase in stolon length and weight of white clover within the two post-fallowing years, the response of white clover growth rate was not significant (Table 7.1). However, grass growth rate was significantly increased from Year 1 to Year 2. This was probably related to an increase of tiller density one year post-fallowing (Table 7.2) and the release of nitrogen shortly after fallowing (Mackay et al., 1991). In spite of protection of clover stolons over the dry period, the vigorous growth of grass species in other periods during the first two years after fallowing may have competed strongly with white clover. This competition would have restricted the growth of white clover.

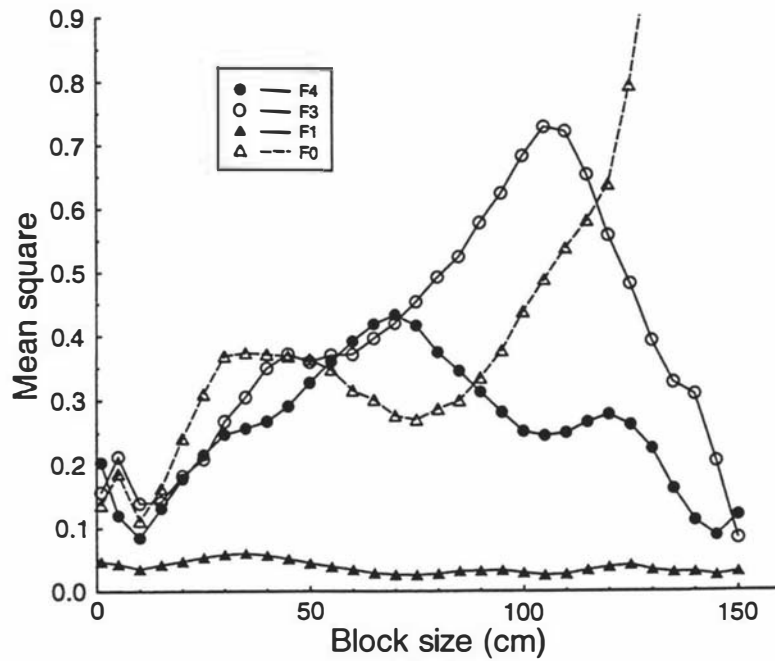


Figure 7.3 The distribution pattern of white clover of various treatments (see 7.3.3 Statistical analysis for explanation of methodology).

Table 7.3 Scale of pattern, average diameter of gap and white clover patch and mean ratio of gap:white clover patch diameter (G:C ratio).

Treatment	Scale (cm) of pattern	Diameter of patch (cm)		G:C ratio
		Gap	Clover	
F4	91.7	122.1	61.3	2.0 a
F3	103.3	140.5	66.2	2.1 a
F1	No pattern	-	-	-
F0	111.7	174.3	49.0	3.8 b

Note: data with different letters indicate significant difference ($P < 0.01$).

The difference in growth rate for all species between Year 1 and 2 (Table 7.1) was probably due to: a) low rainfall during January - March 1995 (mean monthly rainfall was 63% of the same period of 1996) of the first measurement year; b) the first measurement year was during autumn, while the pasture growth rate is generally lower than in summer and spring. The increase of total herbage and white clover yield by fertiliser applied 1-2 years earlier in this study supports the finding of Lambert et al. (1983) who showed that fertiliser previously applied still has an effect, though reduced in magnitude and beyond that in the immediate year of application.

7.5.2 Long-term post-fallowing effects

Little attention has been paid to detailed analyses of the spatial distribution of species within temperate grassland systems, although the fact that white clover is distributed in patches in mixed species pasture is recognised (Edwards, 1994; Grant and Marriott, 1989). The yield (Y , kg/ha) of white clover in a mixed sward can be described as $Y = PD * PS * CMP$, where PD is patch density (No./ha), PS is patch size ($m^2/patch$) and CMP is clover mass per patch ($kg/m^2/patch$). Each of the three components is positively correlated with white clover yield. Many studies (Wilman and Acuna-P, 1993; Collins et al., 1991; Laidlaw and Withers, 1989; Grant et al., 1991; Turkington et al., 1994) have concentrated on the management and climate factors that influence growth of branches, growing points and leaves. This has contributed to an understanding of CMP and PS , but little of PD . This was evident from Edwards (1994) who demonstrated that increases in white clover content with various seasons and by different grazing management were predominately the result of increases in the size of clover patches with no new patches developed.

The patch density of white clover is initially determined by seeding rate and genotype interaction with variable surface topography. Recruitment from buried seed within established populations is rare in white clover and other communities dominated by clonal plant species (Chapman, 1987). Thus, the possibility of

increased clover patch density in a sward relies on stolon dispersion, unless new white clover seeds are introduced. The significance of fallow in this study was that, in spite of initial depression of clover density, it stimulated internode elongation which resulted in more extensively distributed stolons in the sward. These widespread stolons may have formed the nucleus of larger and/or new patches for subsequent expansion after grazing management had been reimposed at the conclusion of fallow. The resultant increase in white clover yield of swards followed 3 and 4 years earlier, was thus probably the result of both greater PS and PD. This was supported by the result of spatial pattern analysis (Table 7.3).

The internode length was found to be negatively correlated to the total stolon length per unit area (Wilman and Acuna-P, 1993), because the increase in main stolon length by internode elongation did not compensate for the loss of secondary stolons when duration between defoliations was prolonged. Therefore, total stolon length cannot be used as a criteria for stolon dispersion within a sward. For example, in the F1 treatment the total stolon length was much lower than F0 (21 vs 39 m/m², respectively), which was not an indication of less dispersed clover stolons in F1 sward.

Changes in sward clover content brought about by longer recovery interval of cutting and grazing management are likely to be less immediate than those from oversowing (Sheldrick et al., 1987). In this study the treatment F1 was inferior, although not significantly, to the grazed control in white clover yield, botanical composition and growing point density. This may be, in part, due to grass competition as there was a flush of grass tillers (36000 tillers/m²) produced within the year after the fallow. Post-fallowing white clover regrowth is of great importance for clover recovery in the sward. In addition to grazing examined in this study, climatic, edaphic and macro-environmental factors, and the interactions between them also probably play a part in the recovery of stolon growth, branching and new patch formation after fallowing. The large difference between F4 and F3 in clover yield, growing point density and total stolon length and weight, although

the order for the two treatments followed the trend along with fallow history (Table 7.2), may result from the interactive effect of grazing with these factors. The duration of increase in sward clover content after fallowing needs further confirmation.

7.6 CONCLUSION

Pastoral fallowing significantly increased grass growth rate in the two subsequent years post-fallowing. The high density of grass favoured stolon survival over dry periods, but the improved grass growth may have imposed strong competition on white clover growth. The increase in clover stolon length and weight and decrease in internode length in the first two years after fallowing, although not resulting in improved growth rate, indicated the restoring of stolon branching and the start of new clover/grass equilibrium post-fallowing. At 4 years post-fallowing, both white clover stolon length and growing point density were significantly increased. Distribution pattern analysis showed that clover patch size and density increased at 3 - 4 years post-fallowing. The increase in white clover post-fallowing was attributed to its ability to disperse through the pasture during fallowing and re-establish in gaps in the pasture where it had previously not been present.

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Chapter 8

General Discussion and Conclusion

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8.1 INTRODUCTION

This thesis presents the results of a series of experiments quantifying the response of plants and soil in hill country pastures of New Zealand during and after a pastoral fallow. The underlying aim was to assess the potential use of pastoral fallow as a management tool to improve the productivity, quality and persistence of hill pastures through oversowing, improved clover growth and natural reseeding.

The effects of pastoral fallow on sward structure, plant population density and soil physical and chemical properties were examined mainly in an October to May pastoral fallow in the field (Chapter 3 and 4). A spring - autumn pastoral fallow produces abundant viable seeds which benefits the persistence of grass population in a sward (McCallum et al., 1991), but may impose a strong competition on oversown species. Thus, the mechanisms of natural reseeding during and after pastoral fallow were studied and techniques to control natural reseeding were evaluated by both field and glasshouse experiments (Chapter 5 and 6). White clover (*Trifolium repens* L.) and pasture growth were repeatedly measured during two growing seasons post-fallowing to examine the short- and long-term effects of a pastoral fallow (Chapter 7). This chapter presents an integrated discussion of all results, with an emphasis on relationships between factors.

8.2 RESPONSE OF PASTURE PLANTS AND SOIL TO PASTORAL FALLOW

The responses of pasture plants, soil and natural reseeding to full (October - May) and partial (early completion or late commencement) pastoral fallows and their practical importance are summarised in Figure 8.1.

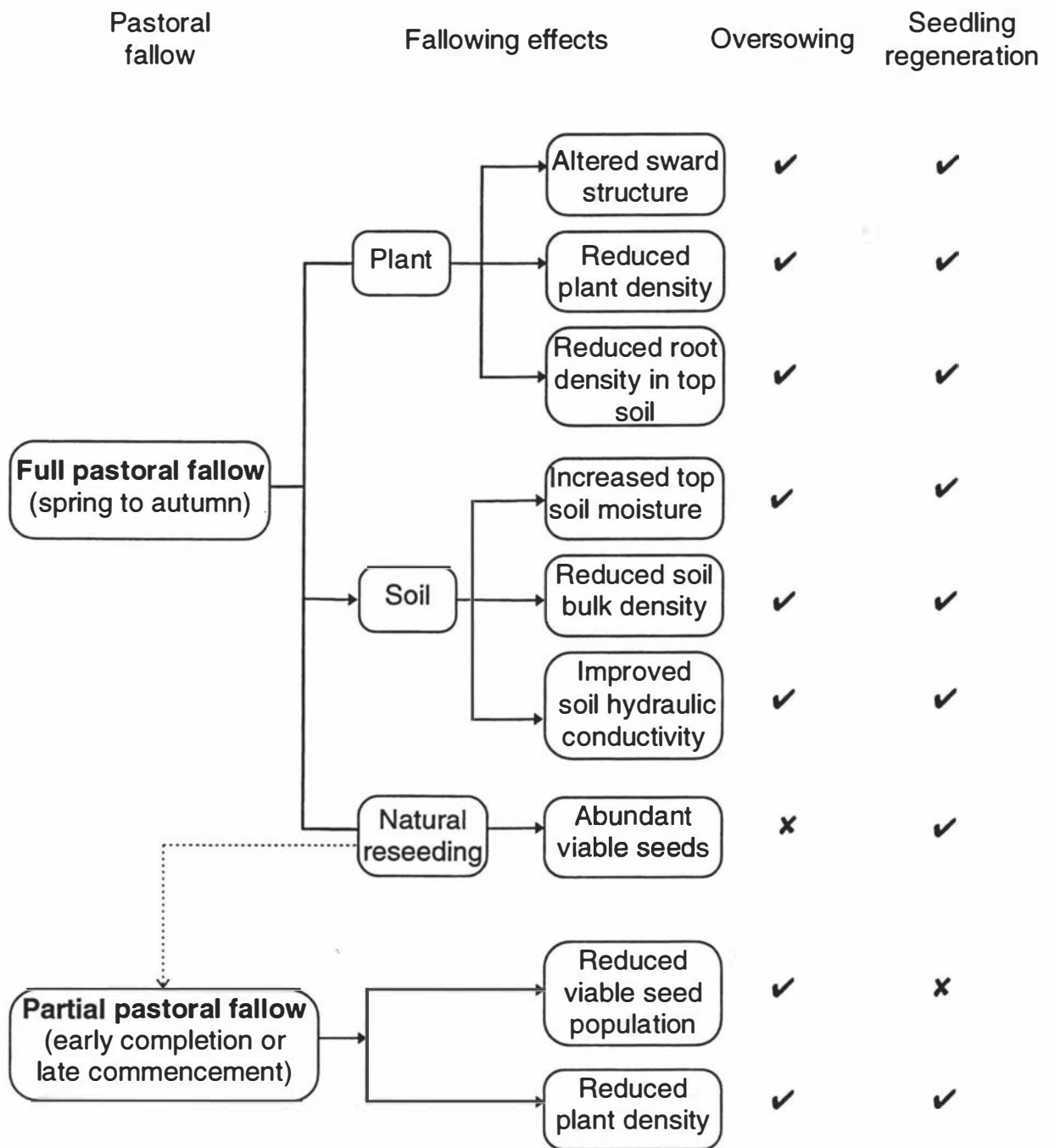


Figure 8.1 The responses of plant, soil and natural reseedling to full and partial pastoral fallows which may favour (✓) or harm (✗) oversowing and natural regeneration in practice.

8.2.1 Above and below ground plant response

The background rationale was to use a pastoral fallow to reduce plant population density as predicted by the self-thinning rule which describes plant mortality due to competition in crowded even-aged stands (Yoda et al., 1963; Westoby, 1984). This would allow the introduction of new germplasm into the open sward following the removal of the standing phytomass by cattle grazing. During an October to May pastoral fallow, the phytomass above 1 cm from ground level increased from 1400 kg/ha at the start of fallow to a maximum of 6600 kg/ha in February (Chapter 3, Figure 3.3). The accumulation of above ground phytomass caused strong inter-plant competition and self-thinning. In addition, the completion of the life cycle of matured plants also contributed to plant mortality. At the end of the fallow, the densities of grass tillers, white clover growing points and other species in the fallowed sward declined by 72, 87 and 87% compared with their initial plant densities, and by 77, 82 and 51% compared with the grazed sward, respectively (Chapter 3). Such a significant reduction in plant population density should achieve the aim of removing above ground competition from resident vegetation on oversown plant germplasm (Figure 8.1).

Principal component analysis revealed that the relationship between above ground plant size and plant density followed the self-thinning rule during the October to May pastoral fallow (Figure 3.2). The self-thinning line was a particularly good fit when calculation was based on all plant species rather than grass alone, although grasses were the dominant species in the sward and most studies of pastures used grass alone to quantify the tiller size/density relationship (Bircham and Hodgson, 1983; Davies, 1988; Matthew et al., 1996). The self-thinning rule also applied to the plant size/density relationships when treatments of pastoral fallows varying in start date and duration were imposed (Figure 6.4).

The key to achieving a well self-thinned sward is the accumulation of above ground biomass. Any factors which promote pasture growth rate will accelerate self-thinning. For instance, addition of N to a March to June pastoral fallow stimulated pasture growth, resulted in a tiller loss 44% greater than the treatment without N added (Table 6.1). The tiller loss (13300 tillers/m²) on the shady aspect, moister in summer (Chapter 4, White, 1990), was 13% greater compared with that (11800 tillers/m²) on the sunny aspect during an October to May fallow (Table 3.1). A March to September fallow, although fallowed longer than a partial fallow in autumn, resulted in a very poor plant density decline due to low above ground biomass accumulation in autumn and winter (Figure 6.1 and 4a). Therefore, use of pastoral fallow as a management tool to suppress competition of existing vegetation for oversowing would be more appropriate to environments, e.g. summer moist hill country, and seasons e.g. spring - autumn with good pasture growth. To use a pastoral fallow for this purpose in environments with low pasture growth rate, timing of fallowing and techniques to stimulate pasture growth rate become important.

An important factor influencing grass seedling survival when oversowing into existing pastures is below ground competition (Seager, 1987). Below ground competition between grass species begins earlier and has a greater impact on the overall competitive relationships between the species than shoot competition (Sangakkara, 1983). As discussed above, plant population density was dramatically decreased at the end of an October to May fallow. If each plant or tiller of grass has its own root system, then substantially less plants/tillers in the fallowed sward should result in significantly lower root biomass than the grazed sward. The reduction in plant number on the fallowed plots was accompanied by a decline in root biomass of the top soil (0 - 50 mm depth) compared with the grazed plots (Chapter 4). Pastoral fallow also encouraged the growth of fewer, larger plants with deeper roots, resulting in a greater root biomass below 200 mm soil profile compared with grazed plots. Low root biomass at 0 - 50 mm depth under the fallowed sward should favour

the practice of using pastoral fallow as a tool to reduce both the plant shoot and root competition on oversown germplasm (Figure 8.1).

8.2.2 Soil physical and chemical properties

Fallowing is a traditional method that has been used to increase soil moisture, build soil fertility and subsequently improve plant growth (Lamb et al., 1985; Bowen et al., 1988; Thorburn, 1992; Yunusa et al., 1994). Mackay et al. (1991) found that the mineralization of soil organic matter and the release of legume-fixed nitrogen or organic matter-contained nitrogen were stimulated by pastoral fallowing. Compared with the grazed treatment, an October to May pastoral fallow reduced soil bulk density by 11%, and increased air permeability at 500 mm tension, saturated hydraulic conductivity and unsaturated hydraulic conductivity at 20 mm tension by 38, 26, 67%, respectively. The reduction in bulk density indicates an increase in soil porosity, but it provides little information on pore size distribution and function. The increase in both saturated, and unsaturated hydraulic conductivity at 20 mm tension on fallowed soil showed an improved water flow rate as a result of increased large functioning pores (>1500 μm) compared with the grazed soil. These results demonstrate that pastoral fallow can be an effective management option to reduce soil structural damage caused by stock treading.

Soil moisture content is the most dominant factor affecting seed germination and seedling establishment (Harper and Benton, 1966; McWilliam and Dowling, 1970). An October to May pastoral fallow increased soil moisture content, especially in the top soil (0 - 50 mm) compared with the grazed sward (Table 4.1), probably due to reduced soil evaporation and plant transpiration by the accumulation of dead standing plant and plant litter at the late stage of fallowing (Figure 3.3a). The increase in soil moisture is particularly important where soil moisture is critical at the site, e.g. sunny aspect, and the time, e.g. around March, for oversowing in hill country.

In general, pastoral fallow did not affect the content of most nutrients in soil both during the fallowing period and after 2 - 3 years post-fallowing (Table 4.3 and 5). The slight differences between the fallowed and the grazed treatment were lower K and mineral N levels at 0 - 75 mm soil depth in the fallowed soil at the end of an October to May fallow, and was probably due to no nutrient return through dung and urine and reduced N fixation by legumes suppressed during fallowing (Chapter 4; Mackay et al., 1991). However, the mineralisation of plant residues and soil organic N stimulated shortly after the conclusion of pastoral fallowing (Mackay et al., 1991) may compensate K and N depletion during pastoral fallowing.

8.2.3 Natural reseeding and partial pastoral fallow

Two possible and conflicting objectives of pastoral fallowing are:

- 1) to increase natural reseeding by encouraging seed production of desirable species during summer/autumn pastoral fallow (L'Huillier and Aislabie, 1988; Boom and Sheath, 1990; Hume et al., 1990; McCallum et al., 1991);
- 2) to reduce plant population density for oversowing new plant germplasm (Chapter 3).

The first objective requires maximal natural reseeding, but the second objective requires maximal self-thinning and minimal natural reseeding in order that the competition of seedlings by natural reseeding on introduced species is minimised (Chapter 5; Figure 8.1).

8.2.3.1 Natural reseeding

A spring - autumn pastoral fallow increased the viable grass, legume, weed and the total seed population by 51-160%, compared with the grazed control

(Chapter 5). Regression analyses revealed the patterns of cumulative seedling appearance under glasshouse conditions and two pools of soil viable seed reserves (Figure 5.3). The rapidly germinable pool (RGP) reflected seeds which remain close to the soil surface and germinate rapidly if conditions for germination allow, and the base pool (BP) reflected seeds which germinate slowly due to either enforced or innate dormancy (Howe and Chancellor 1983). Calculation of the size of RGP and BP showed that seeds of various plant species freshly shed during pastoral fallow entered RGP and BP in very different proportions (Table 5.4). Of the grass seeds (17590 viable seeds/m²) produced by fallow, 82% went into RGP and only 18% went into BP. Weeds had a similar distribution to grasses. Of the legume seeds (628 viable seeds/m²) produced by fallow, most seeds (65%) went into BP with only 35% entering the RGP.

The fact that most (82%) of the grass seeds germinated rapidly after the conclusion of a pastoral fallow favours the practice of using pastoral fallow to increase the persistence of grasses through natural reseeding (Figure 8.1; Hume et al., 1990; McCallum et al., 1991). The rapid appearance of regenerated seedlings should avoid the strong competition from new tillers produced by the resident plants after the conclusion of fallowing. However, rapid seedling appearance will impose strong competition on oversown species, if the purpose of the pastoral fallow is to prepare a seedbed (Figure 8.1). The small proportion (35%, 220 viable seeds/m²) of legume seeds in the RGP suggests that seedling regeneration plays little role in the persistence of legumes on a short-term basis.

The seasonal variation in the viable seed population of the dominant grasses followed a regular pattern during a spring - autumn pastoral fallow (Figure 5.2a). The viable grass seed population increased slightly from October to December, but rapidly from December to March, as the maturity of seeds for most species occurred after December. The viable grass seed population decreased from March to May, predominantly due to seed loss by germination

during this period. Compared with grasses, the viable seed populations of legumes and weeds were very low.

8.2.3.2 Partial pastoral fallow

Although an October - May pastoral fallow reduced potential competition between established plants and seedlings of introduced species, competition from seedlings resulting from natural reseeding during the fallow would likely be intense. The seasonal variation of viable grass seed population during an October - May pastoral fallow (Figure 5.2a) suggested that a partial pastoral fallow either completing earlier, for example late December, or starting later, for example from December to March, may achieve the goal of restricting viable seed production during pastoral fallowing while retaining the benefit of reduced plant population density (Chapter 6).

Pastoral fallows starting from December, January, February and March, and ending in June produced total viable seed populations of 2368 to 2597 seeds/m², which were not significantly different from that (2012 seeds/m²) of the grazed sward (Table 6.2). The only significant increase was the viable grass seed population (1121 seeds/m²) in a December - June fallow, which was significantly higher than that (522 seeds/m²) of the grazed control, but still much lower than an October - May fallow (6360 seeds/m²). From a plant density perspective, pastoral fallows starting from December, January and February and completing in June reduced the total plant/tiller (grass + legume + weed) population density by 51 - 71% compared with the grazed control (Chapter 6). Late-starting partial fallows were effective in both controlling natural reseeding and reducing plant density for oversowing new plant germplasm in hill country.

An early partial pastoral fallow (October - December) was also effective in reducing plant population density and viable seed population (Chapter 3 and 5). However, there are difficulties in successfully oversowing species at the

completion of this partial fallow due to the risk of low summer rainfall (or drought) which reduces the survival rate of oversown species (Chapter 6).

8.3 SHORT- AND LONG-TERM EFFECTS OF PASTORAL FALLOW

The short- and long-term effects of pastoral fallow on white clover and grass growth are illustrated in Figure 8.2. Emphasis has been put on changes in white clover growth behaviour during and after pastoral fallowing.

8.3.1 White clover stolon growth during pastoral fallow

The survival of a vigorous stolon network, which supports the growth of new growing points, leaves and stolons, ensures the persistence of white clover in grazed swards (Marriott and Smith, 1992). When a grass-clover sward is closely grazed, white clover increases branching and stolon density and reduces internode length (Thomas, 1972; Wilman and Acuna-P, 1993). When a grass-clover sward was released from close defoliation by a partial pastoral fallow, white clover changed its growth behaviour so that branching and stolon density declined, but internode length increased (Chapter 6). Similar results were observed six months after the conclusion of an October - May fallow (Chapter 7). Increased internode length of white clover during pastoral fallow indicates greater stolon dispersion in the mixed sward (Figure 8.2).

8.3.2 Post-pastoral fallow white clover and grass growth

The widespread white clover stolons during pastoral fallowing resumed branching when the accumulated above ground plant material was grazed by cattle at the conclusion of fallowing (Chapter 7). This resulted in a cumulative increase of stolon length and weight and a decline of average internode length in the following years. At the same time, there was a flush of grass tillers

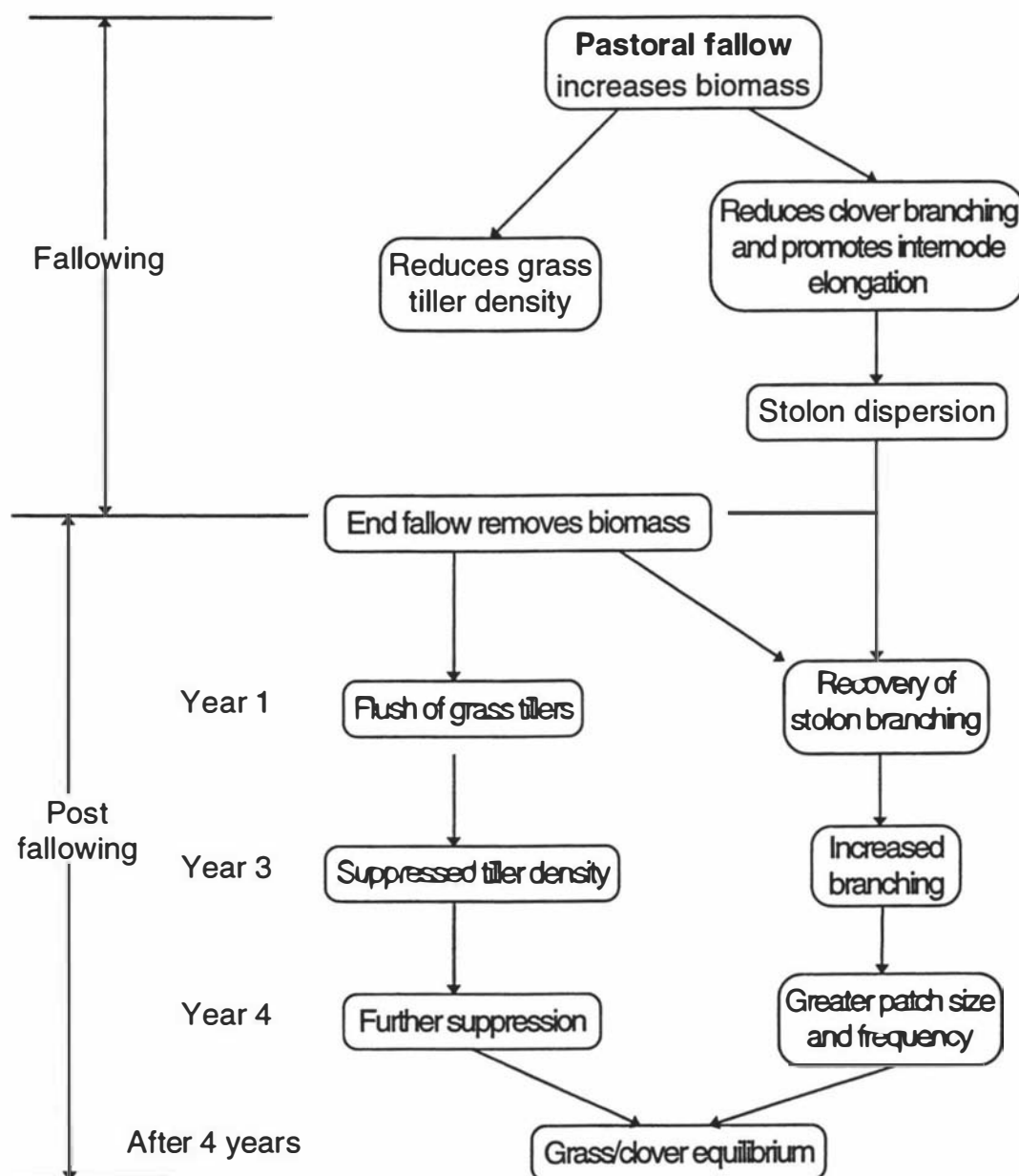


Figure 8.2 Change of white clover growth behaviour and clover/grass competition during and post pastoral following.

appearing shortly after the conclusion of fallowing, which, in combination with the increased soil nitrogen level after fallowing (Mackay et al., 1991), resulted in a high growth rate of grass in the second year post fallowing (Chapter 7). The vigorous growth of grass in the first two years post fallowing imposed a strong competition on white clover, which explained why it took three to four years for the widely distributed clover stolons to raise clover yield significantly (Chapter 7).

The fact that white clover is distributed in patches in mixed species pasture is well recognised (Edwards, 1994; Grant and Marriott, 1989). The yield (Y , kg/ha) of white clover in a mixed sward can be described as $Y = PD * PS * CMP$, where PD is patch density (No./ha), PS is patch size ($m^2/patch$) and CMP is clover mass per patch ($kg/m^2/patch$). Edwards (1994) demonstrated that increases in white clover content with various seasons and by different grazing management were predominately the result of increases in the size of clover patches (PS) with no new patches developed. Close defoliation which stimulates branching would increase CMP , rather than PS or PD . The significance of pastoral fallow in this study was that, in spite of initial depression of clover density, it stimulated internode elongation which resulted in more extensively distributed stolons in the sward. These widespread stolons may have formed the nucleus of larger and/or new patches for subsequent expansion after grazing had been reimposed at the conclusion of fallow. The resultant increase in white clover yield of swards fallowed three and four years earlier, was thus the result of both greater PS and PD (Chapter 7). This result is of particular significance in summer moist hill country where recruitment of white clover from natural reseeding is rare in mixed swards (Chapman, 1987).

8.4 CONCLUSION

An October-May pastoral fallow substantially altered sward structure and reduced plant population density in a summer-moist hill pasture environment. The plant size/density relationship during the pastoral fallow in this mixed species sward followed the self-thinning rule, particularly when the calculation

was based on all plant species rather than grass alone. The decline in grass tiller density by pastoral fallow was enhanced on the shady aspect. Application of P and S increased white clover growing point density on the shady aspect and grass tiller density on the sunny aspect. Application of N accelerated plant mortality during pastoral fallowing.

The October-May pastoral fallow reduced the root biomass at top soil (0 - 50 mm), but encouraged a deeper root system. It also improved soil physical properties, e.g. soil porosity, air permeability, hydraulic conductivity and soil moisture. Pastoral fallowing had little effect on soil chemical properties.

A spring-autumn pastoral fallow considerably increased the viable seed population, especially for grass species. A two-pool (rapidly germinable pool and base pool) model was developed to quantitatively describe the proportion of viable seeds in each pool and their germination rate. The variation of viable seed population during the pastoral fallow followed a predictable pattern, which provided useful information for either utilising or restricting natural reseeding in practice.

Partial pastoral fallows starting from December, January and February or March + N and completing in June considerably reduced plant population density. Except for the viable grass seed population of December - June fallow, other partial fallows and other species in the December fallow had no significant difference in viable seed population compared with grazed. The viable grass seed population of December - June fallow was still much lower compared with a spring - autumn fallow.

Pastoral fallow significantly increased internode length of white clover which indicated greater stolon dispersion in the sward. The widespread clover stolons during pastoral fallowing resumed branching at the conclusion of fallowing, resulting in a cumulative increase of stolon length and weight in the following years. As a result, white clover yield significantly increased 3 - 4 years post

fallowing. This increase was the result of both greater patch size and patch density of white clover.

Based on the conclusions above, impact diagrams have been developed for a) either creating low plant density and low reseeding environment in the autumn for oversowing improved plant germplasm or encouraging natural reseeding for improving the persistence of grass (Figure 8.1); b) improving white clover content in low fertility hill country (Figure 8.2).

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