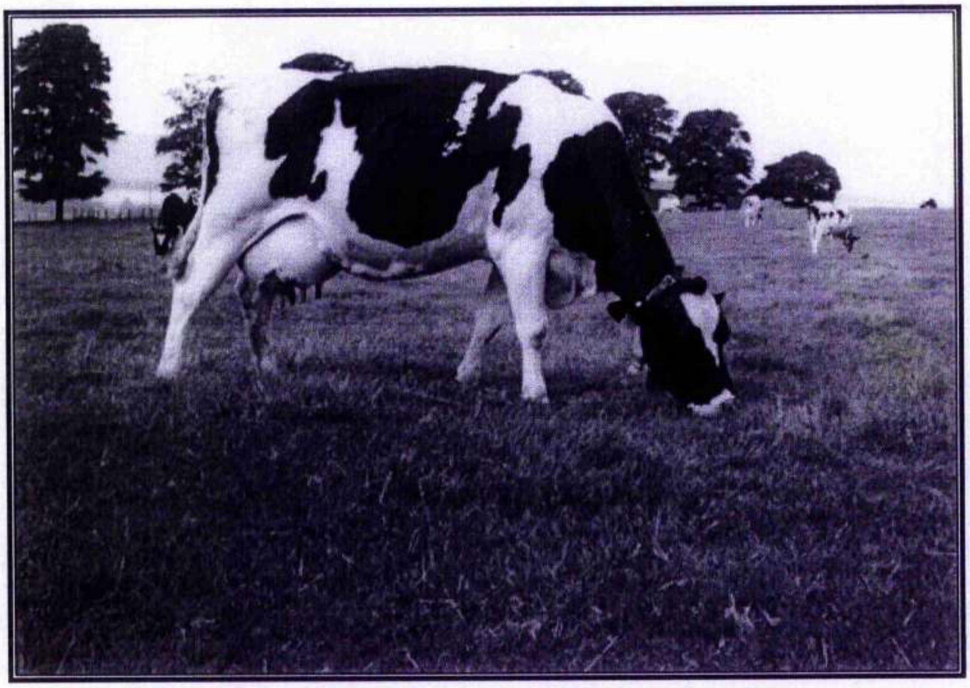
EFFECTS OF SWARD CHARACTERISTICS AND CONCENTRATE SUPPLEMENTATION ON HERBAGE INTAKE AND PERFORMANCE OF LACTATING DAIRY COWS AT PASTURE

LYNN ALICE WILSON

2003

A thesis submitted towards the fulfilment of the requirements for the degree of Doctor of Philosophy comprising a report of studies undertaken at SAC, Animal Biology Division, Crichton Royal Farm, Dumfries; in the Faculty of Science, University of Glasgow



ABSTRACT

Sward characteristics have a major effect on intake and performance of dairy cows at pasture. Milk production from grazing cows however can be restricted by herbage intake, and concentrate supplementation can allow them to perform closer to their production potential. This study investigates effects of sward characteristics and concentrate supplementation on intake and performance of grazing dairy cows.

Grazing cows yielding on average 36.8 kg milk day $(d)^{-1}$ were offered high levels of concentrates in late summer. Milk yield response was 1.01 kg milk kg^{-1} concentrate dry matter (DM) d^{-1} when concentrate was increased from 5.2 to 7.7 kg DM d^{-1}. Milk yield response declined to 0.83 kg milk kg^{-1} DM when concentrate was increased from 7.7 to 10.2 kg DM d^{-1}. Grazing time and herbage intake were reduced at higher levels of supplementation. Increasing concentrate level by 1.7 kg DM d^{-1} when cows were housed overnight had no effect on animal performance. In another experiment, there was no significant difference in animal performance between cows offered either a high starch or high fibre concentrate at a rate of 5.3 kg concentrate DM d^{-1}. Supplementation with an additive formulated to reduce dietary protein degradability however had a positive effect on milk yield, which was on average 34.4 and 32.9 kg d^{-1} for additive and control treatments respectively. Inclusion of the additive also increased milk protein yield and herbage intake.

Interactions between sward characteristics and intake were examined. Bite mass was predicted from estimates of bite dimensions and measurements of vertical distribution of herbage mass in cut swards. A general relationship observed between sward height and vertical distribution of mass could be used to predict bite mass from sward height and total herbage mass. Methods to make detailed measurements of intake and grazing activity within patches of a sward using grazing cows were developed and demonstrated an effect of time of day on bite mass. Research to quantify interactions between sward structure, supplementation and grazing activity, focusing on bite mass, should enable development of strategies to exploit the potential of grazed grass and provide appropriate supplementation, which will ultimately contribute to improved profitability of milk production.

ACKNOWLEDGEMENTS

I would like to thank my supervisors, Dr David Swain and Dr David Roberts, for their helpful advice, encouragement, and valuable discussions, which have allowed me to complete this study.

The British Grassland Society provided me with a post-graduate studentship, and I am grateful to them for allowing me to attend their meetings and conferences. In particular, I would like to thank Jan Crichton for her friendly assistance throughout.

John Dickinson and Donna Nixon provided excellent and willing technical support, and I thank David Webster, Hugh McClymont, and all of the farm staff for their co-operation and help with experimental work. My thanks also go to Jennifer Bell for her encouragement and assistance; all other staff at Mid Park for creating a friendly working atmosphere; and Dr Katharine Leach and Anne Dowdeswell for their help during the earlier stages of my study.

Ian Nevison offered helpful advice on statistical analysis and experimental design. BOCM PAULS provided support that enabled completion of my concentrate supplementation experiments, and I am grateful to Dr Anna Henderson for her advice during this part of my project.

Finally, I am indebted to my family and friends, and in particular my parents, for their support and encouragement throughout.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY OF TERMS

AD	Additive
ADF	Acid detergent fibre
AFRC	Agricultural and Food Research Council
AHEE	Acid hydrolysis ether extract
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
cm	Centimetre
CI	Concentrate intake
CP	Crude protein
Cr_2O_3	Chromic oxide
CV	Coefficient of variation
d	Day
DE	Digestible energy
DM	Dry matter
DMTP	Digestible microbial true protein
DUP	Digestible rumen undegradable protein
EB	Energy balance
eRDP	Effective rumen degradable protein
FME	Fermentable metabolisable energy
FW	Fresh weight
g	Gram
h	Hour
Ha	Hectare
HF	High fibre
HFRO	Hill Farming Research Organisation
HS	High starch
K	Potassium
kg	Kilogram
l	Litre
LSD	Least significant difference
m	Meter

MCP	Microbial crude protein
ME	Metabolisable energy
Min	Minute
mg	Milligram
MJ	Mega Joule
MP	Metabolisable protein
N	Nitrogen
n	Number
NDF	Neutral detergent fibre
NE	Net energy
NCGD	Neutral cellulose gaminase degradability
NPN	Non-protein nitrogen
OM	Organic matter
P	Phosphorous
PI	Pasture intake
PLI	Profitable Lifetime Index
RDP	Rumen degradable protein
r.s.d.	Residual standard deviation
s.e.d.	Standard error of difference
s.e.m.	Standard error of mean
s.d.	Standard deviation
SR	Substitution rate
t	Tonne
T	Treatment
VFA	Volatile fatty acid
WSC	Water soluble carbohydrate

CHAPTER 1.0 INTRODUCTION

In recent years, the United Kingdom (UK) dairy industry has focused on intensive systems of production, maximising milk output per cow and breeding animals for high yields of milk, fat and protein (Agnew *et al.*, 1998; Coffey, 1992). The rate of genetic improvement for milk production traits in the UK dairy herd has correspondingly increased rapidly since the mid-1980s. UK production evaluations in 1997 for the 10 years between 1985 and 1994, have demonstrated an average rate of genetic progress in milk yield for Holstein Friesian cows of proportionately 0.012 per year, and in the last 5 years of 0.022 per year (Lindberg *et al.*, 1998). Coffey (1992) reports rates of gain of proportionately 0.013 per year in milk fat plus protein yield in the UK and Republic of Ireland. The more recent improvements in genetic merit can be attributed to genetics imported from Europe and North America, advances in progeny testing schemes, and introduction of advanced statistical techniques to evaluate progeny test data from different countries (Agnew *et al.*, 1998).

Pressure on milk price and subsequent profitability of dairy farming in the UK, is now increasing the emphasis on efficiency of production per litre, and in particular on lowering costs of production (Mayne *et al.*, 2000a; Peyraud and Delaby, 2001). The trend for low milk price is likely to continue in the future, particularly as a consequence of Common Agricultural Policy reform, expansion of the European Union, globalisation and the need to compete with world prices.

Grazed grass can contribute to the competitiveness of milk production and has potential to reduce costs of production (Leaver, 1985; Peyraud and Delaby, 2001). In the UK, the relative economic cost on a metabolisable energy (ME) basis of grazed herbage, conserved forage and compound concentrates has been estimated to be in the ratio of 1:2:4.5 (Leaver, 1983). More recently, Keady and Anderson (2000) estimate the relative costs of grazed grass and good quality grass silage to be closer to 1:1.3. Grazed grass however is still generally recognised to provide the cheapest source of nutrients for dairy cows (Mayne, 2001; Peyraud and Delaby, 2001).

Milk production from grazed pasture is dependent upon herbage intake, nutritional value of herbage consumed and the production potential of the cow (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000). Increases in milk yield potential of grazing dairy cows can have major implications for energy requirements (Mayne *et al.*, 2000b), and herbage intake is the major constraint on milk production from grazed pasture, especially in relation to management of higher yielding animals (Peyraud and Gonzalez-Rodrigez, 2000).

Herbage intakes of up to 20.7 kg dry matter (DM) d^{-1} (Buckley and Dillon, 1998) have been reported, and it is suggested that grazed grass theoretically has potential to support 27 to 33 kg milk d^{-1} under ideal spring grazing conditions (Mayne, 2001; Peyraud and Gonzalez-Rodrigez, 2000). These levels of milk production from grazed pasture however are rarely achieved in practice.

Herbage intake depends upon interactions between sward, animal, management and environmental factors (Figure 1.1) (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000; Rook, 2000), which makes prediction of intake and development of a system with a predictable outcome difficult. Progress in development of efficient grazing systems has also been limited by difficulty in making detailed measurements of herbage intake.

Daily herbage intake is a product of grazing time, bite rate and bite mass (Spedding *et al.*, 1966). Bite mass however is the most variable, and therefore the most critical, factor determining intake rate and makes an important contribution to total daily DM intake (McGilloway and Mayne, 1996). Bite mass and hence total daily herbage intake, is highly dependent upon sward characteristics and in particular sward height, density, and leafiness (McGilloway *et al.*, 1999; Orr *et al.*, 2001; Parga *et al.*, 2000).

There is a conflict between maintaining sward conditions that allow high individual levels of herbage intake and production per cow, and efficient herbage utilisation. A high herbage allowance required to achieve maximum intake can reduce efficiency of utilisation of herbage, increase the cost of grazed herbage (Mayne, 2001), and contribute to deterioration in sward quality (Stakelum and Dillon, 1991).

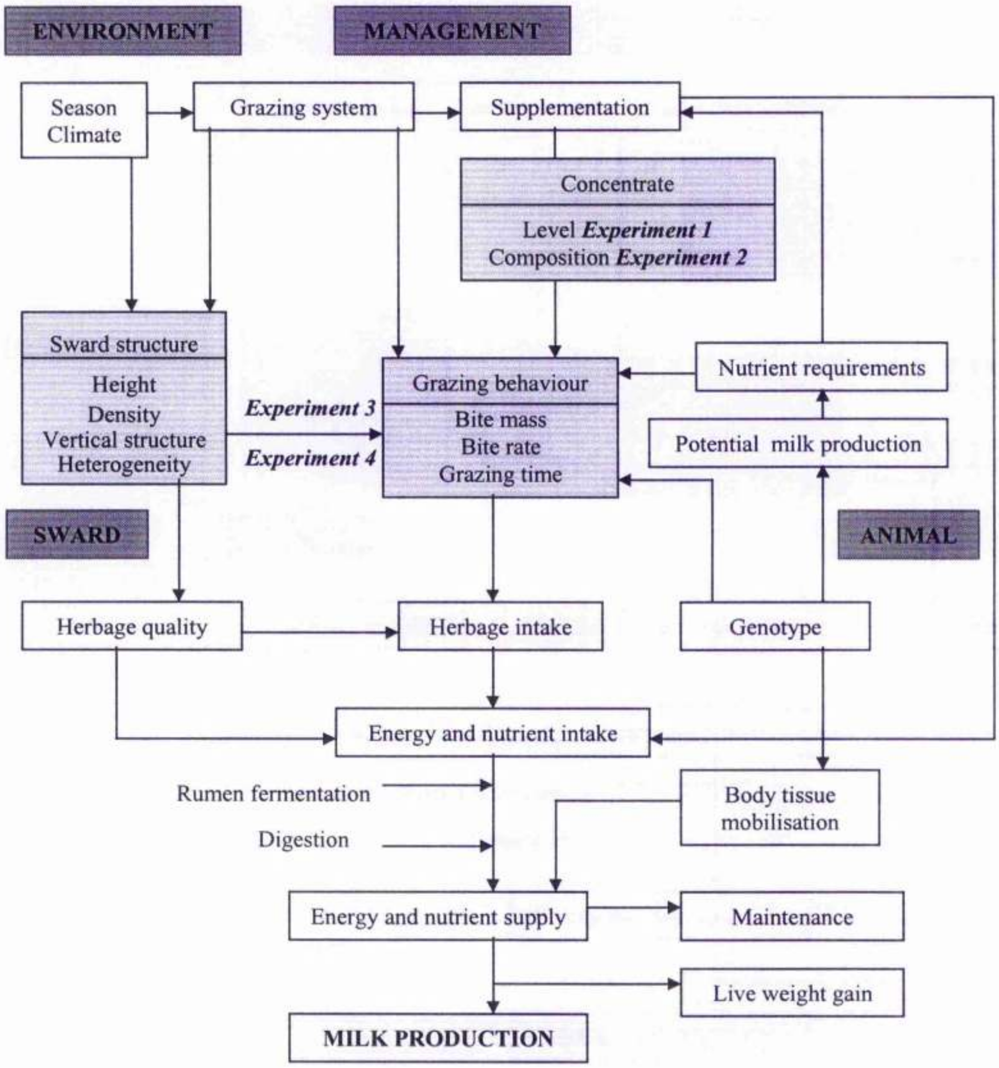


Figure 1.1 Interactions between major factors determining milk production from grazing dairy cows, and areas of investigation by experiments in this study

Supplementation to complement potential intake from pasture allows grazing animals to support higher levels of milk production than are possible from grazed herbage alone (Gibb *et al.*, 2002b; Reis and Combs, 2000). Responses to supplementation however are highly dependent upon their effect on herbage intake and substitution of herbage for supplements (Peyraud and Delaby, 2001). This substitution rate tends to be lower for concentrate supplements compared to forages, especially when herbage availability is high (Mayne *et al.*, 2000b). Supplementation with concentrates to complement grazing conditions can therefore be an appropriate method to achieve the high DM intakes required to manage high yielding dairy cows at pasture.

Responses to supplementation are greater for cows with a higher milk production potential (Dillon *et al.*, 1999). Recent experiments have demonstrated high responses of close to or greater than 1.0 kg milk kg^{-1} concentrate DM from cows yielding between 25 and 30 kg milk d^{-1} (Delaby *et al.*, 2001; Reis and Combs, 2000). There is a strong interaction between supplementation and grazing conditions, and in particular the proportion of an animals energy requirements met from grazed herbage alone (Peyraud and Delaby, 2001). Milk production responses to supplementation and substitution rate can also be affected by the level and composition of concentrate supplementation (Delaby *et al.*, 2001; Gibb *et al.*, 2002ab; Hongerholt and Muller, 1998; Sayers *et al.*, 2000). It is important therefore to be able to predict potential herbage intake from a sward and interactions with supplementation, and to define conditions where supplementary feeds will minimise the reduction in herbage intake.

The necessity to improve efficiency of milk production, and in particular reduce costs of production, presents a major challenge for research and the dairy industry. The aim of this study is to contribute to the development of grazing systems, especially for high genetic potential cows, that maintain full exploitation of the potential of grazed grass and make optimum use of supplementary feeds.

Experimental work was conducted at SAC Crichton Royal Farm and the main areas of study by 4 separate experiments are highlighted in Figure 1.1. Effects of supplementing grazing cows with high levels of concentrate supplements in late summer; and effects of concentrate energy source and an additive formulated to reduce degradability of dietary protein, on herbage intake, grazing behaviour and animal performance are examined. Interactions between sward characteristics, grazing behaviour and herbage intake are investigated. Measurements of sward structure, and in particular the vertical distribution of herbage mass, are utilised to predict potential bite mass from swards for specified bite dimensions. Methods to obtain estimates of bite mass from grazing cows within patches of a sward, and at different stages of herbage depletion are examined and developed. Quantification of interactions between sward characteristics and grazing behaviour, in particular at the individual bite level, should enable development of appropriate grazing and supplementation strategies for high genetic merit cows and so contribute to the future profitability of dairy farming.

CHAPTER 2.0 BACKGROUND INFORMATION

2.1 THE GRAZED SWARD

2.1.1 Herbage species and varieties

Perennial ryegrass (*Lolium perenne*) is the most widely sown grassland species in the United Kingdom (UK) (Hopkins, 2000b). It establishes rapidly from seed and shows strong tillering to produce a dense sward that withstands grazing and responds well to fertile conditions and inputs of nitrogen (N) (Frame, 1991; Hopkins *et al.*, 1990). Advances in plant breeding have more recently developed tetraploid varieties that tend to be slightly higher yielding, with higher sugar levels and higher digestibility than diploids (Camlin, 1997). Perennial ryegrass however does not thrive under very dry conditions or on infertile soils when it becomes stemmy and poorly tillered (Sheldrick, 2000). The second most sown grassland species in the UK is Italian ryegrass (*Lolium multiflorum*) (Hopkins, 2000b). It establishes vigorously in the sward but only has a two-year lifespan. Highest levels of production are achieved in the first year after sowing, and spring growth is earlier than for perennial ryegrass (Sheldrick, 2000). Lowland swards can also include a smaller proportion of other grass species and in particular Cocksfoot (*Dactylis glomerata*) and Timothy (*Phleum pratense*), as well as some sown legumes, principally white clover (*Trifolium repens*) (Hopkins, 2000b).

As the sward ages, its composition becomes dependent upon climatic, environmental and management factors (Hopkins, 2000b). There may be a succession of sown to unsown and less desirable grasses such as meadow grass (*Poa* species), bent (*Agrostis*), Yorkshire fog (*Holcus lanatus*), and meadow fescue (*Festuca pratensis*), together with an increase in the range of dicotyledonous, or broad-leaved species (Sheldrick, 2000).

2.1.2 Herbage growth and morphology

The characteristic of most grass species and some legumes that makes them suitable for grazing is the closeness of their growing points to the soil surface, which ensures that they are rarely damaged by defoliation (Jewiss, 1993).

The vegetative grass plant consists of a collection of shoots or tillers (Figure 2.1). When a grass seed germinates, root and shoot systems develop from the embryo. Tiller growth occurs from the stem apex which consists of a meristematic apical dome (Parsons and Chapman, 2000). Primordia appear on alternate sides below the apical dome and develop into leaves, which grow up around the apex. Each leaf is attached to the shoot apex at a node and stem tissues separating nodes are known as internodes. New leaves grow up within an encircling base of older leaves; and this collection of leaf sheaths forms a pseudo stem. The true stem, which comprises an apical meristem and accumulating nodes and internodes, is concealed at the base of this pseudo-stem (Jewiss, 1993).

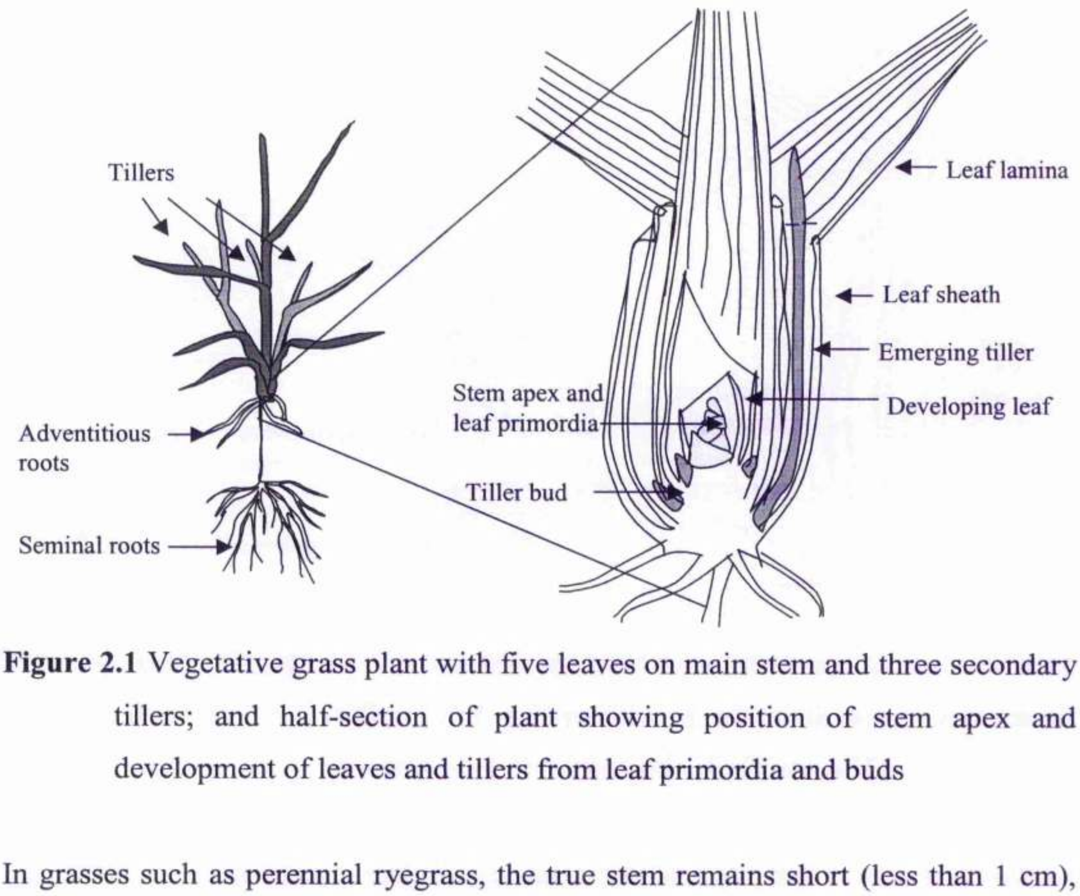


Figure 2.1 Vegetative grass plant with five leaves on main stem and three secondary tillers; and half-section of plant showing position of stem apex and development of leaves and tillers from leaf primordia and buds

In grasses such as perennial ryegrass, the true stem remains short (less than 1 cm), and at ground level, for as long as the shoot remains vegetative (Parsons and Chapman, 2000). Each time the apical meristem produces a new leaf, it also produces an axillary meristem, which is a potential site for a new tiller. When an axillary bud becomes active, its apex develops its own leaves and a secondary tiller is formed. The first tiller normally emerges from the axil of the first formed leaf on the main shoot as soon as this leaf and its successor are fully expanded (Jewiss, 1993).

The development of new tillers from buds depends upon environmental conditions and physiological changes in the plant associated with flowering (Parsons and Chapman, 2000). In a plant growing free from competition, virtually all sites for new tillers are filled (Robson *et al.,* 1988). However, as a plant grows larger and denser, adjacent tillers and plants compete for limiting resources, and many sites remain unfilled (Simon and Lemaire, 1987).

Tillers root from the nodes of the tiller stem (Parsons and Chapman, 2000). These roots are known as adventitious or secondary roots, in comparison to the seminal roots that arise from the embryo of the germinating seed (Figure 2.1).

Flowering can have major effects on many aspects of the physiology, growth and utilisation of grass (Parsons and Chapman, 2000). The first sign of reproductive development is an acceleration of development of leaf primordia and lengthening of the shoot apex. Changes in the stem apex limit its potential to produce further sites for leaf production and therefore for tillering (Parsons and Chapman, 2000). The internodes start to elongate and their leaves are carried above ground, and so this reduces the likelihood that their buds will produce viable tillers. Stem extension and reproductive development in temperate grasses is dependent upon day length and to a lesser extent upon temperature (Cooper, 1951; Ryle and Langer, 1963). In the UK, reproductive development usually begins between March and May, depending upon species and variety (Jewiss, 1993). Varieties of perennial ryegrass are classified according to heading date, which can be defined as ear emergence in at least half of the reproductive tillers in the crop (Parsons and Chapman, 2000). Ear emergence of perennial ryegrass varieties in central England occurs between 7 May and 15 June; and between 17 May and 28 June in Scotland, although after a particularly cold spring it can be delayed by between 5 and 7 days (Sheldrick, 2000).

White clover is a leguminous, perennial plant. Following emergence from its seed, it develops a tap root and a short vertical primary stem with trifoliate leaves (Parsons and Chapman, 2000). Stolons, or branches, arise from axils of the leaves on the primary stem, which grows out horizontally close to the soil surface (Figure 2.2). As in grasses, leaves develop from primordia, which are laid down by a meristematic apex on each stolon. Each leaf is attached to its node by a petiole. The petiole extends rapidly from a meristem just below the leaf, and the final length of this petiole is dependent upon the light environment in the sward (Dennis and Woledge, 1985). Each node has two root primordia, the lower one of which may root if it makes contact with soil. When the primary stem of the tap root eventually dies, the clover plant becomes fragmented and daughter stolons become independent plants.

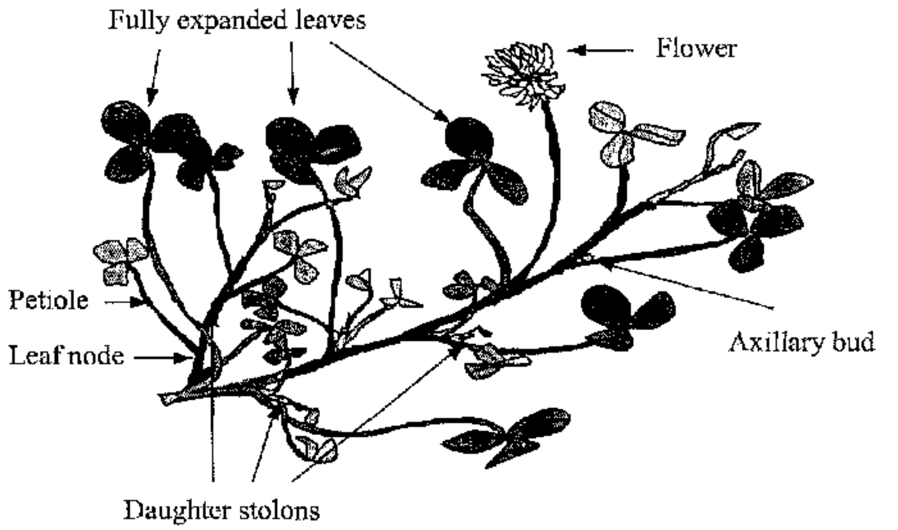


Figure 2.2 Undefoliated parent stolon of white clover plant

White clover requires a critical day length of between 13.5 and 15 hours before some axillary buds on the plant become reproductive (Parsons and Chapman, 2000). Unlike grass species however, the main shoot apex continues to produce leaves and survives after flowering.

2.1.3 Herbage production and yield

Annual herbage yields of over 25 tonnes dry matter hectare^{-1} (t DM ha^{-1}) are theoretically possible from a perennial ryegrass sward in the best grass growing regions, although the high inputs of N required would be both uneconomic and environmentally damaging (Cooper, 1970; Leafe, 1988). In practice, maximum yields from newly sown perennial ryegrass swards receiving around 250 kg fertiliser N ha^{-1} have been shown to vary between 10 and 18 t DM ha^{-1} (Frame, 1991; Hopkins, 2000b; Hopkins *et al.*, 1990). These measurements have been obtained from swards under cutting regimes and in seasons with good grass growing conditions. The higher values are associated with exceptionally good grass growing sites. In mixed grass and legume swards, legumes contribute to crop yield and, through N fixation, they also provide N which can be utilised by other plants (Parsons and Chapman, 2000). Annual levels of production from mixed grass and white clover swards without N fertiliser are similar to yields achieved from grass swards which receive up to 200 kg N ha^{-1} (Davies and Hopkins, 1996).

Herbage growth and production is dependent upon photosynthesis. During the process of photosynthesis, solar radiation is intercepted by green leaves to provide energy required to convert CO_2 and water into simple sugars. Green leaves also respire and CO_2 and water are released when substrates are oxidised to produce energy required for metabolism (Parsons and Chapman, 2000). Plant growth involves cell division, cell expansion, and deposition of materials such as cellulose, which accounts for most of the accumulation of DM in the sward (Lemaire and Chapman, 1996).

The proportion of light energy received that is converted into plant material is described as photosynthetic efficiency (Williams, 1980). Photosynthetic efficiency is affected by leaf area index (LAI) which can be defined as the ratio of leaf area to ground area (Hopkins, 2000b). On temperate grasslands, the sward covers the ground almost completely so that the LAI typically ranges from 2 to 6 (Hopkins, 2000b).

The rate of net herbage accumulation in a sward depends upon the relationship between gross photosynthesis, respiration, gross tissue production, net herbage accumulation and death (Figure 2.3).

When leaf area and shading of leaves in a sward are low, for example after defoliation, photosynthesis per unit area of leaf is high (Lemaire and Chapman, 1996). Not all light energy however is intercepted and gross photosynthesis and tissue production in the canopy is low (Figure 2.3). Leaf area increases with growth and although photosynthesis per unit leaf area declines, overall efficiency of utilisation of light energy is increased and herbage growth rate and net herbage accumulation increases.

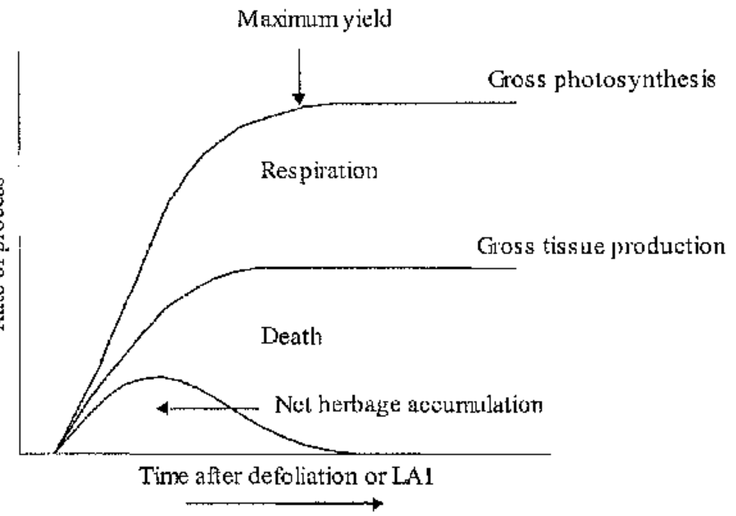


Figure 2.3 Herbage growth, accumulation, respiration and senescence (adapted from Lemaire and Chapman, 1996)

With continued growth green leaves eventually intercept all incident light energy. Herbage growth rate becomes maximal and remains so until respiration of the lower parts of the sward, which receive no light energy, becomes a contributing factor (Williams, 1980). Senescence in the sward increases and a greater proportion of energy is utilised for respiration, so that there is eventually a decline in net herbage accumulation (Lemaire and Chapman, 1996).

2.1.4 Factors affecting herbage growth and production

Plant growth, and especially cell division, cell expansion, and the rate of appearance of new leaves, is affected by temperature, light, water, and nutrient supply (Hopkins, 2000a). Environmental variables therefore affect the growth and characteristics of individual plants, and in particular they determine the rate and extent of leaf appearance, elongation and lifespan (Lemaire and Chapman, 1996). These components then establish the main structural characteristics of the sward which have been described as leaf size, tiller density, and green leaves per tiller (Lemaire and Chapman, 1996) (Figure 2.4). The product of these three sward characteristics determines the LAI, which in turn affects the rate of further herbage growth and production. Sward management and the defoliation regime interacts with herbage growth and sward structure particularly through its effect on LAI. The interaction between individual plant structure, sward characteristics, LAI and management is demonstrated in Figure 2.4.

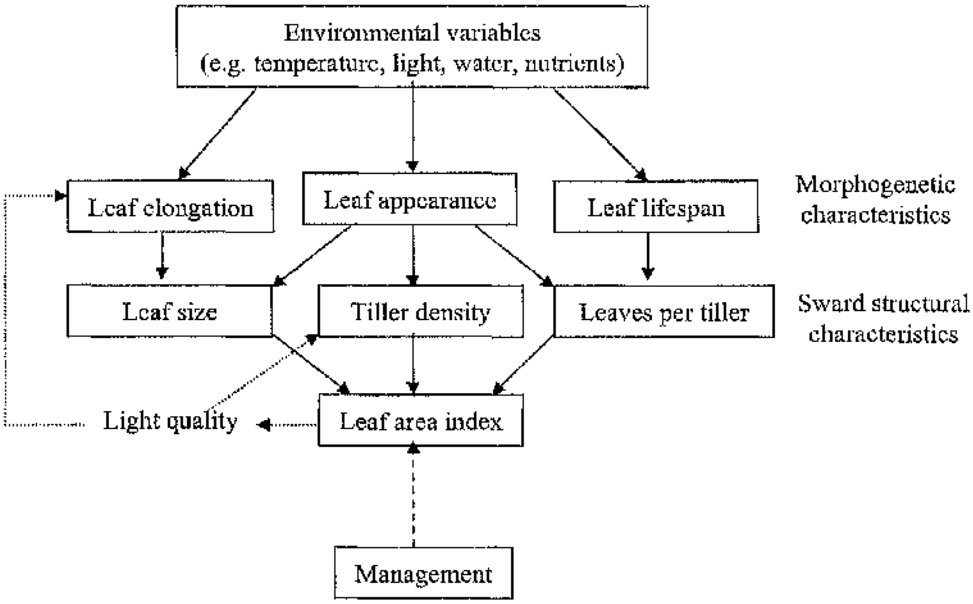


Figure 2.4 Relationship between environmental variables, characteristics of individual plants, sward structure, LAI, and interaction with sward management (Lemaire and Chapman, 1996)

2.1.4.1 Temperature

Temperature affects enzyme-controlled processes such as photosynthesis and respiration; and rates of growth and senescence are affected by temperature pattern, including the diurnal range in temperature (Hopkins, 2000a). The threshold soil temperature for grass growth is between approximately 5 and 6 °C (Cooper and Tainton, 1968; Hopkins, 2000a; Parsons and Chapman, 2000). Temperature is therefore an important factor affecting the length of the growing season in temperate grasslands (Hopkins, 2000a). In the UK, the grass growing season ranges from 200 to 250 days in upland areas and summer drought-prone areas of eastern England; to over 300 days in some lowland, western regions (Lazenby, 1981). Rate of appearance and extension of leaves increases as temperature rises (Parsons and Chapman, 2000; Robson *et al.*, 1988), and the optimum range of temperatures for leaf growth of temperate grasses is within the region of 20 to 25 °C (Cooper and Tainton, 1968; Robson, 1972; Robson *et al.*, 1988). Temperature also affects duration of extension and the final size of leaves (Robson *et al.*, 1988). In general, at higher temperatures leaves extend more rapidly but for a shorter period, although they tend to be longer and thinner with a higher proportion of lamina to sheath (Robson *et al.*, 1988).

2.1.4.2 Soil moisture content

Soil moisture content is a critical factor affecting herbage production and it is dependant upon the amount and distribution of precipitation, as well as temperature and soil conditions (Hopkins, 2000a). When adequate water is available to the plant, stomata remain open during daylight and transpiration of water occurs (Hopkins, 2000a). If a plant comes under water stress, stomata close to prevent further water loss through transpiration, however this also prevents uptake of CO_2 and so the rate of photosynthesis is reduced (Hopkins, 2000a). Water shortage limits leaf extension and severely reduces leaf appearance, and so tiller site production and tiller numbers per unit of ground area are reduced (Parsons and Chapman, 2000). Cell expansion is more sensitive to water stress than cell division and so when water is supplied after a dry period, accumulated cells expand rapidly and this can offset some of the effects of drought (Clark *et al.*, 1999).

2.1.4.3 Light energy

Light energy is essential for photosynthesis and hence for plant growth (Parsons and Chapman, 2000). Absorbed photosynthetically active solar radiation enables transformation of CO_2 into biomass and so determines the level of herbage production (Hopkins, 2000a). Increasing light intensity increases the rate of both appearance of green leaves and of tillering (Parsons and Chapman, 2000). The seasonal pattern of light energy, and in particular day length and light intensity, can therefore account for much of the observed seasonal differences in herbage growth and production (Parsons and Chapman, 2000). Within plant communities, shade from other plants particularly affects the amount of light and light quality received by the leaves. Leaves developed in the shade or under low light intensities have poorer photosynthetic capacity to function at high light intensities, although they also have lower rates of respiration (Woledge, 1971).

2.1.4.4 Soil nutrient status and fertiliser application

The major nutrients affecting herbage growth are N, phosphorous (P) and potassium (K) (Hopkins, 2000a). Nitrogen is required for cell division and is a primary component of enzymes for all living systems and processes (Parsons and Chapman, 2000). Nitrogen directly increases the rate of leaf extension and so increases light capture for photosynthesis and plant growth (Parsons and Chapman, 2000). It has little effect on the rate of new leaf appearance however it does stimulate development of existing axillary tiller buds (Lemaire and Chapman, 1996). Nitrogen will therefore increase the number of tillers in a sward but it also accelerates the reduction in tiller numbers if faster growth is allowed to lead to high LAI (Parsons and Chapman, 2000). In grass-clover swards, grass growth is stimulated by fertiliser N more than clover growth, and so clover can become disadvantaged relative to grass as fertiliser N supply increases (Parsons and Chapman, 2000).

Supply of N to grass and other plants must be in the form of ammonium or nitrate (Hopkins, 2000a). The main sources of N are mineral fertilisers, N fixation by rhizobial bacteria associated with legumes in the sward, and animal manure and excreta. Nitrogen concentration in herbage is typically in the range of 10 to 50 g kg^{-1} DM and large quantities of N can therefore be removed when herbage is harvested (Hopkins, 2000a).

Herbage production can respond markedly to N application, particularly when growth is not limited by other environmental factors or essential nutrients (Hopkins, 2000a). Response of a sward to fertiliser N depends upon its application rate, site conditions, and sward characteristics such as legume content, grass tiller density and root development; as well as season, environmental factors and availability of other essential nutrients (Hopkins, 2000a). In general however, herbage production response follows an initial linear phase of 15 to 30 kg DM kg N^{-1} ha^{-1}, usually up to an application rate within the range 250 to 400 kg N ha^{-1} (Frame, 1991; Hopkins, 2000a; Hopkins *et al.*, 1990). With further increases in application, response diminishes until a maximum is reached. Temperature is an important factor affecting production response and N losses through leaching, and so spring temperature has been used as a basis for recommending fertiliser N application dates (Baker, 1986). In the UK, application is appropriate from mid-February onwards when an accumulated mean air temperature of 180 to 200 °C from 1 January has been reached (T-sum 180-200) and if ground conditions permit (Baker, 1986). Poor responses and loss of N through leaching can also occur when N is applied late in the growing season (Hopkins, 2000a).

2.1.4.5 Sward management and defoliation

Herbage production is affected by frequency and severity of defoliations, which are in turn dependant upon sward management and stocking rate. Grass species, for example, respond to frequent and severe defoliations by reducing the size of individual tillers and increasing tiller density (Johnson and Parsons, 1985; Lemaire and Chapman, 1996). When an established sward is cut or grazed, increased light can penetrate the base of the sward and so limitations to tillering due to shading are removed and new tillers are produced rapidly. Tillering continues until light interception is almost complete. Production of new tillers then ceases and herbage mass increases however, as a result, smaller tillers become shaded and die and the tiller population declines (Lemaire and Chapman, 1996). If defoliation removes virtually all leaf tissue, photosynthesis is significantly reduced and respiration rate can exceed uptake of carbon by photosynthesis (Parsons and Chapman, 2000). Subsequent accumulation of DM depends upon capacity of the crop to re-establish leaf area, and so restore inputs from photosynthesis. For a limited period, growth can be supported from stored nutrients such as sugars, which are often found in sheath bases; or from mobilised structural material and proteins (Parsons and Chapman, 2000).

Parsons *et al.* (1988) used a model to compare the effect of 6 defoliation severities, over a range of defoliation intervals, on aspects of herbage growth and production (Figure 2.5 and Figure 2.6). They summarise how residual sward state affects growth rate. Swards defoliated to a specific level can show a wide range of growth rates depending upon how long they are allowed to regrow. After severe defoliation, there is a considerable delay before maximum LAI and rate of photosynthesis per unit area are regained. Maximum instantaneous growth rate, ceiling DM yield, and leaf death rate also occur later. Average growth rate over the season and hence annual herbage production are therefore reduced. Residual sward state alone therefore provides a poor indication of average growth rate or yield. They show that the yields achieved under continuous and intermittent defoliation are similar for any given average LAI (Figure 2.6). Annual harvested yield per unit area is generally maximised at the same low average LAI in both continuous and rotational grazing systems.

Grazing or cutting management therefore affects the extent of tillering, tiller density and weight, and overall herbage production from a sward. Grass varieties can demonstrate a range of combinations of number and size of tillers and this can account for similar levels of herbage production from contrasting grazing management systems, which generate very different sward structures (Parsons and Chapman, 2000).

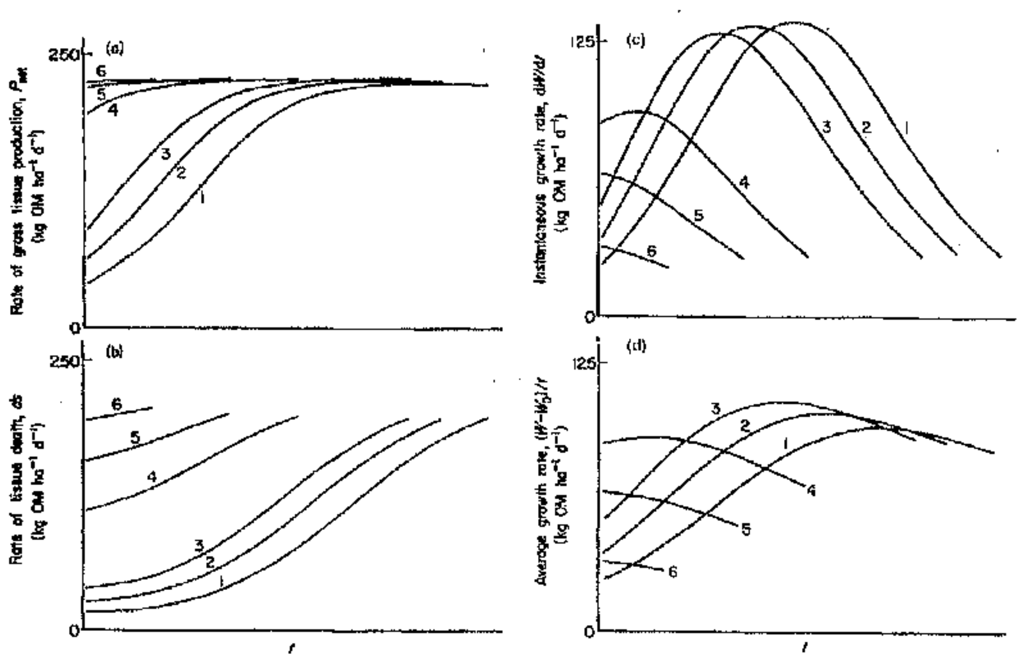


Figure 2.5 Effects of severity of defoliation on (a) rate of gross tissue production (P_{net}); (b) rate of tissue death (ds); (c) instantaneous growth rate (dW/dt); (d) and average growth rate ($(W\text{-}Wo)/t$); as duration of regrowth is extended over time (t). LAI to which swards had been cut and were regrowing were 0.5, 0.8, 1.1, 3.4, 5.3, and 6.8 (numbered 1-6 respectively) (Parsons *et al.*, 1988)

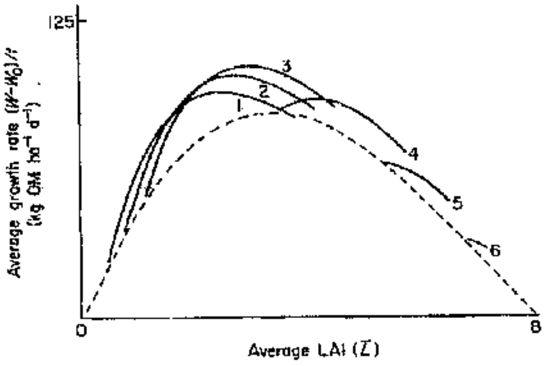


Figure 2.6 Relationship between average growth rate and average LAI according to severity of defoliation, and after every duration of regrowth (t), as described in Figure 2.5. Dashed line is average growth rate in swards maintained same average LAI by continuous grazing (Parsons *et al.*, 1988)

Grazing management can also affect sward structure through its influence on reproductive development of the plants (Lemaire and Chapman, 1996). Removal of the stem apex of a reproductive tiller by cutting or grazing destroys its potential for regrowth from the main axis, and so regrowth must come from new tillers arising from axillary sites on the remaining part of the reproductive tiller. The ability of the sward to regenerate consequently depends upon availability and position of the sites for further tillering, and condition of the buds at those sites (Lemaire and Chapman, 1996). If a perennial grass sward is not harvested after flowering, basal axillary buds do eventually regenerate the sward, however cutting or grazing generally reduces this time period (Parsons and Chapman, 2000).

Intensity of grazing during the spring has considerable effect on the number of new vegetative tillers produced and hence on the total number of tillers and proportion of reproductive tillers in the sward later in the season (Table 2.1) (Johnson and Parsons, 1985).

In swards maintained at a low LAI of between 2 and 3 at sward heights of 3 to 6 cm, only between 14 and 31 percent of tillers showed stem elongation by June (Table 2.1) (Johnson and Parsons, 1985). Reproductive apices were removed from the majority of these tillers so that their growth ceased and the amount of stem tissue in the sward was small. Reproductive stem elongation and ear emergence only became more apparent under more lenient continuous grazing at higher mean sward heights, and on the cut swards. Reduced frequency and severity of defoliation is therefore associated with reduced tiller density, a higher proportion of reproductive tillers and increased stem in the sward.

Table 2.1 Effect of some cutting and grazing managements on the expression of reproductive development in a perennial ryegrass sward in June (Johnson and Parsons, 1985)

Treatment	Number tillers m^{-2}	Percentage reproductive tillers	Weight of elongated stem (g DM m^{-2})	Stem length (cm)	LAI during spring
Cut swards					
Uncut until 7 June	8330	74	548.0	-	-
4-weekly cuts over season	12097	69	388.2	-	-
Continuous grazing					
Sward surface height (cm)					
3	43464	14	44.2	1.3	1.6
6	33765	31	105.5	3.6	2.3
9	20132	47	201.7	7.1	3.8
12	14311	59	333.0	9.2	4.6

2.1.5 Sward structural heterogeneity

In grazed swards, herbage defoliation and plant regrowth contribute to create spatial variability in terms of height, quality and plant morphology (Garcia *et al.*, 2002). Swards grazed by dairy cattle become a mosaic of tall infrequently grazed patches and short frequently grazed patches (McBride *et al.*, 2000). Frequently grazed patches tend to be characterised by vegetative, high quality sward, while lack of defoliation of the infrequently grazed patches allows reproductive growth of tillers by mid-season (Ginane and Petit, 2002). Less frequently grazed patches therefore have high biomass but their quality declines as the season progresses (Ginane and Petit, 2002). Grazing pressure contributes to the proportion of infrequently grazed areas in the sward. High grazing pressure results in reduced selection by grazing animals and hence less rejected areas (Connell and Baker, 2002; McBride *et al.*, 2000). Increasing grazing pressure reduces the height of frequently grazed patches (Connell and Baker, 2002; McBride *et al.*, 2000) and the difference between mean height of frequently and infrequently grazed patches becomes more marked at high than low mean sward heights (Gibb *et al.*, 1997; Gibb and Ridout, 1988).

2.1.6 Seasonal effects on herbage growth and production

Herbage growth rate varies considerably over the course of the year. This can arise as a consequence of a combination of factors, and in particular, seasonal changes in temperature, rainfall, and day length; as well as stage of plant maturity and progress towards reproductive development (Parsons and Chapman, 2000). Sward and grazing management has a substantial effect on herbage production, and so it is not possible to describe a single seasonal pattern of production. Seasonal patterns of herbage growth however have been observed under some standard management regimes, and from systems of overlapping cutting on replicate paddocks (Alberda and Sibma, 1968; Corrall and Fenlon, 1978). In general, these studies have shown measurable growth in the UK begins in March and accelerates rapidly through April to reach a peak daily growth rate at some time in May, depending upon species and variety. Growth rate declines after this peak is reached at approximately the same rate for between 4 and 5 weeks to a rate of around half that of peak production. Growth rate then recovers slightly to reach a second but much lower peak in early August, and declines to non-measurable proportions in November (Alberda and Sibma, 1968; Corrall and Fenlon, 1978).

Herbage production under infrequent cutting however can be biased if plants are allowed to enter reproductive development, resulting in higher measurements of production in spring and early summer, compared to production from a continuously grazed sward (Orr *et al.*, 1988). Removal of the apical meristem of reproductive tillers during harvest of these cut swards in late spring also causes poor regrowth and depression of net production in mid summer (Corrall and Fenlon, 1978). A comparison of the pattern of seasonal herbage production measured by infrequent cutting and by estimation of herbage intake on a continuously grazed sward is demonstrated in Figure 2.7.

The seasonal pattern of production from grazed swards, and especially those under continuous grazing, is therefore more uniform when plants are harvested at earlier stages of maturity (Orr *et al.*, 1988).

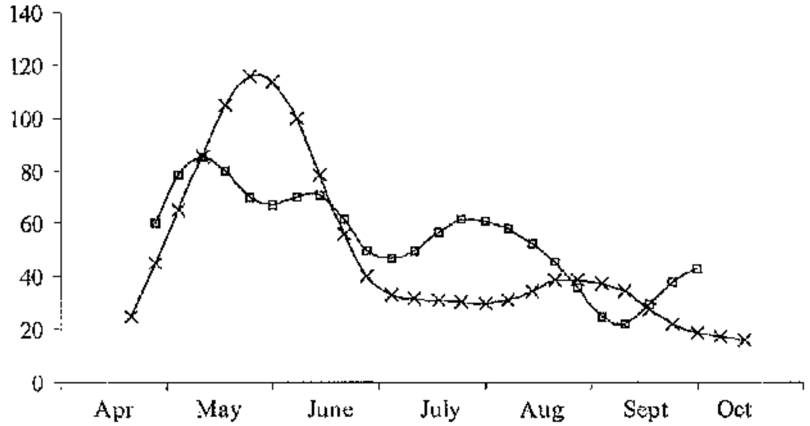


Figure 2.7 Seasonal pattern herbage production under 4-weekly overlapping sequence of cuts (x), and herbage intake by continuously grazed ewes (□) (Orr *et al.*, 1988)

2.1.7 Herbage utilisation under grazing

The efficiency of herbage utilisation in a grazed sward can be defined as the proportion of total herbage produced which is removed by grazing animals before becoming senescent (Lemaire and Chapman, 1996). Efficiency of herbage utilisation is dependent upon sward management and stocking rate, which determines the relationship between herbage growth and defoliation (Figure 2.8).

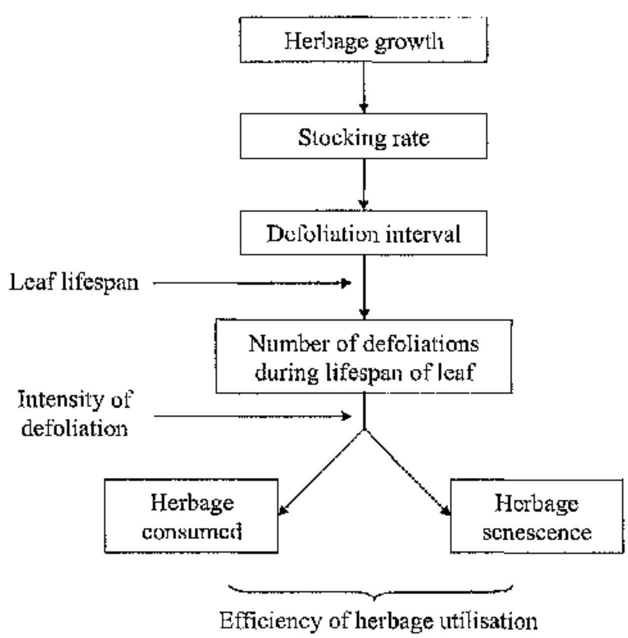


Figure 2.8 Herbage growth and efficiency of herbage utilisation on a continuously grazed sward (adapted from Lemaire and Chapman, 1996)

The effect of grazing intensity, described as the average LAI at which the sward is sustained, on the balance of the major physiological components of growth and utilisation, and potential intake that can be achieved from the sward, is demonstrated in Figure 2.9. This relationship between herbage production and intake highlights a major limitation to production under continuous grazing. High gross photosynthetic uptake and a high production of shoot can not be achieved together with high efficiency of harvest and maximum harvested yield (Parsons *et al.*, 1983a).

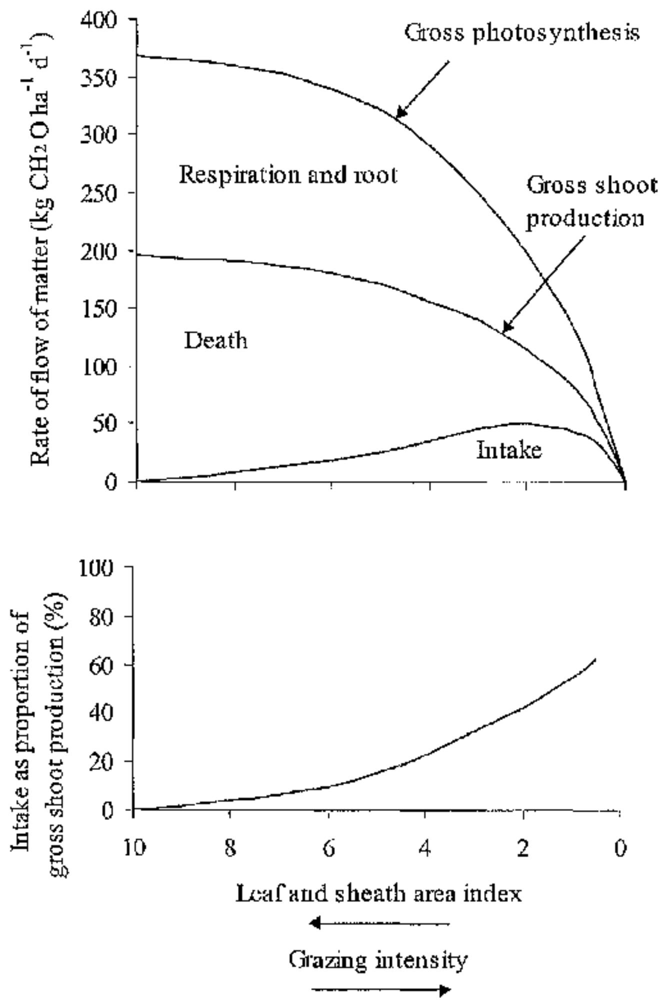


Figure 2.9 Effect of grazing intensity and average LAI at which the sward is sustained; on herbage production, intake and death (adapted from Parsons *et al.*, 1983a)`

When the sward is maintained at a high average LAI, gross photosynthesis is high however losses due to respiration are also close to a maximum and to maintain the sward at a high LAI, only a small proportion of the leaves produced can be harvested (Figure 2.9). To increase efficiency of utilisation, the intensity of defoliation must be increased. When LAI is reduced, a greater proportion of leaf is harvested however less light is intercepted and photosynthesis and shoot growths are reduced. At very high intensities of defoliation, all components of production and utilisation are reduced. Maximum intake per hectare is achieved in a sward maintained at a LAI which is substantially below the optimum for photosynthesis (Parsons *et al.*, 1983a). To achieve maximum yield therefore, a balance must be struck between photosynthesis, gross tissue production, yield or intake, and senescence of plant material.

2.2 THE NUTRITIONAL VALUE OF HERBAGE AND INTAKE FROM PASTURE

Animal production from grazed pasture is highly dependent upon herbage intake and the nutritional value of the herbage ingested (Beever *et al.*, 2000; McGilloway and Mayne, 1996). Nutritional value depends upon nutrient content and nutrient availability, which can be defined as the ability of the animal to absorb and utilise these nutrients (Beever *et al.*, 2000). The nutrient content of herbage is discussed in the following section. Animal factors affecting intake and principals of ruminant digestion are reviewed later, followed by discussion of the interaction between sward and animal factors that affect intake and animal performance at pasture.

2.2.1 Nutrient and energy content of herbage

From a nutritional perspective, herbage can be separated into two major fractions, the cell walls and cell contents. Cell walls include pectic substances, the structural polysaccharides; hemicellulose and cellulose, and lignin. Cell contents consist of the cell nucleus and cytoplasm, and account for the major proportion of herbage proteins, peptides, nucleic acids, lipids, sugars and starches (Beever *et al.*, 2000).

Concentrations of cellulose, hemicellulose and lignin are variable and their concentration has a significant effect on herbage digestibility. There is usually an inverse relationship between neutral detergent fibre (NDF) content and organic matter (OM) digestibility (Delagarde *et al.*, 2000b; Marshall *et al.*, 1998), and between lignin content and OM digestibility (Beever *et al.*, 2000; Delagarde *et al.*, 2000b; Givens *et al.*, 1993). Equations describing these relationships however rarely apply across different forages as forages differ in their structure of cell wall material. The nature and development of linkages between lignin and the polysaccharides are particularly important and have a significant effect on the rate and extent of digestion of the forage (Delagarde *et al.*, 2000b). The sugar fraction (glucose, fructose, sucrose, fructans) of grasses and other forages is also highly labile, and amounts present in the plant are dependent upon environmental conditions, and in particular light and temperature (Beever *et al.*, 2000).

Herbage protein content is largely determined by the distribution of protein between cell contents and cell walls, and between 80 and 90 percent of forage protein is usually present in the cell contents (Tamminga and Sudekum, 2000). True proteins, which are high molecular weight polypeptides, generally account for over 80 percent of herbage crude protein (CP) (Beever *et al.*, 2000). The remainder is present as non-protein nitrogen (NPN) and includes nitrates, amines and amides (peptides, amino acids, amines, and inorganic nitrate). A large proportion of herbage protein is therefore rapidly and extensively degradable in the rumen and Beever *et al.* (1986) suggest less than 30 percent of ingested grass protein reaches the duodenum.

2.2.2 Factors affecting nutrient content

2.2.2.1 Maturity

Much of the variability in the nutrient content of grazed herbage is related to stage of plant maturity (Beever *et al.*, 2000) (Figure 2.10). As herbage matures, the proportion of DM that comprises cell contents declines, while that of cell walls increases (Givens *et al.*, 1989). With increasing maturity, concentrations of cellulose, hemicellulose and lignin therefore increase, and digestibility decreases (Givens *et al.*, 1989; Givens *et al.*, 1993; Marshall *et al.*, 1998). The proportion of protein, lipid and minerals declines with increasing maturity, while the concentration of readily fermentable, non-structural carbohydrates; mainly fructans in the stem, stem base and inflorescence, tends to increase (Beever *et al.*, 2000; Givens *et al.*, 1993). The proportion of CP which is true protein plus amino acids can also decline from around 90 to 70 percent (Beever *et al.*, 2000).

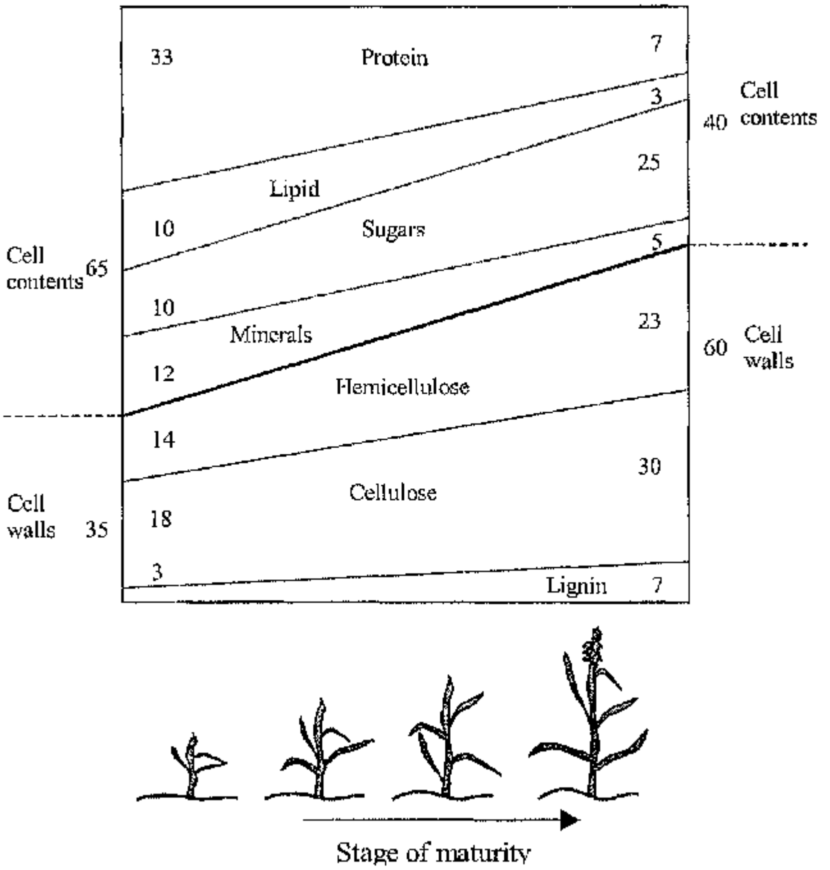


Figure 2.10 Changes in chemical composition of grasses with maturity (Beever *et al.*, 2000)

2.2.2.2 Season

Many of the changes in chemical and physical characteristics of herbage over the season can be attributed to increasing plant maturity (Givens *et al.*, 1989; Marshall *et al.*, 1998). Herbage digestibility and metabolisable energy (ME) content declines after the spring grazing period (Leaver, 1985; Weisbjerg and Soegaard, 2000) and this rate of decline is greater in the spring than autumn (Givens *et al.*, 1993). Periods of high light intensity and temperature increase synthesis of water soluble carbohydrate (WSC) and cell walls, however this often leads to increased cell wall lignification and reduced digestibility (Beever *et al.*, 2000).

Crude protein concentration rises over the season, while there is a tendency for protein degradability to decrease from spring until early August, and then increase until the end of the grazing season in early October (Weisbjerg and Soegaard, 2000). Weisbjerg and Soegaard (2000) found variation in CP degradability was correlated with OM digestibility over the season, and so suggest it may be possible to predict some of variation in CP degradability from OM digestibility. NPN content may be significantly increased during periods of impaired growth. In particular, autumn herbage growth can contain significant amounts of nitrate N and true protein may only account for 50 percent of total CP (Beever *et al.*, 2000). Weisbjerg and Soegaard (2000) found total protein digestibility followed the same trend as that of rumen degradable protein (RDP) and a decline in protein degradability over the season was due to a decrease in the readily degradable fraction and a slight reduction in rate of degradation. Wales *et al.* (1999) similarly found effective rumen degradable protein (eRDP) levels tended to be lowest in summer and higher in autumn than spring, and they observed a positive relationship between CP content and eRDP.

2.2.2.3 Plant structure

The ratio of cell walls to cell contents differs between stems and leaves. Leaf material is generally more digestible with higher crude protein, and lower levels of cell wall constituents (Leaver, 1985). Vascular tissue and sclerenchyma, which are both more abundant in the stem than leaf, are more sensitive to lignification as the plant matures. This makes cell walls of these tissues less accessible to microbes and can reduce accessibility of the cell contents (Tamminga and Sudekum, 2000). Proportions of leaf and stem in the plant are dependant upon its developmental stage and whether it is in its vegetative or reproductive phase of growth (Parsons and Chapman, 2000). Increasing plant maturity and progression of the season is generally associated with an increasing proportion of stem (Beever *et al.*, 2000). Stage of development is affected by herbage species and variety, the environment, and previous sward management (Chilibroste *et al.*, 2000; Givens *et al.*, 1989). Re-growths for example usually have a higher proportion of leaf although this is affected by stage of growth when the plant was harvested and whether the inflorescence primordia were removed (Chilibroste *et al.*, 2000). Decline in digestibility (D-value) is also greater for reproductive growth, at between 3 and 5 units week^{-1}, compared to 1.5 and 2 units week^{-1} for vegetative growth (Beever *et al.*, 2000). Management of grazing can therefore be adjusted to remove stem primordia at early stage to prevent production of stem and inflorescence, and to encourage tillering of the plants

(Johnson and Parsons, 1985). This will therefore lead to a leafier sward of high digestibility.

2.2.2.4 Herbage species and variety

Nutrient content of herbage differs between species and variety (Givens *et al.*, 1989). Within grasses, ryegrass (*Lolium)* varieties have higher digestibility than cocksfoot (*Dactylis glomerata*) or tall fescue (*Festuca arundinacea*) at the same stage of growth (Beever *et al.*, 2000). Legumes are generally more digestible than grasses having a lower cell wall content, higher pectin content, lower ratio hemicelluloses to cellulose and a higher lignin content than grasses at comparable growth stages (Leaver, 1985; Steg *et al.*, 1994). Crude protein content of legumes is generally higher than grasses (Leaver, 1985), and white clover has a much slower rate of decline in D-value compared to grasses, of approximately 0.8 units week^{-1} (Beever *et al.*, 2000). Tamminga and Sudekum (2000) also suggest the rate of protein degradation is higher for legumes compared to grasses however Steg *et al.* (1994) found similar CP degradation rates for intensively fertilised grass and clover although seasonal effects on degradation differed between species.

2.2.2.5 Nitrogen fertiliser

Increasing the level of N fertiliser increases grass CP content (Valk *et al.*, 1996). CP content in grass reaches a maximum soon after fertiliser application as a result of the rapid uptake of N by the plants, and then declines rapidly as growth progresses (Peyraud and Astigarraga, 1998). Nitrogen fertiliser can therefore have a substantial effect on the amount of NPN in herbage and generally increases the rate of herbage protein degradability (Valk *et al.*, 1996). As a result of higher CP content of legumes compared to grasses (Leaver, 1985), an increase in N fertilisation of a mixed sward can have less of an effect on overall sward CP content (Peyraud and Astigarraga, 1998) if the clover population is reduced by N fertiliser application (Parsons and Chapman, 2000). Nitrogen fertiliser can reduce WSC concentration of herbage (Valk *et al.*, 1996; Valk *et al.*, 2000) although effects on the structural carbohydrates are minimal (Peyraud and Astigarraga, 1998).

2.2.2.6 Vertical distribution of nutritional quality in the sward

A sward is composed of an upper leaf canopy of highly digestible material above a lower layer of relatively low digestibility (McGilloway and Mayne, 1996). Variation in chemical composition tended to reflect the proportion of leaf, sheath, stem and dead material in each of the layers (Delagarde *et al.*, 2000b). Grass species show an increase in sheath, stem and senescent material with increasing depth in the sward. Nutritional value therefore tends to decrease with increasing depth of sward.

Delagarde *et al.* (2000c) found large variations in the chemical composition from the top to base of a rotationally grazed perennial ryegrass sward. Mean variations from the upper to lower layer of the sward in 5 cm layers were; + 80 g DM kg^{-1} fresh grass, -100 g CP kg^{-1} OM, -30 g total soluble carbohydrates kg^{-1} OM, +250 g NDF kg^{-1} OM, +22 g acid detergent lignin kg^{-1} OM and -25 units pepsin-cellulase OM digestibility. Variations in chemical composition linked to height in the sward were often found to be greater than variations measured for the whole plant between months, regrowth ages, or time of day in the vegetative stage. Vertical distribution of chemical composition was also generally more affected by ageing than season suggesting the effect of season is largely mediated through the effects of plant maturity.

2.3 THE GRAZING ANIMAL

2.3.1 Ruminant digestion

Ruminants have evolved a system of digestion that involves microbial fermentation of food, mainly in the reticulo-rumen, prior to its exposure to the animals' own digestive enzymes (McDonald *et al.*, 1995). This enables ruminants to utilise β-linked polysaccharides, such as cellulose and hemicellulose, which can not be broken down by normal mammalian digestive enzymes, as their main source of energy from forages.

The reticulo-rumen provides a continuous culture system for anaerobic bacteria, protozoa and fungi (Orskov, 1982). Food entering the rumen is partially fermented and this supplies microbes with energy in the form of adenosine triphosphate (ATP) for their maintenance and growth. The main end products of this anaerobic rumen fermentation of carbohydrates however are volatile fatty acids (VFAs), methane and carbon dioxide (Orskov, 1982). The principal VFAs produced are acetic, butyric and propionic acids and these are utilised by the animal as a source of energy. VFAs are mainly absorbed directly from the rumen, reticulum and omasum, although some may pass through the abomasum and be absorbed from the small intestine (McDonald *et al.*, 1995).

WSCs are comprised of simple carbohydrates and are rapidly digested by rumen microbes (McDonald *et al.*, 1995). Starch is a more structurally complex carbohydrate and under most circumstances is reduced to glucose in the rumen. The form of starch, for example maize or wheat, and the degree of processing, can however have a significant effect on the rate and extent of its degradation (Beever *et al.*, 2000; Knowlton *et al.*, 1998; Orskov, 1982). Fibre is the most complex carbohydrate fraction in forages and comprises cellulose, hemicellulose and lignin. Lignin can be considered as indigestible and while cellulose and hemicellulose are themselves highly digestible, their spatial distribution in the feed relative to lignin can affect the rate and extent of their degradation in the rumen (Beever *et al.*, 2000; Delagarde *et al.*, 2000b; Givens *et al.*, 1993).

The end products of carbohydrate fermentation are determined by the microflora present in the rumen, which is dependent upon the animal's diet (Beever *et al.*, 2000; McDonald *et al.*, 1995). On a high fibre diet for example, bacteria that promote acetate production predominate, while a high starch diet is generally associated with increased propionate levels. Butyrate is produced in smaller quantities but is found in its highest levels on diets containing high proportions of rapidly fermentable carbohydrates (Chilibroste *et al.*, 2000; Knowlton *et al.*, 1998; van Vuuren *et al.*, 1986).

A further function of rumen microbes is the breakdown of dietary protein and associated nitrogenous fractions (Figure 2.11). This provides a supply of N containing intermediaries, some of which are used in microbial protein synthesis (Orskov, 1982). True proteins are likely to form the major part of the protein fraction in most ruminant feeds (Beever *et al.*, 2000). The rate and extent of true protein degradation however is dependent upon its chemical characteristics (Orskov, 1982). In fresh forages, the major protein is ribulose dicarboxylase, which as a fraction 1 protein, is rapidly degraded in the rumen (Beever *et al.*, 2000). Some feeds however, and especially fresh herbage, can contain significant quantities of

NPN, and up to 30 percent of the N in ruminant diets can consist of simple organic compounds, such as amino acids, amides and amines (McDonald *et al.*, 1995). Most of these compounds are rapidly degradable in the rumen and so can provide a N supply for microbial growth, with the most common substrate being ammonia (Beever *et al.*, 2000; Orskov, 1982).

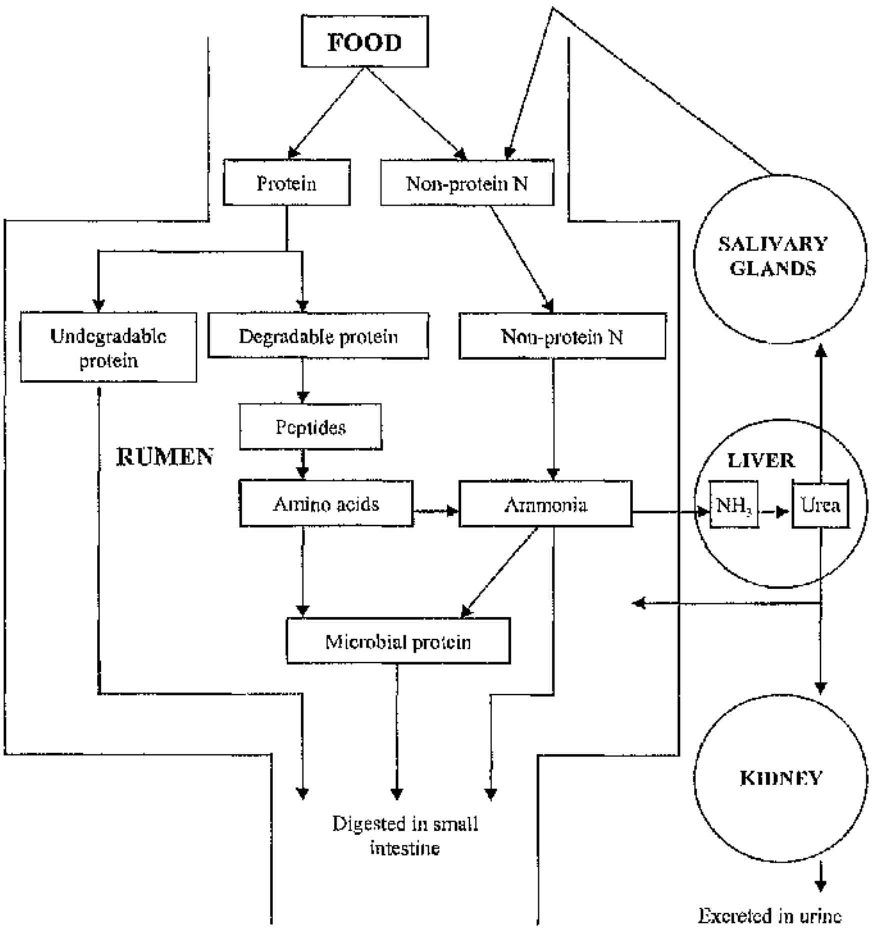


Figure 2.11 Digestion and metabolism of nitrogenous fractions in the rumen (McDonald *et al.*, 1995)

Protein synthesis is an energy consuming process and ATP generated from microbial fermentation of dietary carbohydrate is used in synthesis of amino acids and formation of peptide bonds between adjoining amino acids (Orskov, 1982). The level of microbial protein synthesis, and hence the rate of rumen fermentation and digestion of food, depends upon nutrients available from the diet and synchronisation of their release (Orskov, 1982). Lack of synchrony may occur because the ratio of nutrients, and in particular energy and N, does not match; or because ruminally available carbohydrate and protein are degraded at different rates and the supply of nutrients does not match in time (Tamminga and Sudekum, 2000). If rumen ammonia concentration becomes too low, for example, microbial growth will be slow resulting in a reduction in breakdown of carbohydrates. However, if protein degradation and ammonia supply exceeds microbial protein synthesis, excess ammonia will be absorbed into the blood stream and carried to the liver where it is converted to urea, the majority of which is excreted in urine (Beever *et al.*, 2000).

Contents of the rumen are continuously mixed by contraction of the rumen walls, and during this process of rumination, material is drawn back into the oesophagus and returned by a wave of contraction to the mouth. Any liquid is immediately swallowed again, but coarser material is thoroughly chewed before being returned to the rumen for further microbial attack (Beever *et al.*, 2000). Ruminants can spend up to a third of the day ruminating, although this is affected by the nature of the food being consumed, and tends to be positively associated with herbage fibre content (Phillips and Leaver, 1986).

Following the period in the reticulo-rumen, microbial cells together with undegraded food components pass into the abomasum and small intestine. Here they are digested by enzymes secreted by the animal, and the products of digestion are absorbed. Protein supply for digestion by the animal is therefore particularly dependent upon the yield of microbial protein and extent of degradation of dietary protein in the rumen. A second phase of microbial digestion occurs in the large intestine (Orskov, 1982). VFAs produced are absorbed but microbial cells are excreted in the faeces along with undigested food components (McDonald *et al.*, 1995).

2.3.2 Metabolisable energy value

Feed energy values for ruminants are described in terms of ME which is defined as digestible energy content less losses of energy in methane and urine (AFRC, 1993) (Figure 2.12). A full description of the UK ME system as currently used is given by AFRC (1993).

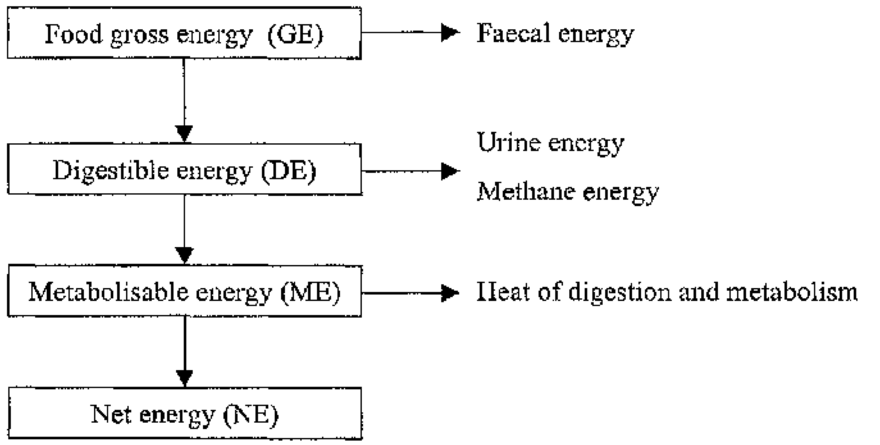


Figure 2.12 Partition of energy during digestion and metabolism according to the ME system (AFRC, 1993; McDonald *et al.*, 1995)

ME values provide useful information regarding total energy yielding nutrients supplied by the feed. Not all ME however can be used for maintenance or production. The efficiency by which ME utilised by the tissues is dependent upon the process for which the energy is used, and can be affected by the nature of the diet (AFRC, 1993). Equations are used to predict efficiency values (NE/ME) from the metabolisability of the diet (q_m = ME/GE), and are provided for maintenance (k_m), growth and fattening (k_f), and lactation (k_l) (AFRC, 1993). An animal's energy requirements can therefore be attributed to specific components, as detailed in Figure 2.13.

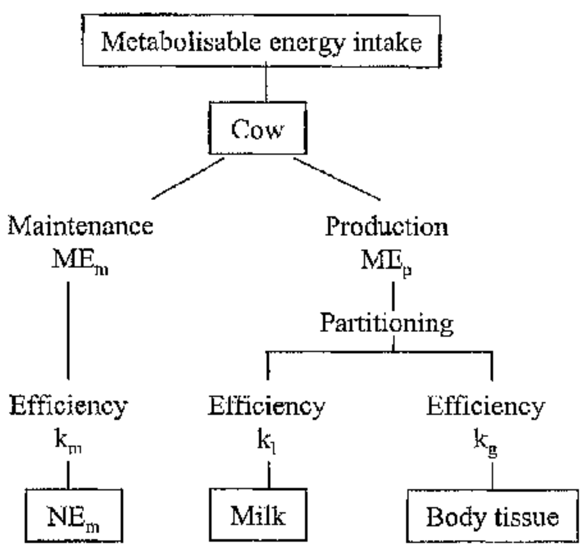


Figure 2.13 Dietary ME utilisation in dairy cows (Agnew *et al.*, 1998)

Evaluation of the ME system has shown that it accurately predicts overall energy balance (Beever *et al.*, 2000). However a limitation to the system is that it does not predict either partition of energy to competing processes in the animal, or the composition of animal products, in particular milk and meat. It is not possible therefore to predict partition of energy between liveweight gain and lactation from a given ME intake.

Efficiency of energy utilisation for maintenance varies with diet composition and is lower for a forage compared to mixed diet (Agnew *et al.*, 1998). Energy use efficiency for growth is more sensitive to diet than efficiency of energy use for maintenance, and it is lower for both a forage and mixed diet compared to pelleted feeds (AFRC, 1993; Beever *et al.*, 2000). Over the course of a lactation, a cow attempts to overcome dietary deficiencies by utilising body reserves. Variability in the efficiency of ME utilisation for lactation however is limited and it appears that k_l is relatively independent of diet (Beever *et al.*, 2000).

The key components that determine ME demand are therefore the maintenance requirement (ME_m), and efficiencies with which the remaining energy is converted to milk energy (k_l) or liveweight gain (k_g). Equations and values to predict efficiency of utilisation of ME and calculate ME requirements for given levels of production are provided by AFRC (1993).

2.3.3 Protein supply

Prediction of protein supply to an animal depends upon knowledge of both the supply of N and energy to rumen microbes for microbial growth, and supply of amino acids to the animal's tissues. The UK metabolisable protein (MP) system (Figure 2.14) provides a set of relationships that allows prediction of protein supply from a detailed characterisation of dietary CP (AFRC, 1993).

The MP system is summarised by Beever *et al.* (2000) and in AFRC (1993). In general, a high proportion of feed CP entering the rumen is potentially degradable and described as rumen degradable protein (RDP). The principal end product of degradation of RDP is ammonia, however some amino acids and peptides are also produced. The actual amount of RDP that is available for microbial protein synthesis is described as effective rumen degradable protein (eRDP). Availability of eRDP in relation to supply of fermentable ME influences the net synthesis of microbial protein (MCP) which passes into the intestine to be digested. Digestible microbial protein (DMTP) is absorbed and usually constitutes the main source of metabolisable protein (MP) to the animal. Dietary CP which escapes ruminal degradation (UDP) can also be digested in the intestine (DUP) and so contribute to the supply of MP.

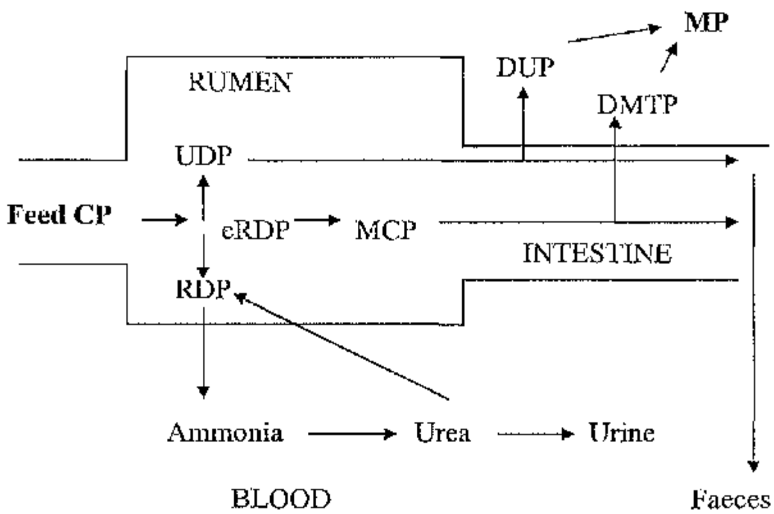


Figure 2.14 UK metabolisable protein system (from Beever *et al.*, 2000)

Microbial protein makes a significant contribution to the amino acid supply to ruminants and so the efficiency of microbial protein synthesis is of great importance. With fresh forages, up to between 30 and 40 percent of dietary N can be lost as rumen ammonia due to the microbial population's poor ability to capture NPN released from degradation of plant proteins (Beever *et al.*, 2000; Lee *et al.*, 2000). This is a consequence of a high proportion of ruminally available N compared to energy supply, and asynchronous release of N and energy for microbial protein synthesis (Tamminga and Sudekum, 2000). Large quantities of ammonia are therefore absorbed from the rumen before this N can be assimilated into microbial protein. Energy supply to the microbes is therefore usually the limiting factor for microbial protein synthesis in the rumen (Tamminga and Sudekum, 2000).

Protein value of a feed is generally expressed as the total amount of protein or amino acids absorbed from the small intestine (Tamminga and Sudekum, 2000). Protein value is dependent upon degradability of protein in the rumen, the extent to which N containing compounds from rumen degradation are captured and incorporated into microbial protein, and the extent to which rumen undegraded protein is digested and absorbed by the small intestine. Incorporation of N containing compounds into microbial protein is in turn highly dependent upon availability of an energy supply for microbial growth. Therefore to optimise the value of a feed protein, N losses need to be minimised and the amount of animal protein form a given amount of plant protein maximised (Tamminga and Sudekum, 2000).

2.3.4 Voluntary food intake

Voluntary food intake is a major factor influencing animal performance (Allen, 2000; Illius and Jessop, 1996; Yearsley *et al.*, 2001). It is determined by animal and dietary factors affecting hunger and satiety (Allen, 2000), and regulated by physical and metabolic control mechanisms (Allen, 1996; Illius and Jessop, 1996). Voluntary DM intake is thought to be controlled by the integration of multiple stimulatory and inhibitory inputs to the brain (Forbes, 1996).

Physical control of intake involves capacity of the digestive tract and rate of passage of digesta (Allen, 1996; Allen, 2000). A good relationship between DM in the rumen and body weight ($r^2 = 0.98$) has been observed for different ruminant species ranging from 3.7 to 720 kg body weight (Illius and Gordon, 1991). Whilst there may also be a relationship between maximum volume or weight of reticulo-rumen contents and live weight within a species or breed, this is expected to be lower since the range in live weight is much less than between species (Allen, 1996). An animal's physiological state also affects its capacity for fill in the reticulo-rumen. Maximum volume of the reticulo-rumen declines for example, as pregnancy progresses (Allen, 1996). Weight of reticulo-rumen contents increases during early lactation however there is some uncertainty as to whether this is an effect of increased capacity of the reticulo-rumen (Allen, 1996).

Voluntary DM intake can be limited for ruminants consuming forages by restricted flow of digesta through the gastrointestinal tract (Allen, 1996). Restricted flow can result in distension of one or more segments of the gastrointestinal tract, resulting in reduced intake. The reticulo-rumen is generally regarded as the site at which distension most often regulates DM intake (Allen, 1996). Distension stimulates stretch receptors in the muscle layer of the wall of the reticulo-rumen and this information is relayed to the central nervous system where it is integrated with other stimuli to signal the end of a meal (Allen, 2000). The extent to which distension regulates DM intake of lactating cows has been shown to be negatively associated with the animal's energy requirement and the filling effect of the diet offered (Allen, 1996). Effects of added fill on DM intake could therefore be lower when cows have greater energy requirements and are in poorer energy balance.

Low herbage DM content is known to adversely affect herbage intake and it is suggested that this could be due to a bulk effect on rumen fill (Leaver, 1985; Peyraud and Gonzalez-Rodrigez, 2000). Water content of herbage includes both internal and external moisture. It can vary from approximately 85 percent in early spring to around 75 percent in mid summer, and is predominantly intracellular (McGilloway and Mayne, 1996). High rainfall and the corresponding high surface water, however can also restrict intake (Burtis and Phillips, 1987). Studies with housed cows have shown that herbage intake is reduced by 1 kg DM per 40 g kg^{-1} fall in DM content below a critical level of 180 g kg^{-1} (Verite and Journet, 1970 as cited in Peyraud and Gonzalez-Rodrigez, 2000).

Voluntary DM intake increases with increasing digestibility of the diet (Allen, 1996). NDF has been found to be the best single chemical predictor of voluntary intake because it generally ferments and passes through the reticulo-rumen more slowly than other feeds and so has a greater filling effect over time (Waldo, 1986). Other factors however also affect fill and these include particle size, chewing frequency and effectiveness, particle fragility, indigestible NDF fraction, rate of fermentation of the potentially digestible NDF, and characteristics of reticular contractions (Allen, 1996). Decreasing particle size of forages by grinding and pelleting for example, generally increases voluntary DM intake as a result of reduction of initial volume and retention time in the reticulo-rumen (Minson, 1963; Moore, 1964). Low ruminal pH from highly fermentable feeds, such as high grain diets, can reduce the rate of fibre digestion and increase the filling effect of the diet, which could increase distension of the reticulo-rumen (Allen, 2000). Fat can also inhibit fibre digestion in the reticulo-rumen and so also have a negative effect on intake (Palmquist and Jenkins, 1980).

Dietary CP content is often positively related to DM intake of lactating cows and this is partly related to increased RDP effects on fermentation and digestibility of feeds (Orskov, 1982). Asynchrony of N and energy supply to rumen microbes limits microbial growth and activity and so can lead to a reduction in the rate of forage digestion (Leng and Nolan, 1984).

Low quality, low digestibility forages are therefore thought to place constraints on intake due to their slow rate of passage through the gastrointestinal tract. As digestibility increases, greater quantities of the food can be eaten before these physical constraints apply. With increasing digestibility, voluntary intake is therefore more likely to be determined by metabolic constraints related to the animal's ability to utilise absorbed nutrients (Illius and Jessop, 1996; Yearsley *et al.*, 2001). There is substantial evidence that absorbed propionate affects satiety, and infusions of propionate into the reticulo-rumen have been demonstrated to reduce DM intake to a greater extent than acetate infusions (Allen, 2000). Nutrient imbalances can also constrain intake due to the build up of excess metabolites, such as blood acetate (Illius and Jessop, 1996). Metabolic constraints on intake have therefore been related to an animals physiological state and productive capacity, it's allocation of nutrients to maintenance and production, and its corresponding optimal diet and tolerance to deviations from this nutrient ratio supplied by the diet (Illius and Jessop, 1996).

2.3.5 Genetic potential for milk production

Factors contributing to greater levels of milk production from cows of higher genetic merit for production include increased nutrient intake, a change in nutrient partitioning towards milk output at the expense of body tissue gain, and increased body tissue mobilisation (Agnew *et al.*, 1998; Buckley *et al.*, 2000b; Veerkamp *et al.*, 1994).

With increasing cow genetic merit, studies demonstrate consistent increases in overall efficiency of conversion of ME from feed to milk energy (Ferris *et al.*, 1999a;

Ferris *et al.*, 1999b; Gordon *et al.*, 1995). These studies however have shown that genetic merit has no effect on digestibility or metabolisability of energy, or on the efficiency with which ME potentially available for milk production was converted to milk energy output (k_l). Therefore while genetic merit improves overall efficiency of use of ME for milk production, it does not alter the individual components of energy digestion and utilisation. Cows of higher genetic merit can therefore be seen as more efficient converters of food into milk, and experiments have shown animals of higher merit can produce significantly more milk and fat plus protein without significantly higher energy intakes. Grazing studies in New Zealand for example, have reported that high merit cows can produce 20 to 40 percent more milk, while consuming only 5 to 20 percent more herbage (Holmes, 1988).

An interaction between stage of lactation and genetic merit for production is also evident. Higher genetic merit cows have increased liveweight loss during early lactation, lower liveweight gain over the lactation as a whole, and greater liveweight gain during the dry period (Buckley *et al.*, 2000a; Dillon *et al.*, 1999). Condition score is generally lower at all stages of lactation for higher genetic merit cows (Buckley and Dillon, 1998; Buckley *et al.*, 2000a; Buckley *et al.*, 2000b; Dillon *et al.*, 1999).

Nutrient partitioning towards milk production and the subsequent efficiency of conversion of ME into milk production is under hormonal control (Agnew *et al.*, 1998). Insulin stimulates incorporation of glucose, amino acids, and fatty acids into body tissue while other hormones, and in particular growth hormone, glucagon and glucocorticoids, inhibit tissue deposition. Plasma insulin levels have been reported to be higher for lower yielding cows that are in energy surplus, and gaining live weight (Agnew *et al.*, 1998). When high yielding cows are in energy deficit, insulin secretion is suppressed and so the partition of metabolites to body tissue is reduced and rates of gluconeogenesis, lipolysis and proteolysis increase. Growth hormone also appears to play an important role in partitioning nutrients away from tissue deposition towards milk production in higher genetic merit cows (Agnew *et al.*, 1998). Sorensen *et al.* (1998) suggest increased body tissue mobilisation in higher genetic merit cows is related to higher levels of growth hormone, and the lower energy status is then reflected in reduced insulin levels. If cows are unable to achieve energy intakes to support their potential levels of production, high genetic merit cows genetically predisposed to increased levels of body tissue mobilisation can lose excessive live weight (Veerkamp *et al.*, 1994). This can lead to health and fertility problems (Pryce *et al.*, 1997; Rauw *et al.*, 1998). A reduction in reproductive performance of higher genetic merit cows for example, has been associated with greater liveweight loss; a larger energy gap, especially in early lactation; and lower condition score (Pryce *et al.*, 2001; Pryce *et al.*, 2002).

2.4 PRINCIPALS OF HERBAGE INTAKE

Herbage intake is a critical factor affecting animal performance at pasture. Low herbage intake has been identified as a major factor limiting milk production from pasture, especially in relation to the management of higher yielding cows (McGilloway and Mayne, 1996). Even when grazing management and forage quality is optimal, high genetic merit cows are unable to realistically consume sufficient quantities of herbage to meet their nutrient requirements for levels of production greater than between approximately 27 and 33 kg milk d^{-1} (Mayne, 2001; Peyraud and Gonzalez-Rodrigez, 2000). Understanding factors controlling herbage intake is therefore critical in determining and improving milk production from grazed grass, and in developing a complementary supplementation strategy.

The normal pattern of a cow's grazing behaviour consists of periods of grazing, ruminating and resting (Leaver, 1985). Intake over a defined period of time depends upon bite mass and mean rate of biting. Herbage intake (HI) is then equal to the product of bite mass (BM), bite rate (BR) and time spent grazing (GT) (Allden and Whittaker, 1970) (Equation 2.1):

$$HI = BM * BR * GT. \qquad (2.1)$$

Bite mass is a product of bite volume and bulk density of the grazed horizon (Parsons *et al.*, 1994; Rook, 2000; Ungar *et al.*, 2001). Bite volume can be described most simply as a product of bite area and bite depth (Parsons *et al.*, 1994). Bite area is defined as the mean surface area of sward from which herbage is severed when an animal takes a bite, and bite depth equals the difference between sward height before grazing and the average residual height of grazed tillers (Laca *et al.*, 1992b).

Changes in bite mass as a result of animal or sward treatments must occur therefore as a consequence of changes in bite dimensions which affect bite volume, or changes in bulk density within that bite volume. Bite mass is sensitive to changes in sward structure (Peyraud and Gonzalez-Rodrigez, 2000); and also constraints of the animals anatomy, in particular mouth and body size (Rook, 2000). An understanding of the relationship between the sward, animal characteristics, and bite dimensions is therefore essential to predict bite mass and determine potential herbage intake from a sward.

Grazing time and bite rate can be important compensatory mechanisms to counter the effects of variation in bite mass. Phillips and Leaver (1986) for example, measured an increase in grazing time and bite rate to compensate for reduced bite mass as the season progressed (Figure 2.15).

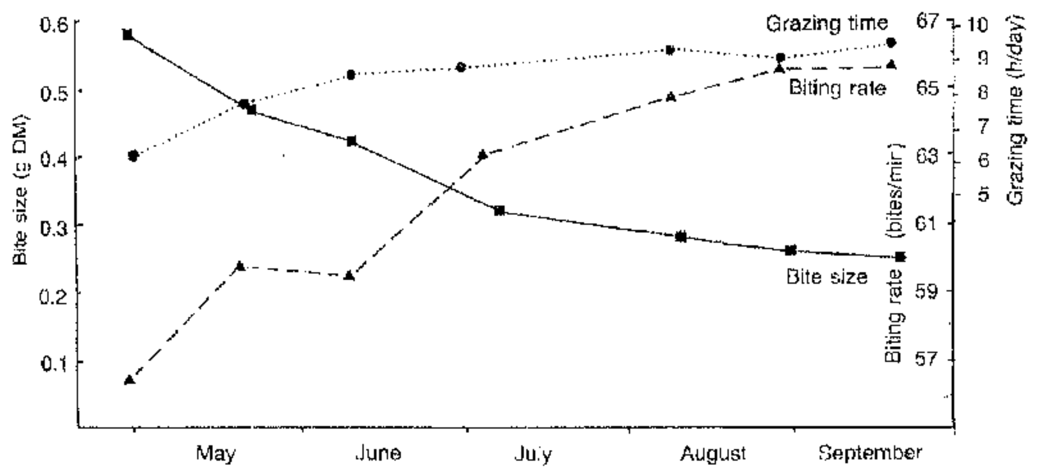


Figure 2.15 Seasonal variation in bite mass, bite rate and grazing time (Phillips and Leaver, 1986)

Animals however may not be able to compensate fully for low intake rate due to constraints on grazing time, and individual lactating cows have been shown to graze for a maximum of around 12 hours d^{-1} (Phillips and Leaver, 1986; Rook *et al.*, 1994). The need to undertake other activities, such as ruminating, places an upper limit on grazing time, as does the amount of available daylight. Grazing time therefore generally tends to reach a plateau at between 9 and 10 hours d^{-1} (Phillips and Leaver, 1986; Rook *et al.*, 1994).

Bite rate is affected by the time required to search for and process each bite (Rook, 2000). Processing time includes time required to sever, chew, and swallow the food, while searching time includes time spent in selection and movement (Laca *et al.*, 1992b). Animals can search for their next bite as they process a bite they have already taken. In dense, homogenous, temperate grass swards where the next bite is readily available, processing time is therefore likely to be limiting since the time to process a bite is usually longer than that required to find the next bite (Rook, 2000). Time taken to sever a bite is relatively constant as it is determined by the time taken to open and close the jaw (Rook, 2000). Chewing time however increases linearly with bite mass (Parsons *et al.*, 1994), and an inverse relationship between bite rate and bite mass is observed (Phillips and Leaver, 1986). Small bites are handled less efficiently since total handling time per unit mass scales exponentially as bite mass declines (Parsons *et al.*, 1994). Bite rate is therefore generally constrained by bite mass. While animals can increase bite rate to compensate for lower bite mass, this is often insufficient to maintain intake rate due to the increase in processing time per unit of bite mass (Rook, 2000). Bite rate can also vary independently from bite mass, and for example, bite rate increases if animals have been fasted prior to grazing (Patterson *et al.*, 1998).

Results from some recent grazing experiments (Table 2.2), demonstrate a range in bite mass from 0.23 to 1.28 g DM; bite rate from 33 to 68 bites minute^{-1}; and grazing time of 358 to 632 minutes day^{-1}.

Table 2.2 Range of treatment means for bite mass, bite rate and grazing time

	Bite mass (g DM bite^{-1}) (*g OM)	Bite rate (Bites min^{-1})	Grazing time (min d^{-1})
Gibb *et al.* (2002b)	0.23-0.34*	51.9-64.2	554-629
Barrett *et al.* (2001)	0.55-0.86	32.9-46.2	-
Christie *et al.* (2000)	0.57-0.73	45-50	429-503
Gibb *et al.* (2000)	0.41-0.51	42.7-60.8	458-568
Parga *et al.* (2000)	0.51-0.59	52-54	454-532
Sayers *et al.* (2000)	0.58-0.61	45-47	358-480
McGilloway *et al.* (1999)	0.47-1.28	51.6-68	-
Gibb *et al.* (1997a)	0.33-0.48	47.5-59.4	632
Gibb *et al.* (1997b)	0.23-0.33	63.9-67.1	581-628
Mayne *et al.* (1997)	0.4-1.1	-	-

Factors responsible for variability in bite mass, bite rate and grazing time, which will ultimately determine herbage intake and animal performance; can be classified into animal, sward, management and environmental factors, many of which are interrelated and will be discussed in the following sections.

2.5 SWARD FACTORS AFFECTING HERBAGE INTAKE AND ANIMAL PERFORMANCE

2.5.1 Herbage allowance

Herbage allowance is an important factor influencing herbage intake, and consequently animal performance, from grazed pasture (Table 2.3, Figure 2.16).

Table 2.3 Herbage intake and milk yield responses to herbage allowance

	Herbage allowance[†] (kg DM cow^{-1} d^{-1}) ([*]kg OM)	Herbage intake (kg DM d^{-1}) ([*]kg OM)	kg change herbage intake kg increase herbage allowance^{-1}	Milk yield (kg d^{-1})	Milk yield response (kg milk kg increase herbage allowance^{-1})
Delaby *et al.* (2001)					
Experiment 1	12.1[§]	11.3		24.4	
	15.8[§]	13.0	0.46	25.6	0.33
Experiments 2 and 3	16.6[§]	12.6		24.7	
	19.6[§]	13.9	0.17	25.3	0.18
Virkajarvi *et al.* (2002)	19[‡]	15.0		21.9	
	23[‡]	16.5	0.38	22.3	0.10
	27[‡]	16.8	0.08	23.2	0.23
Delagarde *et al.* (2000c)	12[§]	10.7		10.1	
	18[§]	11.8	0.18	11.5	0.23
	24[§]	13.8	0.33	12.6	0.18
Delagarde *et al.* (2000a)	18[§]	11.4		24.7	
	22[§]	12.1	0.17	25.6	0.22
Wales *et al.* (1999)					
Experiment 1	20	7.1		21.8	
	70	16.2	0.18	27.1	0.11
Experiment 2	20	9.9		24.7	
	70	19.3	0.19	32.0	0.15
Peyraud *et al.* (1996)					
Experiment 1	19[*]	13.5[*]		20.6	
	26[*]	14.9[*]	0.20	22.0	0.20
Experiment 2	19[*]	13.8[*]		20.4	
	29[*]	16.2[*]	0.24	21.7	0.13
	46[*]	16.7[*]	0.03	23	0.08
Stakelum (1986a)	14.3[*]	12.4[*]		8.2	
	21.4[*]	16.0[*]	0.50	9.5	0.18

(Continued over)

Table 2.3 Herbage intake and milk yield responses to herbage allowance (continued)

	Herbage allowance† (kg DM cow^{-1} d^{-1}) (*kg OM)	Herbage intake (kg DM d^{-1}) (*kg OM)	kg change herbage intake kg increase herbage allowance^{-1}	Milk yield (kg d^{-1})	Milk yield response (kg milk kg increase herbage allowance^{-1})
Stakelum (1986b)	13.3* (L)	11.6*		17.8 $^{\Omega}$	
	13.9* (H)	14.7*			
	20.0* (L)	12.6*	0.45	18.2 $^{\Omega}$	0.06
	21.0* (H)	16.2*	0.44		
Stakelum (1986c)	16 (L)	11.6*		13.0 $^{\Omega}$	
	16 (H)	12.5*			
	24 (L)	13.6*	0.15	13.3 $^{\Omega}$	0.04
	24 (H)	16.6*	0.45		
Combellas and Hodgson (1979)	14.4	11.0*		15.5	
	29.0	12.8*	0.12	17.0	0.10
	42.9	12.8*	0	17.1	0.01
Le Du *et al.* (1979)					
Experiment 1	12.2	10.7*		12.5	
	25.7	13.3*	0.19	15.3	0.21
	36.2	14.1*	0.08	16.0	0.07
Experiment 2	15.6	11.5*		11.8	
	24.5	12.1*	0.07	14.3	0.28
	36	12.5*	0.03	15.2	0.08
Greenhalgh *et al.* (1966)	11.3	10.8*		14.8	
	15.9	11.9*	0.24	14.7	-0.02
	20.4	12.6*	0.16	15.8	0.24
	24.9	12.6*	0	15.5	-0.07

† Herbage mass measured above ground level unless stated otherwise; ‡ Herbage mass above 3 cm; § Herbage mass above 5 cm; (L) low herbage mass, (H) high herbage mass within studies; $^{\Omega}$ mean milk yield for both levels herbage mass.

Results from the studies presented in Table 2.3 indicate a response in herbage intake of up to 0.5 kg OM kg^{-1} increase in herbage allowance cow^{-1} d^{-1} (Stakelum, 1986a), and in milk yield of up to 0.28 kg milk kg^{-1} herbage allowance (Le Du *et al.*, 1979). Direct comparisons between studies however are difficult, particularly due to differences in methodologies to measure and describe herbage allowance, animal factors such as milk yield level, and the grazing system employed. Reporting of results as either OM or DM values must also be noted.

Mayne and Laidlaw (1999), as cited by Mayne (2001) summarised a number of grazing studies and concluded the marginal response in herbage intake to additional herbage allowance, could be defined as:

$$MI = 0.405 - 0.0089\ HA \qquad \text{(s.e. 0.00208, } P < 0.001) \qquad (2.2)$$

where *MI* represents marginal increase in herbage intake (kg) kg^{-1} additional herbage allowance, and *HA* represents herbage allowance (kg DM cow^{-1} d^{-1}) assessed above ground level (Equation 2.2). This relationship indicates no further increase in intake when herbage allowance exceeds 45.5 kg DM cow^{-1} d^{-1}. Also, even when herbage allowance is relatively low at 20 kg DM cow^{-1} d^{-1}, only 0.227 kg DM d^{-1}, or 22.7 percent, extra herbage will be consumed when cows are offered an additional 1 kg DM d^{-1}.

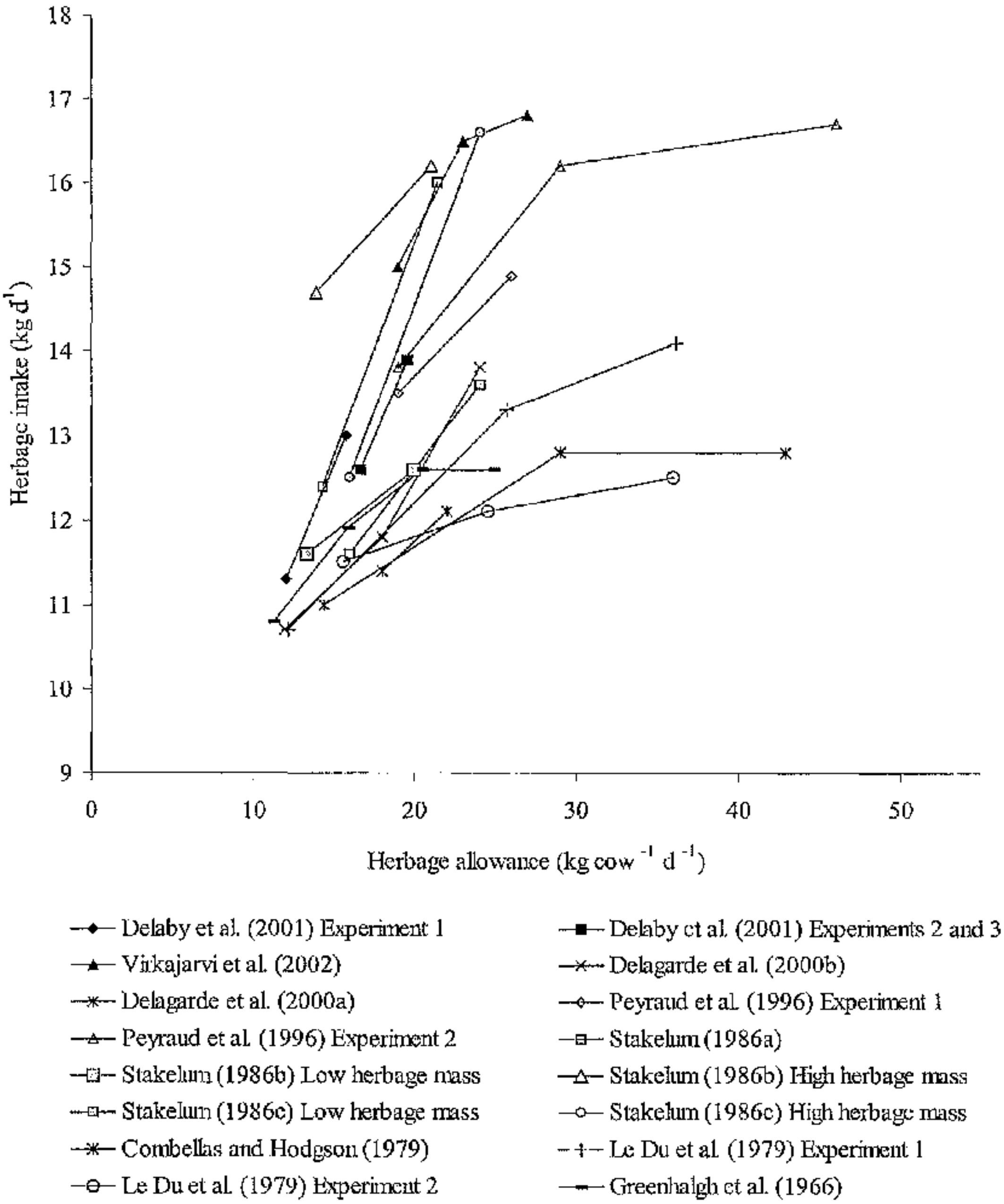


Figure 2.16 Effect of herbage allowance on herbage intake

Results from individual experiments demonstrate a curvilinear response in herbage intake to increasing levels of herbage allowance (Figure 2.16) (Combellas and Hodgson, 1979; Le Du *et al.*, 1979; Peyraud *et al.*, 1996; Virkajarvi *et al.*, 2002). Another recent study similarly reports an increase in herbage intake of 0.25 kg OM kg^{-1} increase in herbage allowance from 11 to 16 kg OM d^{-1}, and a much smaller increase of 0.05 kg OM d^{-1} above 20 kg OM herbage cow^{-1} d^{-1} (Peyraud and Gonzalez-Rodrigez, 2000). From their data set of 187 lactations, Delaby *et al.* (1999) show an average increase in milk yield of 0.25 kg d^{-1} per kg DM increase in herbage allowance over the same range of herbage allowance.

Analysis of results presented in Table 2.3 as a single data set also indicates a curvilinear relationship between the two variables (Figure 2.17).

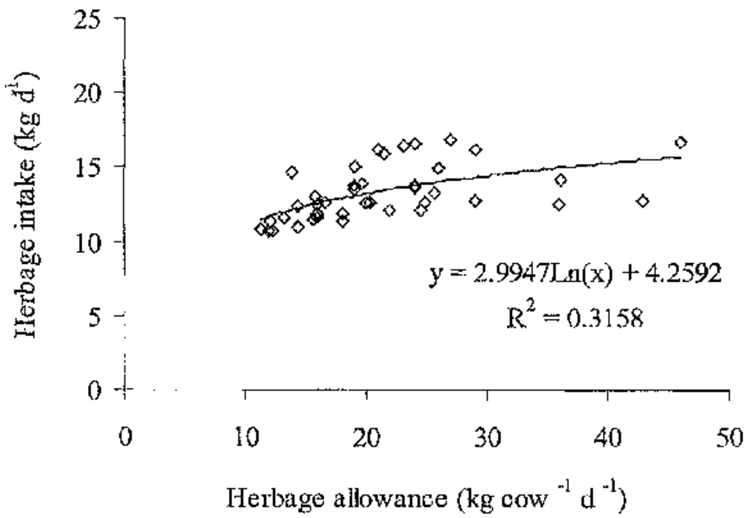


Figure 2.17 Relationship between herbage allowance and herbage intake from results of experiments presented in Table 2.3

Marginal increases in herbage intake become less as the actual level of herbage allowance increases (Figure 2.18).

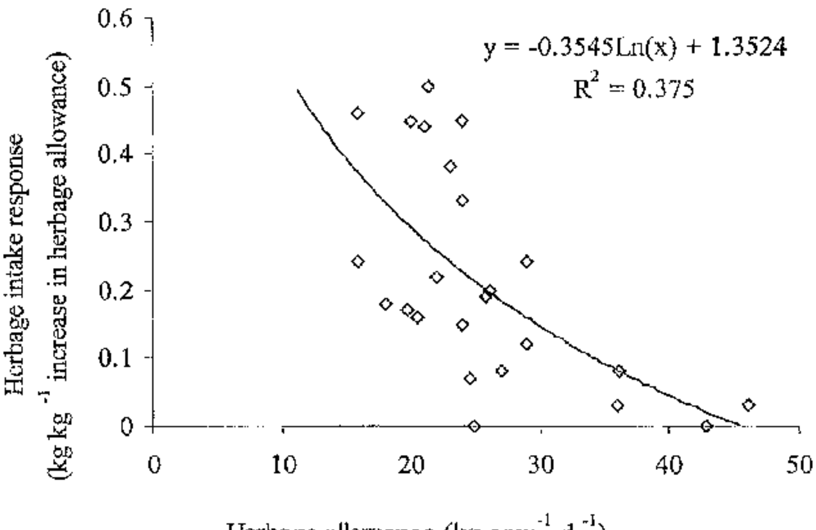


Figure 2.18 Herbage intake response to increasing herbage allowance from results of experiments presented in Table 2.3

Responses to increasing levels of herbage allowance however are extremely variable between studies. This can arise as a consequence of both sward and animal factors. At similar herbage allowances for example, herbage intake can be affected by differences in herbage mass per unit area. Wales *et al.* (1999) conducted an experiment with lactating cows on perennial ryegrass-white clover swards at herbage masses of 3.1 or 4.9 t DM ha^{-1}, and herbage allowances of approximately 20, 35, 50, and 70 kg DM cow^{-1} d^{-1}. At equivalent levels of herbage allowance, herbage intake and milk production was higher on swards of higher herbage mass. Daily herbage DM intake increased linearly from 7.1 to 16.2 kg at the lower herbage mass and from 9.9 to 19.3 kg DM cow^{-1} d^{-1} at the higher level of herbage mass. This was equivalent to increases in DM intake of 2.29 kg DM t^{-1} increase in herbage mass, and 0.18 kg DM kg^{-1} increase in herbage DM allowance. Milk production increased linearly with increasing herbage allowance from 21.8 to 27.1 kg, and 24.7 to 32.0 kg cow^{-1} d^{-1}, at low and medium levels of herbage mass respectively. Peyraud *et al.* (1996) found herbage OM intake was related to herbage allowance, milk yield and live weight (r^2 = 0.60). However when herbage allowance was split into its components of herbage mass and daily offered area, more of the variance in herbage intake was accounted for ($r^2 = 0.70$). Stakelum (1986b) and Stakelum (1986c) also reported higher herbage intakes with increased levels of herbage mass.

Maximum herbage intake is probably attained later in the season at a higher herbage allowance than in spring. Similar experiments conducted in autumn (Delagarde *et al.*, 2000a) and spring (Peyraud *et al.*, 1996) have shown increases in herbage intake with increasing herbage allowance are linear to a higher herbage allowance in autumn compared to spring. This could be related to changes in sward structure and quality, with a higher proportion of dead material and more rejected areas in autumn resulting in reduced levels of herbage intake (Delagarde *et al.*, 2000a). Herbage intake is therefore affected by herbage allowance however sward structure has an independent effect on regulation of herbage intake.

2.5.2 Sward structural characteristics

The major sward structural characteristics that affect herbage intake are sward surface height, sward density, and sward leafiness (Parga *et al.*, 2000; Peyraud and Gonzalez-Rodrigez, 2000). Sward factors interact to affect bite mass, bite rate and grazing time, and therefore influence overall herbage intake from a sward. Ungar (1996), for example, summarises interactions between sward structure, grazing behaviour, and intake rate at the individual bite level (Figure 2.19).

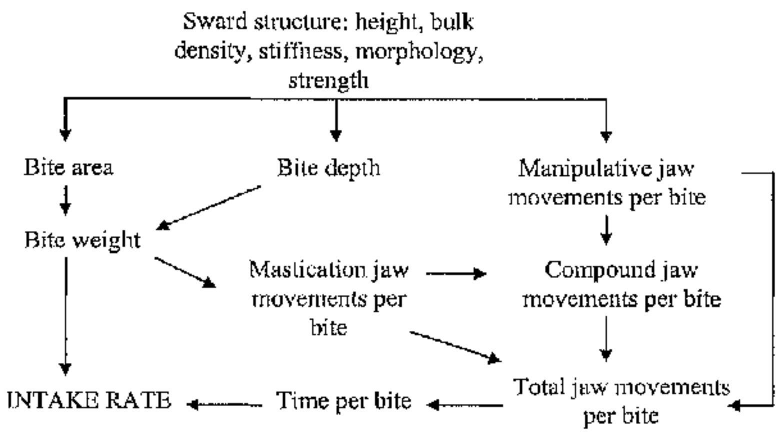


Figure 2.19 Components of ingestive behaviour that mediate between sward structure and short-term intake rate

Results from recent experiments which have measured effects of sward characteristics on aspects of herbage intake of grazing lactating dairy cows are presented in Table 2.4. When interpreting results between studies differences in methodologies to measure sward structure and aspects of grazing behaviour, as well as differences in grazing management systems, and reporting of values in terms of either OM or DM, must be observed. Results from Table 2.4 indicate a slight decline in bite rate with increasing bite mass (Figure 2.20).

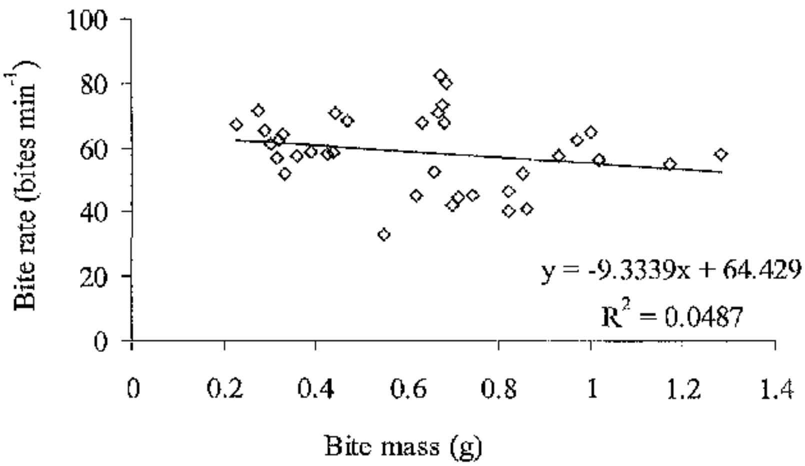


Figure 2.20 Relationship between bite mass and bite rate from results of experiments presented in Table 2.4

It is generally accepted however that bite mass is the main determinant of daily herbage intake (McGilloway *et al.*, 1999; McGilloway and Mayne, 1996). Results presented in Table 2.4 and summarised in Figure 2.21 support this strong relationship between bite mass and herbage intake.

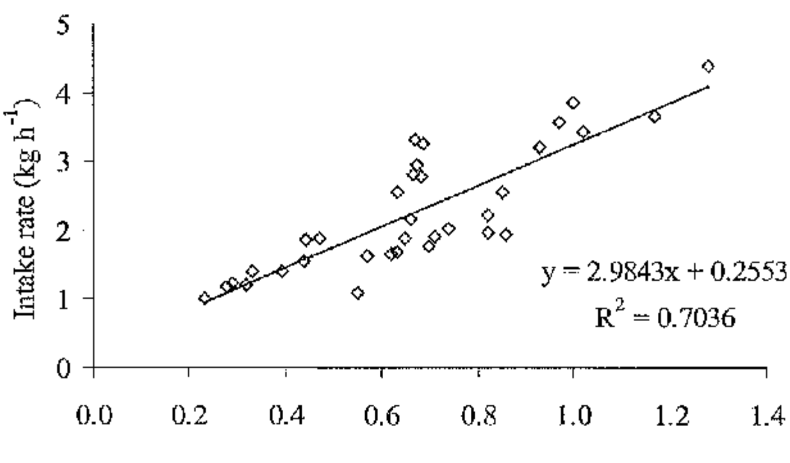


Figure 2.21 Relationship between bite mass and rate of herbage intake from results of experiments presented in Table 2.4

Table 2.4 Effect of sward characteristics on aspects of herbage intake, grazing behaviour and milk production

	Sward height (cm)	Herbage mass [§] (kg DM cow^{-1} d^{-1}) (*kg OM)	Sward bulk density [Φ] (kg DM m^{-3})	Herbage intake (kg DM d^{-1})	Bite mass (g DM)	Bite rate (bites min^{-1})	Grazing time (min d^{-1})	Intake rate (kg h^{-1})	Leaf proportion	Milk yield (kg d^{-1})
Gibb *et al.* (2002b)	7.3			10.2*	0.30*	60.7	605	1.11*		20.8
	7.3			10.8*	0.33*	51.9	563	0.98*		17.8
	7.1			11.4*	0.32*	56.8	605	1.07*		10.5
Gibb *et al.* (2002a)	7.7			11.2*	0.42*	58.2	468	1.48*		21.8
	8.0			9.6*	0.36*	57.2	458	1.23*		20.8
Barrett *et al.* (2001)					0.74	45		2.01	0.80	
Experiment 1	3.8	1882 Ψ	1.30							
	16.9	1639 Ψ	1.66		0.70	42.3		1.78	0.76	
	13.6	1532 Ψ	2.23		0.55	32.9		1.09	0.67	
	13.0	1412 Ψ	2.16		0.62	45.2		1.66	0.67	
Experiment 2	18.5	1652 Ψ	1.65		0.71	44.8		1.92	0.80	
	17.4	1551 Ψ	1.75		0.82	40.4		1.96	0.80	
	18.0	1828 Ψ	1.85		0.86	41.1		1.93	0.74	
	17.9	1799 Ψ	1.80		0.82	46.2		2.23	0.78	
Orr *et al.* (2001)										
Week 1-10	16.0 †	5903	3.69		0.67	70.9		2.80	0.35	25.7
	16.1 †	5720	3.55		0.68	80.0		3.26	0.33	26.5
Weeks 4-10	15.7 †	4894	3.12		0.68	73.4		2.95	0.31	
	8.2 †	3631	4.43		0.28	71.1		1.18	0.14	
	7.6 †	3539	4.66		0.44	71.0		1.85	0.13	
	16.0 †	5444	3.40		0.67	82.4		3.31	0.26	
Pulido and Leaver (2001)										
Experiment 1	4.5 †	1794	3.99	10.1			587	1.03	0.82	20.6
	6.0 †	2203	3.67	11.0			502	1.31	0.83	23.7
	8.9 †	2790	3.13	12.1			458	1.61	0.85	24.4
Experiment 2	4.3 †	1680	3.91	11.0			488	1.35	0.80	26.7

(Continued over)

Table 2.4 Effect of sward characteristics on aspects of herbage intake, grazing behaviour and milk production (continued)

(Continued)	Sward height (cm)	Herbage mass § (kg DM cow^{-1} d^{-1})	Sward bulk density Φ (kg DM m^{-3})	Herbage intake (kg DM d^{-1})	Bite mass (g DM)	Bite rate (bites min^{-1})	Grazing time (min d^{-1})	Intake rate (kg h^{-1})	Leaf proportion	Milk yield (kg d^{-1})
	7.7 †	2686	3.49	14.2			471	1.82	0.82	26.9
Christie *et al.* (2000)	25.7	2450 Ψ	1.13	14.1	0.63		503	1.68	0.59 Ψ	26.9
	28.7	3110 Ψ	1.26	15.2	0.71		476	1.92	0.53 Ψ	25.6
	33.8	3480 Ψ	1.17	11.7	0.57		429	1.64	0.53 Ψ	24.0
	39.8	5470 Ψ	1.53	14.4	0.65		456	1.89	0.43 Ψ	21.9
Parga *et al.* (2000)										19.7
Control sward	31.6 ‡	5589*	1.77*	14.1*		52.3	530	1.60*	0.33	
	31.6 ‡	5590*	1.77*	14.8*		53.0	484	1.83*	0.33	20.9
Leafy sward	28.9 ‡	5857*	2.03*	14.7*		53.0	532	1.66*	0.37	20.8
	28.9 ‡	5857*	2.03*	14.5*		54.0	454	1.92*	0.37	21.3
Gibb *et al.* (1999)	5.1			12.5*	0.32*	62.5	624	1.22*		
	7.2			13.3*	0.39*	58.6	601	1.41*		
	8.9			13.2*	0.44*	58.5	547	1.54*		
McGilloway *et al.* (1999)										
Experiment 1										
ς Ungrazed	21.2	3141 Ω	1.67		1.28	57.9		4.39	0.37	
ς Low	12.7	2243 Ω	2.19		1.17	55.1		3.66	0.28	
ς Moderate	10.4	1968 Ω	2.49		0.93	57.5		3.20	0.24	
ς High	8.9	1666 Ω	2.63		0.85	51.6		2.56	0.22	
Experiment 2										
ς Ungrazed	11.4	2156 Ω	2.45		1.00	65.4		3.86	0.39	
ς Moderate	8.7	2097 Ω	3.38		0.68	67.6		2.77	0.22	
ς High	6.4	1850 Ω	4.90		0.66	52.4		2.15	0.24	

(Continued over)

Table 2.4 Effect of sward characteristics on aspects of herbage intake, grazing behaviour and milk production (continued)

(Continued)

	Sward height (cm)	Herbage mass § (kg DM cow^{-1} d^{-1})	Sward bulk density Φ (kg DM m^{-3})	Herbage intake (kg DM d^{-1})	Bite mass (g DM)	Bite rate (bites min^{-1})	Grazing time (min d^{-1})	Intake rate (kg h^{-1})	Leaf proportion	Milk yield (kg d^{-1})
McGilloway *et al.* (1999)										
Experiment 3										
Low bulk density	12.7	2397 Ω	2.34		1.02	56.3		3.44	0.70	
Low bulk density	5.5	1272 Ω	4.30		0.47	68.0		1.88	0.35	
High bulk density	11.4	2671 Ω	3.02		0.97	62.0		3.57	0.55	
High bulk density	6.5	2221 Ω	5.47		0.63	67.9		2.57	0.29	
Gibb *et al.* (1997b)	5.1			10.5	0.23	67.1	628	1.00		
	7.2			14.1	0.33	63.9	604	1.40		
	9.1			12.1	0.29	65.2	581	1.25		
Rook *et al.* (1994a)										19.0
Period 1	4.0 †			13.1						
	6.0 †			14.6						22.9
	8.0 ‡			16.7						23.8
Period 2	7.7			13.5						23.2
	9.9			14.0						23.0
Le Du *et al.* (1981)										
Experiment 1	4.8	2430*	5.06*	11.1*						16.2
	7.2	2570*	3.57*	12.6*						17.2
	8.6	3260*	3.79*	12.9*						18.5
	6.1	3700*	6.07*	12.1*						18.0
Experiment 2	5.1	2240*	4.39*	12.2*						16.7
	6.9	2800*	4.06*	13.2*						18.4
Experiment 3	5.0	1970*	3.94*	12.4*						14.5
	7.2	3250*	4.51*	15.2*						19.5

- OM, † compressed sward height, ‡ extended tiller height; § Herbage mass above ground level, unless stated otherwise; Ω Herbage mass above 2.5 cm; Ψ Herbage mass or proportion leaf above 4 cm; Φ Sward bulk density refers to canopy above herbage mass cutting height; ς Grazing pressur

2.5.2.1 Sward surface height

Sward surface height is positively associated with herbage intake (for example, Le Du *et al.*, 1981; Pulido and Leaver, 2001; Rook *et al.*, 1994b). Results from Table 2.4 show a response in herbage intake to a 1 cm increase in sward height of up to 1.74 kg OM d^{-1} (Gibb *et al.*, 1997). This response however varies considerably between experiments. Results from Pulido and Leaver (2001) and Le Du *et al.* (1981) demonstrate a curvilinear response in daily herbage intake to increasing sward height from approximately 4 to 9 cm for continuously grazed paddocks. Laca *et al.* (1992a) found bite mass from their artificially constructed swards increased linearly with increasing sward height from 8 to 30 cm, while McGilloway and Mayne (1996) reports linear increases in bite mass under normal pasture conditions with increasing sward height from 8 to 20 cm. Some earlier work however has suggested that bite mass reaches a plateau at lower sward heights and Hodgson (1981) advised a target sward height of 7 to 10 cm to maximise bite mass.

In rotationally grazed swards, bite mass declines as sward height is reduced through grazing. McGilloway *et al.* (1999) for example, found the level of sward height reduction influenced DM intake rate principally through changes in DM intake $bite^{-1}$. Pooled regression analysis for their three experiments indicates a significant asymptotic relationship between sward height on DM intake $bite^{-1}$ and DM intake $hour^{-1}$. Barrett *et al.* (2001) similarly reports a decline in bite mass at increasing levels of sward height reduction through grazing.

Bite mass and herbage intake however have been shown to decline when cows are presented with very tall swards. For example, Christie *et al.* (2000) measured a decline in herbage intake and bite mass when rotationally grazed cows were offered swards above approximately 30 cm high at the start of the grazing period. Similarly, for continuously grazed swards, Gibb *et al.* (1997) demonstrated a reduction in herbage intake, and intake per grazing jaw movement, when target sward surface height was 9 cm compared to 5 or 7 cm. Decreasing herbage intake at increasing sward heights could be a consequence of lower herbage quality (Christie *et al.*, 2000), or an effect of increasing sward structural heterogeneity (Gibb *et al.*, 1997), both of which are discussed later.

Figure 2.22 provides a summary of the relationship between sward height and bite mass from results of experiments presented in Table 2.4. A trend for increased bite mass with increasing sward height is evident however results between studies are extremely variable. A better relationship ($r^2 = 0.39$) is observed if results from Christie *et al.* (2000), which were recorded from animals grazing very tall swards, are taken out of the regression analysis.

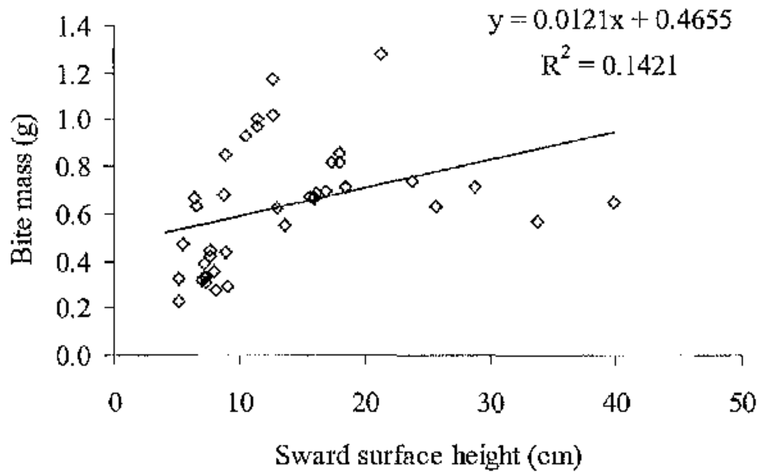


Figure 2.22 Relationship between bite mass and sward surface height from results of experiments presented in Table 2.4

Variability in bite mass and herbage intake responses to increasing sward height suggests the importance of factors other than sward height *per se* in determining herbage intake.

2.5.2.2 Sward density and its interaction with sward surface height

A strong negative correlation exists between mean sward height and bulk density (Le Du *et al.*, 1981; Pulido and Leaver, 2001); and between sward height and bulk density through the vertical profile of the canopy (Barrett *et al.*, 2001; Delagarde *et al.*, 2000b; McGilloway *et al.*, 1999) (Table 2.4, Figure 2.23). This creates difficulty in determining an independent effect of each variable.

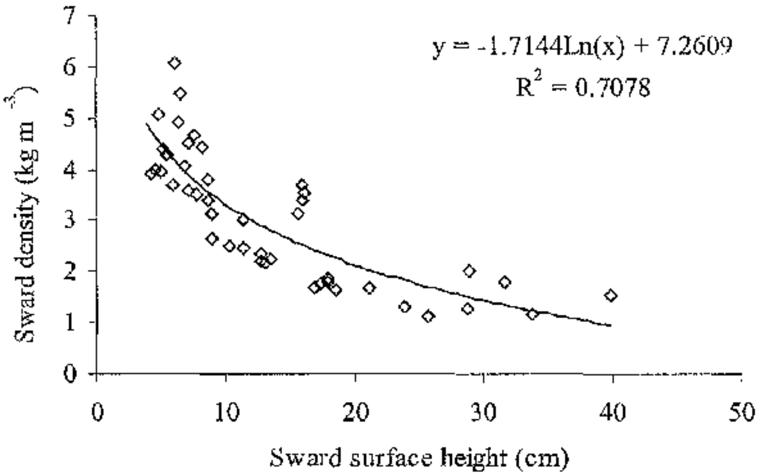


Figure 2.23 Relationship between sward surface height and sward density from results of experiments presented in Table 2.4

On a rotational grazing system, sward height will decline during the grazing process as a function of herbage allowance (Barrett *et al.*, 2001; McGilloway *et al.*, 1999). Herbage mass and the leaf fraction are also reduced, while the proportion of stem and dead material will increase. As grazing reduces sward height, sward bulk density will therefore increase and there tends to be a strong negative correlation between sward surface height and bulk density. Additionally, as the sward is grazed herbage availability and the cow's ability to prehend leaf becomes more limited (Barrett *et al.*, 2001; McGilloway *et al.*, 1999).

A summary of the relationship between sward bulk density and bite mass from studies presented in Table 2.4 indicates a substantial amount of variation in results (Figure 2.24).

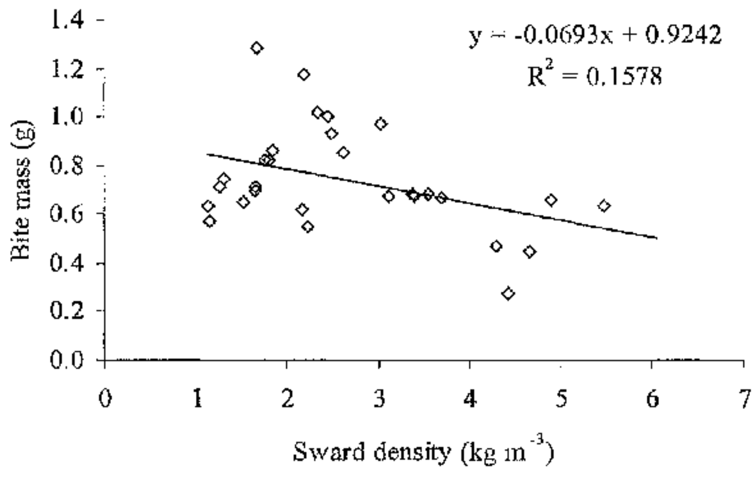


Figure 2.24 Relationship between bite mass and sward density from results of experiments presented in Table 2.4

Individual studies however have demonstrated that bite mass is greater on a denser sward, irrespective of sward height (Figure 2.25, McGilloway and Mayne (1996)).

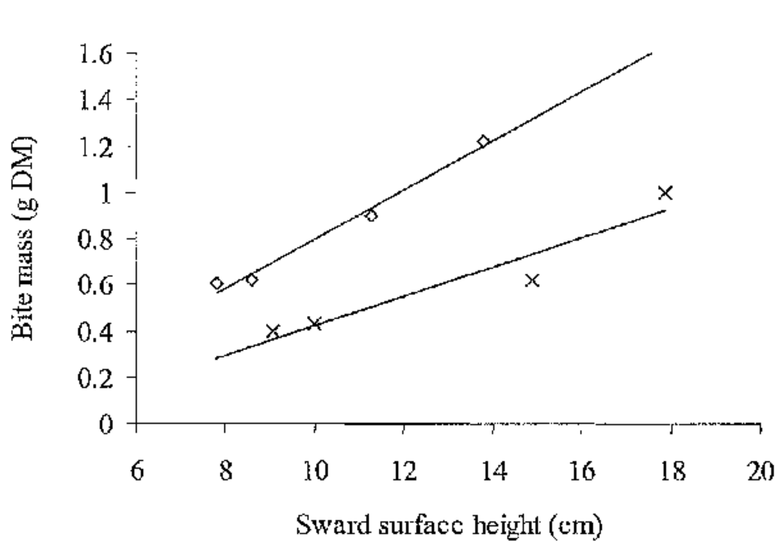


Figure 2.25 Relationship between pre-grazing sward height, bite mass and sward bulk density: 1.2 t FW ha^{-1} cm^{-1} (◊) or 0.6 t FW ha^{-1} cm^{-1} (X) (McGilloway and Mayne, 1996)

A further experiment reported by Mayne *et al.* (1997) found bite mass ranged from 0.4 to 1.1 g DM. Bite mass had a strong positive correlation with sward height, but there was also an interaction with sward density. On taller swards, bite mass was largely influenced by sward height, reflecting increased bite depth, whereas on shorter swards, differences between swards were largely attributable to differences in bulk density. There was no significant effect of sward height or density on bite rate. Bulk density therefore had an increasingly important influence on intake rate on shorter swards. Irrespective of bulk density, a maximum DM intake rate of approximately 3.5 to 4.0 kg DM h^{-1} was achieved with sward heights of approximately 18 to 20 cm (Figure 2.26).

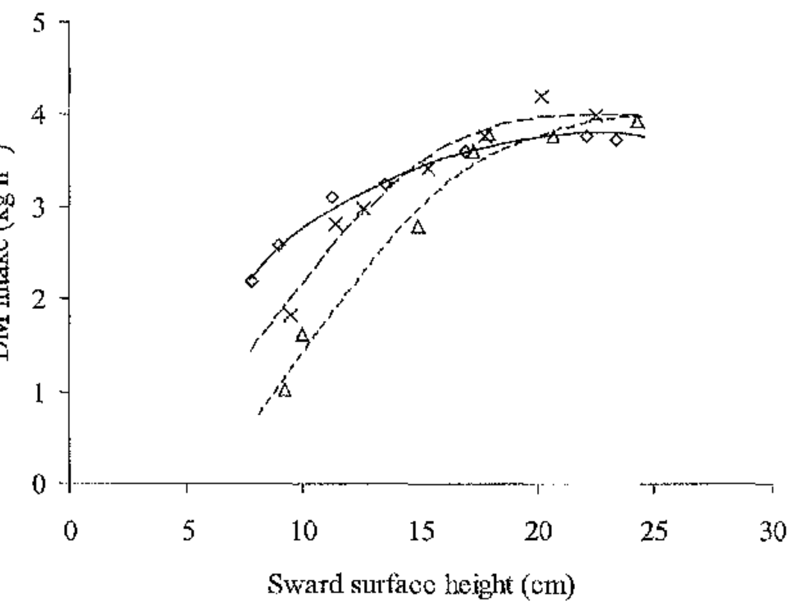


Figure 2.26 Effect of sward height on DM intake rate at different bulk densities; high (◊) medium (x) and low (Δ) (Mayne *et al.*, 1997)

On swards subject to similar levels of depletion, McGilloway *et al.* (1999) also found decreasing bite depth as swards were grazed down led to reduced bite mass, despite increases in bulk density. McGilloway *et al.* (1999) carried out experiments on rotationally grazed swards of low or high initial bulk density (Experiments 1 and 2 respectively). Results demonstrate a range in bite mass from 0.66 to 1.28 g DM. Bite mass declined as the swards were progressively grazed down however, differences in sward height make it difficult to quantify effects of density at equivalent levels of sward height reduction. A third experiment was therefore designed to separate the confounding effects of sward surface height and bulk density. Sward surface height was similar for a high and low density sward in a grazed and ungrazed state. Bulk density had little effect on DM intake in previously ungrazed tall swards but as the level of sward height reduction increased, DM intake tended to be higher on swards of high bulk density. The evidence suggests that the absence of a relationship between density and bite mass on the taller, ungrazed swards could be attributed to the fact that bulk density of the sward as a whole does not reflect differences in bulk density of the grazed horizon. Accumulation of DM in the lower horizons (Delagarde *et al.*, 2000b) may have determined differences in mean sward bulk density.

Artificially hand constructed swards have been used to study effects of sward height and bulk density independently. Black and Kenney (1984) found intake rate by sheep was related to sward height only at constant bulk density, and to bulk density only at similar sward heights. Herbage mass per unit area was therefore concluded as a better predictor of intake rate than either measurement independently. Results from Laca *et al.* (1992a) have shown bite mass to vary less than bite dimensions due to compensatory effects between bite area, bite depth and density. Animals obtained heavier bites on tall sparse swards than on short dense swards of equal mass per area. Bite mass was more sensitive to sward height than bulk density. However these results from artificial swards do not test the effects of presence of barriers or undesirable plant parts such as stem within the vertical profile of the sward. The evidence from Laca *et al.* (1992a) therefore suggests that even on homogenous artificial swards, recording of herbage mass is insufficient, and both density and height are needed to predict bite mass.

In conclusion sward surface height has a major effect on herbage intake, however bulk density is also important and becomes increasingly significant as sward height declines (Mayne *et al.*, 1997; McGilloway *et al.*, 1999).

2.5.2.3 Green leaf mass

Sward surface height is positively correlated with green leaf mass, and leafiness declines as a sward is grazed down (Delagarde *et al.*, 2000b; McGilloway *et al.*, 1999). The relationship between sward height and leafiness however is dependant upon a number of factors including grazing management and season (Delagarde *et al.*, 2000b; Lemaire and Chapman, 1996).

The proportion of green leaves in the sward canopy can affect the amount of herbage ingested. Decreasing sward height and a reduction in intake when animals are grazing into deeper layers of a sward for example, are correlated with a reduction in the biomass of green leaves (McGilloway *et al.*, 1999). Furthermore, while sward height measurements can provide a good indication of sward state, research has demonstrated bite mass can be more closely correlated with green leaf mass than sward surface height (Penning *et al.*, 1994).

A positive effect of a high proportion of green leaf material in the deep layers was clearly shown by Parga *et al.* (2000) (Table 2.5). They examined effects of sward structure on daily herbage intake of strip grazing cows in spring. A control and leafy sward differed in the proportion of green leaf below 15 cm (39 and 49 percent respectively), and swards were compared at two herbage allowances of 18 and 12 kg DM cow^{-1} d^{-1}.

Table 2.5 Effect of sward canopy structure on herbage intake and milk yield (Parga *et al.*, 2000)

	Control Sward		Leafy Sward	
Herbage Allowance	Low	High	Low	High
Herbage intake (kg OM d^{-1})	14.1	14.8	14.7	14.5
Post grazing tiller height (cm)	8.4	12.2	10.3	15.8
Milk yield (kg d^{-1})	19.7	20.9	20.8	21.3

Sward height and herbage mass were the same between swards, while tiller density and green leaf mass in the lower layers were higher for the leafy sward. On a high herbage allowance, herbage intake did not differ between the leafy and control sward (14.7 kg OM d^{-1}) (Table 2.5). At a low herbage allowance, herbage intake was higher on the leafy sward. An interaction between herbage allowance and type of sward shows that daily herbage intake in a strip grazing situation is determined more by sward characteristics of the lower horizons of the sward compared to the higher layers. An increased proportion of green lamina in the lower horizons of the sward could allow for reduction in herbage allowance without adverse effects on intake. Grazing time and bite rate were not affected by treatment and so it appears the difference in intake was mediated through lower bite mass. The variations between swards however were limited. This could be partially attributed to relatively low intake requirements of the cows, which had a mean milk yield of 19.8 kg d^{-1} at the start of the experiment, and so were easily able to attain their nutritional requirements from both sward treatments.

Increasing green leaf mass at the bottom of the sward by appropriate grazing management or selection of varieties could therefore help increase herbage intake whilst maintaining a lower residual sward height.

2.5.3 Effects of sward characteristics on bite dimensions

Variability in effects of sward structure on bite mass must occur as a result of changes in bite dimensions. Measurement of these bite dimensions can therefore improve understanding of how sward characteristics affect bite mass, and ultimately daily intake and animal performance.

2.5.3.1 Bite depth

Bite depth has been measured when animals are grazing pasture or biting hand constructed sward (Table 2.6).

Table 2.6 Effect of sward surface height on bite depth

	Animal	Herbage[†]	Sward height (cm)	Bite depth as proportion height	r^2
Grazed pasture					
Barrett *et al.* (2000)	Dairy cows mid-lactation	PRG	17.9	0.32	
McGilloway *et al.* (2000)	Lactating dairy cows			0.5	0.89
Wade *et al.* (1989)	Dairy cows	PRG	12 - 39	0.34	
Carrere *et al.* (2001)	Sheep	PRG		0.36 - 0.38 [‡] 0.57 [§]	
		White clover		0.7 - 0.8	
Milne *et al.* (1982)	Sheep	PRG and white clover		0.33	
Curll and Wilkins (1982)	Sheep	PRG and white clover	5 - 20	0.38 - 0.70	
Hand constructed swards					
Laca *et al.* (1992a)	Steers 750 kg	Dallisgrass (pure lamina)		0.55	0.83
		Lucerne		0.48	

[†] PRG, Perennial ryegrass; [‡] whole tiller; [§] leaf

Dairy cows grazing under normal field conditions have been shown to remove approximately one-third of tiller height in a bite, irrespective of pre-grazing tiller height and whether or not tillers have been grazed previously. Barrett *et al.* (2001) has shown a constant bite depth of 0.32 extended tiller height when bite dimensions were recorded at four time periods over the day, on a sward with a high pre-grazing surface height. Wade *et al*, (1989) reported depth of grazing declined exponentially and was a constant proportion, 0.34 ± 0.03, of ungrazed tiller height over the height range 12 to 39 cm, as cows grazed down paddocks. Studies with sheep grazing under normal pasture conditions have also demonstrated bite depths equivalent to approximately one third (0.33 ± 0.056) of tiller height (Milne *et al.*, 1982).

Although it appears a constant proportion of sward height is removed per bite, there is some variation between experiments in the actual proportion removed. Cows that have been fasted prior to grazing may remove a larger proportion of tiller height per bite. McGilloway *et al.* (2000) measured bite dimensions of lactating dairy cows grazing a range of swards with different surface heights at constant bulk densities and lamina contents, and at different bulk densities at various stages of grazing down. Cows were fasted for 6 hours before being allowed to graze and in this case bite depth averaged 0.5 of extended tiller height. There is therefore potential for bite depth to vary independently of sward surface height.

Differences in bite depth can arise due to variation in plant structure, and especially the distribution and proportions of leaf and stem in the sward. Studies with grazing cows are limited, but experiments with sheep by Carrere *et al.* (2001) have found that while they grazed a constant 0.36 to 0.38 of the whole tiller, they removed approximately 0.57 of the leaf fraction. A more severe defoliation intensity of 0.7 and 0.8 was reported for clover leaves. Milne *et al.* (1982) found depth of the grazed horizon was related to both sward height and height of pseudostem material in the sward and Curll and Wilkins (1982) similarly report a much higher proportion of leaf lamina length removed per bite. Curll and Wilkins (1982) found increasing stocking rate from 25 to 55 sheep ha^{-1} slightly reduced the proportion of leaf lamina removed from 0.58 to 0.47. Furthermore, a much greater proportion of leaf lamina length was removed when leaf length was reduced. Leaf length ranged from approximately 5 to 20 cm. At leaf lengths of 161 and 53 mm, the proportion removed in a bite was 0.38

and 0.70 respectively. The proportion of sward height removed in a bite may therefore be dependent upon leafiness of sward and presence of stem, with animals grazing deeper into more leafy herbage.

Although the relevance of results from hand constructed swards to normal pasture conditions is questionable, they have allowed detailed study of bite dimensions not possible under field grazing conditions. Laca *et al.* (1992a) demonstrated that bite depth was primarily a function of sward height and concluded that sward height explained 83 percent of the variation in bite depth. Consideration of bulk density as well as sward height however explained 88 percent of variation in bite depth. When bulk density was low, the slope of bite depth as a function of sward height was approximately 0.5 and a negative interaction between bite depth and bulk density was observed. Results however do not test the effects of presence of barriers or undesirable plant parts, especially stem, within the vertical profile of the sward and the dallisgrass swards used in the study were made up wholly from leaf lamina. Density of hand constructed swards was also relatively constant through horizons of each sward, which is not representative of a normal grazed sward (Delagarde *et al.*, 2000b; Parga *et al.*, 2000). This could explain the lower bite depths reported from studies under field conditions. Furthermore, proportion of leaf lamina removed in a bite may be greater than that reported in other studies since animals were fasted and offered swards more than 7 hours after their last meal.

It would be expected that there is a maximum physical depth to which animals can bite which may explain the lower proportion of height removed from the very tall swards. This could also explain the ramp function that has been used by some authors to predict bite depth from sward height (Ungar and Noy-Meir, 1988). This is based on the assumption that there is a critical height below which animals can not graze. It is suggested that animals will graze down to this critical height until they reach a maximum bite depth imposed by their mouth dimensions (Ungar and Noy-Meir, 1988).

Illius *et al.* (1995) conclude that the reason for animals biting to a constant proportion of sward height can not be explained by energy cost as it has been calculated that energy gain is greater than energy cost whatever the depth of a bite.

A more likely explanation and constraint is the greater force required to sever the sward at lower depth and they suggest tiller density is a more important determinant of the force needed to sever a mouthful of herbage than the mechanical properties of individual plants.

Under normal field grazing conditions therefore, the majority of evidence suggests that grazing animals will remove a constant proportion of sward height, equal to approximately one third of tiller height. The proportion of sward height removed however can vary independently according to the animals hunger drive and also sward structure and leafiness.

2.5.3.2 Bite area

Measurements of bite area presented in the literature are limited but they do indicate a positive relationship between bite area and sward surface height (Table 2.7).

Table 2.7 Measurements of bite area from some recent experiments

	Sward surface height (cm)	Bulk density (kg DM m^{-3})	Bite area (cm^2)	s.e.m.
McGilloway *et al.* (2000)	Ungrazed †		95.4, 75.1, 72.4, 70.7, 96.9	
	Moderate †		79.7, 57.4, 39.1	
	Low †		73.1, 70.1, 41.4, 46.7	
	High †		68.8, 57.9, 34.1, 33.8, 47.1	5.22 - 8.39
Barrett *et al.* (2001)	17.9	1.76	124.3	10.96

† Level of sward height reduction by grazing

On swards at varying levels of sward height reduction and bulk density of rotationally grazed swrads, McGilloway *et al.* (2000) found bite area of lactating cows generally increased from means of 48 to 85 cm^2 for short and tall swards respectively. Barrett *et al.* (2001) reports a higher mean bite area from of 124 cm^2 from previously ungrazed, tall swards. Their study also found bite area does not vary according to time of day when cows are grazing swards of similar structure (Barrett *et al.*, 2001).

Detailed measurements from hand constructed swards have reported higher bite areas compared to measurements made on grazed pasture (Laca *et al.*, 1992a). In their study with steers Laca *et al.* (1992a) found bite area increased quadratically with sward surface height when animals were able to sweep their tongue beyond the area of the incisor arcade. Bite area reached a plateau of approximately 170 cm^2 although individual bites were observed to reach 220 cm^2. These observations however were made on hand constructed, tall swards of 8 to 30 cm, and it would seem that extension of the tongue to increase the area of a bite is likely to have less of an effect at lower sward heights. As with their measurements of bite depth, steepness of the response to sward height declined with increasing bulk density, possibly due to the higher force required to bite and remove the herbage (Laca *et al.*, 1992a).

2.5.3.3 Estimating bite mass from bite dimensions

Height and bulk density have been described as the most important sward features that determine bite depth and bite area on green and leafy vegetative swards (Laca *et al.*, 1992a). Hodgson (1981) suggests that from a description of bite dimensions, the profile of an initially uniform sward can be divided into grazing horizons, each with a characteristic bite depth and bite area. Regression of sward height on bite mass however differs for swards of different structures. If bite depth is a constant proportion of sward height, and bite area is less affected by sward height than bite depth, bite mass will be dependant on bulk density of herbage in the grazed horizon. Investigation of the interaction between sward height and density could therefore allow a better prediction of bite mass.

McGilloway *et al.* (2000) created models of bite mass from their measurements of bite depth, area and bite bulk density, as follows:

Bite depth = 0.4831 extended tiller height	$r^2 = 0.89$
Bite area = 97.2 – 123.1 (0.9674) leaf %	$r^2 = 0.73$
Bulk density bite = (2258 – 31.7 leaf %) + 0.411 sward bulk density	$r^2 = 0.68$

Bite mass = ((bite depth/10)* bite area) + bulk density bite.

Their model of bite mass predicts a bite mass of 0.69 and 0.66 g for AM and PM grazing respectively. This compares with actual estimates of bite mass by liveweight change over 1 hour periods of 0.78 and 0.65 g. Models similar to this could in turn be used to simulate grazing and estimate herbage intake from a sward, however differences in bite rate in response to differences in bite mass need to be considered, as does total grazing time.

2.5.4 Importance of sward structural variability and spatial heterogeneity

Considering the importance of sward characteristics on grazing behaviour and intake, variability in sward structure across a grazed paddock could potentially have considerable impact on intake at the individual bite level and hence on total intake over a period of time. Frequently grazed patches tend to be characterised by leafy, vegetative, and high quality herbage however a lower mean sward height reduces herbage availability (Ginane and Petit, 2002). Infrequently grazed patches have high biomass and are taller which gives them a high potential intake rate, however intake is discouraged by lower herbage quality, especially as the season progresses (Ginane and Petit, 2002).

Animals will tend to increase grazing of infrequently grazed patches as the height of frequently grazed patches declines (Dumont *et al.*, 1995); although they are less prepared to graze infrequently grazed patches as herbage becomes more mature (Ginane and Petit, 2002). Infrequently grazed patches in a continuously grazed sward are utilised when there is high grazing pressure in the mid-season, however this can be at the expense of milk yield per cow (McBride *et al.*, 2000). At a low frequently grazed patch height of 6 cm, Connell and Baker (2002) found increased utilisation of infrequently grazed patches compared to treatments which maintained the height of frequently grazed patches at 8 or 10 cm. They also report DM intake was maintained or increased on the 6 cm treatment suggesting that cows were spending less time selecting, and perhaps defoliating to a greater depth in the sward, than cows on the other two treatments. Herbage quality however would be expected to be lower in these infrequently grazed patches, and so support lower levels of milk production.

On a rotationally grazed sward, Stakelum and Dillon (1990) reported greater utilisation of infrequently grazed patches by cows in summer resulted in lower DM intake and daily milk yield, compared to when cows grazed swards conditioned in spring by high grazing pressure to reduce the proportion of tall under-grazed areas. Low grazing pressure to maintain high target sward heights and high herbage availability is therefore expected to result in increased spatial heterogeneity and greater qualitative and quantitative variability in the sward. The effect is likely to develop as the season progresses when animals become less prepared to graze the infrequently grazed patches as they become more mature (Gibb *et al.*, 1997).

Mean bite size will depend upon structure of different patches of the sward and proportion of bites taken from them. Swain (2000) demonstrated that averaging measurements of the distribution of herbage over a field could overestimate intake from a sward. Quality of herbage ingested will similarly be dependant upon variability across the paddock and the opportunity and willingness for selection.

2.6 ANIMAL FACTORS AFFECTING HERBAGE INTAKE

2.6.1 Live weight and body size

The size of an animal's mouth determines maximum bite area, and hence bite mass and total herbage intake. The breadth of the incisor arcade is proportional to body mass $^{0.36}$ (Illius and Gordon, 1987), and these authors predict that when sward height is not limiting, bite mass will scale with the animal's metabolic requirements, body mass $^{0.75}$. On very short swards however, where the animal has no opportunity to vary bite depth, bite mass scales with the size of the incisor arcade; body mass $^{0.36}$ (Illius and Gordon, 1987). The sward height at which this will occur is shorter for smaller animals. Small animals therefore become limited at a lower sward height and can subsist on shorter swards. Animals however can increase bite area beyond the size of their mouth by inserting their mouths sideways into the sward to increase bite size, or by sweeping their tongue to cover a larger surface area of sward (Laca *et al.*, 1992a).

Allometric relationships constrain digestion as well as the ingestion of food, and herbage intake is restricted by capacity of the alimentary tract (Allen, 1996; Allen, 2000). Capacity of the alimentary tract increases faster than metabolic rate as body size increases (Rook, 2000), however its close relationship with body size means that food consumption increases with live weight. Increases in herbage intake of 1.0 to 1.5 kg OM 100 kg live weight^{-1} have been reported by Peyraud *et al.* (1996).

2.6.2 Milk yield level and genetic merit

Cows will alter their intake to meet their nutritional requirements (McGilloway and Mayne, 1996). The animal's productive potential affects its ability to utilise nutrients and so this interacts with the balance of absorbed nutrients to regulate intake (Illius and Jessop, 1996). Higher yielding cows can absorb VFAs from the rumen faster than lower yielders principally as a result of a greater demand for nutrients from the mammary gland. This results in a weaker negative feedback from metabolic control mechanisms that affect voluntary food intake, and voluntary food intake is likely to be higher (Illius and Jessop, 1996). Herbage intake is therefore expected to vary according to production potential of the cow, and numerous studies report a positive relationship between herbage intake and milk production or genetic merit (for example, Buckley and Dillon, 1998; Buckley *et al.*, 2000a; Dillon *et al.*, 1999). Results from the experiments presented in both Table 2.3 and Table 2.4 show a slight positive relationship between milk yield and herbage intake, although there is a large amount of variation in the relationship between studies (Figure 2.27).

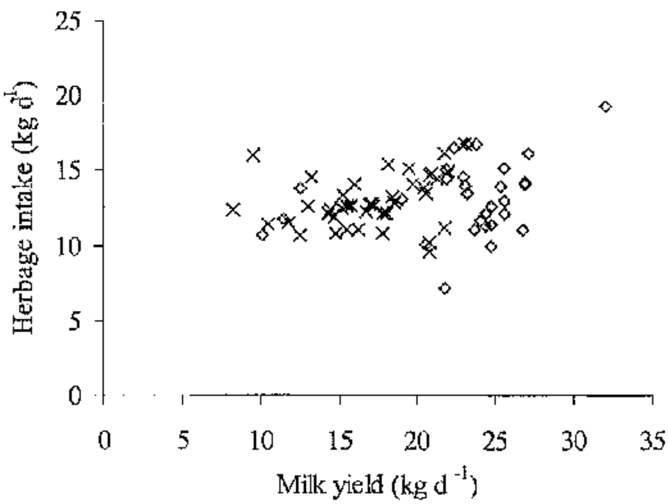


Figure 2.27 Relationship between herbage intake and milk yield from experiments presented in Table 2.3 and Table 2.4 (OM, $y = 0.1364x + 10.608$, $r^2 = 0.0823$ (x); DM, $y = 0.1757x + 9.1961$, $r^2 = 0.10$ (◊))

The ability of an animal to achieve its intake requirements to support its production potential depend upon sward characteristics; and in particular sward structure and herbage quality, which determine potential nutrient intake from the sward. Furthermore, the availability of supplementary feeds, as discussed later, will alter the level of herbage intake required for an animal to meet its nutritional requirements. The relationship between herbage intake and milk yield will therefore interact with production potential of the cow, sward characteristics and supplementation.

For cows yielding between 12.5 and 32.5 kg milk d^{-1}, Caird and Holmes (1986) report increases in herbage intake of between 0.18 and 0.32 kg OM kg^{-1} milk d^{-1}. Peyraud *et al.* (1996) found increases in intake with increasing levels of milk production were within a similar range, averaging 0.25 kg OM kg^{-1} milk yield at turnout, when milk yield at turnout ranged from 17 to 35 kg d^{-1}. In experiments with cows which had initial milk yields between 16.9 and 35.5 kg milk d^{-1} Pulido and Leaver (2001) estimated increases in herbage intake of 0.18 and 0.21 kg DM kg^{-1} increase in initial milk yield. The results of studies reported by McGilloway and Mayne (1996) however, suggest greater increases in herbage intake of 0.4 to 0.5 kg DM d^{-1} for each kg increase in milk yield over the range 15 to 30 kg milk d^{-1}.

It is expected that the relationship between milk yield and intake will tend towards a plateau, due to sward and animal constraints on further increases in herbage intake. Delaby *et al.* (1999) suggest that the relationship between intake and milk yield is linear up to 40 kg milk d^{-1} on ideal grazing conditions. However with less favourable grazing conditions, it is expected that a plateau in herbage intake will be reached at a lower level of milk yield. McGilloway and Mayne (1996) for example, suggest herbage intake will tend towards a plateau above 30 kg milk d^{-1}. In general, the evidence suggests that the shape of the response in herbage intake to milk yield level will depend upon the point at which sward and animal constraints that restrict further increases in herbage intake are reached, and also upon the animal's nutrient demand and potential level of production. A summary of some studies which have investigated effects of milk yield level and genetic merit on herbage intake and grazing behaviour is presented in Table 2.8.

Table 2.8 Effect of milk production potential on herbage intake and behaviour

	Initial milk yield (kg d^{-1})	Milk yield (kg d^{-1})	Herbage intake (kg DM d^{-1})	Bite mass (g DM)	Bites min^{-1}	Intake rate (kg h^{-1})	Grazing time (min d^{-1})
Pulido and Leaver (2001)							
Experiment 1	16.9	13.1	8.5			1.10	480
	21.1	18.1	11.0			1.40	482
	28.0	23.3	11.3			1.33	536
	31.5	26.9	11.3			1.27	529
	35.5	32	13.4			1.47	552
Experiment 2	21.3	21.2	11.3			1.45	459
	35.5	32.3	14.0			1.67	500
Christie *et al.* (2000)	37.9	30.8	15.8	0.73	49.9	1.91	496
	28.1	24.9	12.6	0.59	47.9	1.71	443
	23.6	22.9	13.5	0.61	45.8	1.64	495
	17.7	17.7	12.6	0.64	46.1	1.59	475
O'Connell *et al.* (2000)	† High	24.7	15.0		58.4	1.48	609
	† Medium	21.2	14.4		51.4	1.41	614

† Genetic merit

Cows can increase herbage intake to support higher levels of milk production by grazing for longer (Phillips and Leaver, 1986). Pulido and Leaver (2001) report increases in grazing time of 4.2 and 2.5 minutes kg^{-1} increase in initial milk yield in Experiments 1 and 2 respectively (Table 2.8). Grazing time however reaches a plateau at 9 to 10 hours d^{-1} (Rook and Huckle, 1996). This can explain why increases in herbage intake have not always been accompanied by increases in grazing time, especially for high yielding cows which may already be grazing for the maximum time that is available (for example, Christie *et al.*, 2000; O'Connell *et al.*, 2000).

Increases in intake rate through higher bite rate and/or bite mass, provides another mechanism for higher yielding cows to achieve increased levels of DM intake. Rook and Huckle (1996) observed that rotationally grazed cows yielding between 20 and 40 kg milk increase herbage intake through a higher rate of intake. Higher levels of herbage intake reported by Pulido and Leaver (2001) were also achieved by increases in rate of intake by 0.16 and 0.32 g DM $minute^{-1}$ per kg increase in milk yield. Increases in grazing time have been accompanied by higher bite rates. Bao *et al.* (1992) for example found grazing time, which was measured in the period between morning and afternoon milkings, and duration of the first grazing bout, were higher with higher merit cows than low merit cows yielding on average 32.0 and 24.8 kg milk d^{-1} respectively. A relatively small difference in grazing time compared to difference in milk production in this study however may suggest a difference in grazing efficiency, and the higher genetic merit cows exhibited an increased rate of biting. O'Connell *et al.* (2000) also found higher biting rates, but no increase in grazing time, between high and medium genetic merit cows yielding 24.7 and 21.2 kg milk d^{-1} respectively.

The effect of genetic merit and nutrient demand on bite mass is less well documented. Christie *et al.* (2000) however has found a trend towards greater intake per bite with higher yielding cows, and concluded that higher yielding cows appear to harvest more herbage primarily by increasing intake per bite rather than biting rate or grazing time.

2.6.3 Temporal pattern of grazing behaviour

Grazing behaviour and intake characteristics can vary depending on time of day. Most grazing occurs in daylight hours (Phillips and Leaver, 1986). Ruminating time is mainly concentrated in the hours of darkness although it is also interspersed between the main grazing bouts during the day (Phillips and Leaver, 1986). A reduction in daylight in the autumn is associated with compression of grazing time to mainly within daylight hours, while the proportion of grazing during the night increases as day length shortens (Rook *et al.*, 1994).

Higher rates of herbage intake have been reported in the evening with cows (Gibb *et al.*, 1998; Orr *et al.*, 2001; Rutter *et al.*, 1998) and heifers (Orr *et al.*, 1996; Rutter *et al.*, 2002). This suggests the animals anticipate the impending long period of darkness during which they can ruminate. An increased DM intake in the evening also corresponds with the time of day when herbage DM and WSC concentrations are at their highest (Orr *et al.*, 2001; Wilkinson *et al.*, 1994). Phillips and Leaver (1986) recorded a linear increase in bite rate of set stocked cows through the day. They suggest this could arise as an effect of high surface water on herbage in the morning causing difficulty in prehension of herbage.

Gibb *et al.* (1998) reports significant effects of time of day on bite mass and bite rate, the net result of which was an increase in intake rate over the course of the day

(Table 2.9). In this experiment, cows were continuously grazed on swards maintained at a target height of 6.5 cm, and so sward characteristics remained relatively constant for each behavioural measurement period.

Table 2.9 Effect of time of day on aspects of grazing behaviour (Gibb et al., 1998)

	Time of day (h)			
	07:00	11:30	16:00	19:00
Bite mass (g DM)	0.33^{a}	0.38^{ab}	0.48^{b}	0.40^{ab}
Bite rate (bites min^{-1})	52.6^{ab}	47.5^{a}	51.6^{ab}	59.4^{b}
Intake rate (g DM min^{-1})	17.1^{a}	18.0^{a}	24.0^{b}	23.0^{ab}

Mean values not sharing a common superscript differ significantly ($P < 0.05$)

Rutter *et al.* (2002) found both total jaw movement rate and proportion of these jaw movements that were bites tended to be greater in the evening, and so by subjecting ingested material to less chews in the evening, intake rate was increased. Orr *et al.* (2001) investigated effects of giving cows their daily grass allowance in a strip-grazing system either in the morning (AM) or afternoon (PM). Compressed sward heights (Holmes, 1974) before and after grazing were on average 16.2 and 7.7 cm respectively. Total grazing time was similar for AM and PM treatment groups however cows receiving their allocation in the afternoon had a longer evening meal. Rate of intake tended to be higher during the first hour after allocation when cows were offered their daily herbage allowance in the afternoon. This was mainly a result of a higher bite rate. Bite mass was also slightly increased although none of these effects were statistically significant ($P > 0.05$) (Table 2.10).

Table 2.10 Measurements of grazing behaviour and herbage intake 1 hour after allocation of new pasture (Orr *et al.*, 2001)

	Time of allocation	
	Morning (AM)	Afternoon (PM)
Intake rate (g DM min^{-1})	46.6	54.4
Bite mass (mg DM bite^{-1})	665	684
Bite rate (bites min^{-1})	70.9	80.0
Total grazing time (min d^{-1})	461	462
Intake (kg DM) 07.45-16.45 h	12.1	2.2
Intake (kg DM) 16.45-07.45 h	5.7	15.8
Total herbage DM intake (kg DM)	17.8	18.0

Despite similar total DM intakes between treatments, Orr *et al.* (2001) found mean milk yields were greater for cows moved after the afternoon milking, 21.8 compared to 23.1 kg milk d^{-1}, which can be attributed to a greater proportion grazing when DM and WSC concentrations are at their highest.

Barrett *et al.* (2001) did not find significant differences in bite dimensions or DM intake rate when cows were presented with a similar sward, which had a mean height of 17.9 cm, at different times throughout the day. Bite rate however tended to be more variable between treatments ($P = 0.07$) than bite mass or intake rate, and was highest in the evening. As a consequence, intake rate was highest at 2.23 kg DM h^{-1} at 19:00 h, compared to 1.92 kg DM h^{-1} at 06:00 h.

Differences in effects of time of day on grazing behaviour between experiments could be related to differences in sward characteristics and ability of cows to meet their desired level of herbage intake from the sward. Sward conditions reported between experiments have been very different; with target mean sward heights for example, of 6.5 cm (Gibb *et al.*, 1998) compared to mean pre-grazing sward height of 17.9 cm (Barrett *et al.*, 2001). The more favourable grazing conditions provided by Barrett *et al.* (2001) allowed cows to obtain higher bite mass and intake rate throughout the day and so they could have easily achieved their desired level of intake without having to increase bite rate or grazing time. Greater ease of harvesting herbage on the taller sward and ability of cows to meet their herbage intake requirements could therefore explain some differences in the effect of time of day between experiments.

2.6.4 Effect of fasting

Experiments have often reported results from animals that have been fasted before being allowed to graze to ensure they have a common hunger drive and to minimise variation due to animal effects (McGilloway *et al.*, 1999). Fasting however may influence grazing behaviour. Patterson *et al.* (1998) examined intake and grazing behaviour for 1 hour periods after cows were fasted for 1, 3, 6, or 13 hours. There was no difference in sward characteristics between treatments, and sward height averaged 16.4 cm. Total DM intake, DM intake per bite, and bite rates were increased significantly ($P < 0.05$) when duration of fasting was increased from 1 to 6 or 13 hours (Table 2.11).

Table 2.11 Effect of duration of fasting on grazing behaviour (Patterson *et al.*, 1998)

	Duration of fasting (h)			
	1	3	6	13
Bite depth as proportion pre-grazing sward height	0.29	0.31	0.33	0.33
Bite mass (g DM)	1.08	1.10	1.38	1.34
Bite rate (bites min^{-1})	44.3	49.9	53.0	56.2
Intake rate (kg DM h^{-1})	2.89	3.29	4.37	4.55

Differences in DM intake per bite were not due to variations in pre-grazing sward height or bite depth and so it appears cows may have been able to increase their bite area by use of the tongue to sweep larger areas of tall herbage into their mouth. Some other results however suggest cows remove a significantly greater proportion of sward height in a bite when they have been fasted (McGilloway *et al.*, 1999), compared to non-fasted animals (for example, Barrett *et al.* 2001). When sward characteristics permit, these data suggest cows can increase intake rate and so compensate for increased hunger drive by increasing bite rate and bite mass.

2.7 GRAZING MANAGEMENT

2.7.1 Herbage utilisation, sward characteristics and herbage intake

Herbage intake is maximised when herbage allowance per cow is high (for example, Delaby *et al.*, 2001; Stakelum, 1986c). The major drawback of this approach is that grazing efficiency can decrease markedly with increasing herbage allowance (Stakelum, 1996) (Table 2.12), and herbage intake increases at a progressively slower rate as herbage allowance increases (for example, Peyraud *et al.*, 1996). Stakelum (1996) illustrates a significant reduction in the proportion of herbage available that is utilised with increasing herbage allowance. At a low herbage allowance, 34 percent more grass was consumed ha^{-1}, but intake cow^{-1} was depressed by up to 10 percent, compared to the high herbage allowance.

Table 2.12 Effect of increasing the quantity of grass offered on herbage intake and efficiency of grass utilisation (Stakelum, 1996)

	Herbage allowance (kg DM cow^{-1} d^{-1} > 3.5 cm)		
	16	20	24
Intake cow^{-1} (kg DM d^{-1})	15.3	16.5	17.1
Intake ha^{-1} (kg DM assuming 1700 kg DM available ha^{-1})	1625	1402	1210
Efficiency of utilisation of available herbage (%)	95.6	82.5	71.2
Sward height post grazing (cm)	5.8	6.7	7.4

With a high herbage allowance, a large proportion of the offered herbage remains uneaten, some of which will senesce and decay before being grazed. This will ultimately result in increased cost kg^{-1} herbage DM actually consumed (Mayne, 2001) (Table 2.13). Systems that are based on maximising herbage intake cow^{-1} can therefore substantially reduce the cost effectiveness of grazing, relative to alternative feed inputs (Mayne, 2001).

Table 2.13 Effect of utilisation efficiency under grazing on grass cost (Mayne, 2001)

	Utilisation (Grazing efficiency)		
	Low	Medium	High
Grass growth (t DM ha^{-1})	12.0	12.0	12.0
Utilisation efficiency (%) (overall season)	55	70	85
Grass utilised (t DM ha^{-1})	6.6	8.4	10.2
UME (GJ ha^{-1})	75.2	95.8	116.3
Cost (£ t DM^{-1}) (Assuming total costs £400 ha^{-1})	60.6	47.6	39.2

In practice, providing a high herbage allowance to achieve high levels of herbage intake cow^{-1} generally involves providing continuously grazed cows with a high herbage mass and sward height (Pulido and Leaver, 2001; Stakelum, 1986b), and leaving a high post grazing herbage mass and sward height in rotational systems (McGilloway *et al.*, 1999).

Mean sward height of continuously grazed pasture, or residual sward height after grazing of rotationally grazed pastures, provides a measure of sward conditions which can be used for management decisions (Baker, 1986a). Guidelines for management of continuously grazed swards have often been based on target sward surface heights. Hodgson *et al.* (1986) suggest a range of target sward heights for grazing cows of between 7 and 10 cm. They also provide a matrix that suggests the percentage change in stocking rate required to maintain average sward height within this target range. Le Du *et al.* (1981) and Baker *et al.* (1981) similarly conclude intake on continuously grazed swards is close to a maximum when sward height is in excess of 7 cm extended tiller height. To allow higher levels of herbage intake for higher genetic merit cows, more recent guidelines suggest a higher range of target sward heights. Peyraud and Gonzalez-Rodrigez (2000) for example, propose an optimal range of pre-grazing sward heights of between 8 and 12 cm. Mayne *et al.* (2000) also take into consideration declining sward quality and changing sward structure over the season. For continuously grazed, high yielding cows, they suggest a sward height of 7 to 8 cm from April to June, 8 to 10 cm from July to August, and 10 to 12 cm from September to October.

For rotationally grazed swards, Hodgson *et al.* (1986) recommend a residual sward height of 7 to 10 cm for lactating dairy cows. These guidelines however are only based on 21 and 28 day cycles, and an assumed pre-grazing height of between 15 and 30 cm. Le Du *et al.* (1979) and Baker *et al.* (1981) conclude intake of cows is close to a maximum when residual height, measured as extended tiller height, is between 8 and 10 cm.

Reduced grazing severity, with high residual herbage mass and residual heights above 8 cm in rotational systems, and above 8 cm in continuous grazing systems, is suggested to result in deterioration in sward quality and structure, particularly during the spring and early summer period (Mayne *et al.*, 2000). Mayne *et al.* (1987) and Stakelum and Dillon (1991) have for example shown increases in the proportion of stem and dead material in the sward, and reduced digestibility of herbage, following lax grazing in early season. The challenge is therefore to achieve a balance between herbage intake cow^{-1}, herbage utilisation and maintenance of sward quality over the season.

2.7.2 Grazing systems

2.7.2.1 Rotational versus continuous grazing

The majority of experimental evidence suggests the difference in herbage production, individual animal performance, or animal production ha^{-1}, between rotational and continuous grazing systems is limited. Unless at high stocking rates, similar levels of herbage production are observed from both systems (Grant *et al.*, 1988). Evans (1981) reported similar average herbage intakes by dairy cows over the whole season from rotational and continuous grazing systems, at comparable stocking rates. However, because rotational grazing allows grazing pressure to be adjusted more easily in response to changes in herbage growth, a more uniform pattern of herbage intake was observed from this system. In a review of published data from western Europe, Ernst *et al.* (1980) concluded milk production was similar from rotational and continuous systems operated at similar stocking rates. There is evidence however that a rotational system is superior to a continuous stocking system at high stocking rates with increases in milk solids of 4 percent and 16 percent being obtained at low and high stocking rates respectively (McMeekan and Walshe, 1963). In a rotational system herbage intake and digestibility declines as the sward is grazed down (Barrett *et al.*, 2001). This can explain cyclic variation in milk output and composition described by Hoden *et al.* (1991).

Rotational systems can provide a number of advantages over continuous grazing. In particular, identification of grass surpluses and deficits is easier with a rotational compared to continuous system, and there is greater flexibility to adjust grass supply by adding or removing paddocks to the grazed area according to grass growth (Mayne *et al.*, 2000). Rotational grazing facilitates management practices, and in particular leader-follower grazing and alternating grazing with cutting, to utilise high residual herbage masses (Mayne *et al.*, 1988). Adopting these practices can then improve the overall efficiency of grassland utilisation. The most important characteristic of a rotational system however is that herbage can be presented to the cow as a tall, dense, and leafy sward, and so in an optimum form to allow high bite mass and herbage intake (Barrett *et al.*, 2001; McGilloway *et al.*, 1999). McGilloway and Mayne (1996) conclude therefore that to provide quality herbage for high merit cows, rotational grassland management systems, based on high inputs of N fertiliser are essential.

2.7.2.2 Leader-follower grazing

A leader-follower system can be employed to utilise high residual herbage masses following grazing by higher producing animals (Mayne *et al.*, 2000). Fresh pasture at a high allowance is offered to the highest producing animals, which are then followed on the same pasture by animals with lower intake requirements.

Mayne *et al.* (1988) gave preferential treatment to high yielding cows in a leader-follower system in mid and late season. High yielders in the leader group produced up to 5.7 kg milk d^{-1} more than high yielders in the control group, and leader-follower grazing increased milk yields by on average 9 percent compared to the control group. Overall, milk yields for the whole lactation however were 19 percent higher for cows on the leader treatment, compared to high yielding animals in the control treatment, indicating the greater opportunity for selective grazing on the leader treatment. A further experiment by Mayne *et al.* (1990) however showed that a leader-follower system had little effect on average animal performance when a higher grazing severity was imposed. In this case, improvements in animal performance of high yielding cows in the leader group were offset by the reduced performance of the follower group. Increased grazing severity reduces opportunity of the leader group for selection of herbage of higher digestibility, and reduces herbage availability for the follower group. Differences in milk yield between the two groups increased as the season progressed so that milk yields became significantly lower for the follower group, reflecting greater restriction of herbage availability. Preferential treatment of the high yielding cows appeared to have greater effect later in the season when sward quality was beginning to decline. Cows in the leader group however had significantly higher herbage intakes and levels of milk production compared to high-yielding cows in the control group, yielding on average 15.8 and 14.5 kg milk d^{-1} respectively over the period from 14 May to 28 September. Cows in the leader group spent on average 50 minutes d^{-1} less grazing each day yet still managed to consume 1.3 kg DM d^{-1} more herbage than high yielding cows in the control group.

Leader-follower systems may therefore enable increased milk production from herbage when herbage availability is poorer, particularly when non-lactating, or much lower producing animals, are used in the follower group. A leader-follower system however increases the complexity of grazing systems and is not compatible with continuous grazing systems.

2.7.2.3 Alternating grazing with cutting

Grazing systems can be developed to alternate grazing and cutting and so utilise high residual herbage masses after grazing. This has been shown to give a small advantage in production of about 1 kg milk cow^{-1} d^{-1} compared to grazing only which could be due to reduced contamination with faeces on the alternately cut and grazed sward, and/or increased herbage production and availability (Leaver, 1985). Conservation however can lead to deterioration in sward structure for grazing. Tiller density of perennial ryegrass swards which are continuously grazed is typically in the range 30 000 to 50 000 m $^{-3}$, while in cut swards a tiller density of between 5 000 and 10 000 m^{-3} is more typical (Parsons *et al.*, 1983b). Tiller structure of a continuously grazed sward takes time to establish, however tiller death and reversion to a more open structure is more rapid when swards are taken out of grazing for conservation (Parsons *et al.,* 1984). Production could then be impaired if the sward is returned to grazing after cutting, and the more spaced tillers will have less leaf area and take longer to recover after defoliation (Parsons and Chapman, 2000).

2.8 SUPPLEMENTATION AT GRAZING

2.8.1 Principles of supplementation

Supplements can be offered to cows at grass to increase total nutrient intake and obtain higher levels of animal performance than are possible from herbage alone. Conserved forages may be offered either once or twice daily after milking (buffer feeding), or when the animals are housed overnight (partial storage feeding). Concentrate supplements are normally fed twice daily to cows, during or after milking. Mobile computerised feeders can provide an alternative system to manipulate the temporal pattern of supplementation, particularly when cows are offered high levels of supplementation (Gibb *et al.*, 2000). Concentrates can be offered at a constant, flat rate to all cows, or at different levels according to milk yield level or production potential of individual animals.

Responses to supplementation are extremely variable and highly dependent upon effects of the supplement on herbage intake (Mayne, 1991; Peyraud and Delaby, 2001). Milk yield response, or efficiency of supplementation, can be expressed as the increase in milk output (kg) per kg increase in concentrate fed. Substitution rate describes the reduction in herbage intake (kg) per kg increase in supplement intake. Substitution rate and hence response to supplementation varies with grazing conditions, production potential of the cow, supplement type and level of feeding (Mayne *et al.*, 2000).

Substitution rates with forage supplements such as grass silage or hay, are normally much higher than for concentrate supplements (Mayne *et al.*, 2000). Under good grazing conditions when herbage allowance is high, offering conserved forage as a buffer feed has resulted in high substitution rates, often over 1.0 (Leaver, 1985; Peyraud and Gonzalez-Rodrigez, 2000; Phillips, 1988; Phillips and Leaver, 1985b). In these situations very low milk yield responses, or even a decrease in milk yield compared to control cows, has been obtained since net energy content of conserved forage is less than fresh forage (Leaver, 1985; Phillips, 1988). Larger substitution rates with conserved forage supplements compared to concentrates appear to be mediated by a greater depression in grazing time of up to 40 minutes d^{-1} kg^{-1} silage DM (Mayne, 1991).

During periods of grass shortage and when herbage quality is poor however, forage supplementation has generally increased DM intake (Phillips, 1988). Greater responses to forage supplementation have also been achieved from higher yielding cows (Phillips and Leaver, 1985a). More recent work with cows yielding 29.0 kg milk d^{-1} for example, has demonstrated no effect on animal performance when cows were fed 2.3 kg DM d^{-1} of maize silage compared to grass only (Holden *et al.*, 1995).

It is generally recommended that forage supplements are offered to cows in situations where herbage availability is low. Concentrates of a high nutrient concentration provide a more appropriate form of supplementation than forages for high yielding cows when herbage availability is high, and the aim is to increase total nutrient intake and milk production at pasture (McGilloway and Mayne, 1996).

2.8.2 Responses to concentrate supplementation

Early reviews by Leaver (1968) and Journet and Demarquilly (1979) report an average response of between 0.4 and 0.6 kg milk kg^{-1} concentrate DM, with average substitution rates of 0.5 to 0.6. More recently, a review of literature by Delaby and Peyraud, (unpublished, as cited in Peyraud and Delaby, 2001) reports a mean milk yield response of 0.66 ± s.e.m. 0.46 kg milk kg^{-1} concentrate DM d^{-1} when concentrate intake was on average 2.8 ± 1.2 kg DM d^{-1} (n = 141). Herbage intake was reduced by on average 0.4 ± 0.3 kg DM kg^{-1} increase in concentrate DM intake (n = 57). A higher response of 0.89 kg milk kg^{-1} concentrate DM d^{-1} is also demonstrated from the results of these experiments which were published after 1990, and the incremental increase in milk response averaged + 0.1 kg milk per kg concentrate DM every 10 years.

Results from some recent concentrate supplementation experiments are presented in Table 2.14. In these studies, grazing cows were fed on average 3.81 ± s.d. 2.06 kg concentrate DM d^{-1}, and up to 10 kg concentrate DM d^{-1}. Mean milk yield of unsupplemented cows was 22.2 ± 2.26 kg milk d^{-1}. On average, the overall efficiency of supplementation in these studies was 0.96 ± 0.36 kg milk kg^{-1} concentrate, and mean substitution rate was 0.29 ± 0.39.

Table 2.14 Effect of concentrate allowance on milk yield response and herbage intake

	Concentrate (kg DM d^{-1}) (* OM)	Milk yield (kg d^{-1})	Marginal efficiency (kg milk kg concentrate^{-1})	Overall efficiency (kg milk kg concentrate^{-1})	Herbage intake (kg d^{-1})	Substitution (kg herbage kg concentrate^{-1})
Gibb *et al.* (2002b)	0	16.4			10.8*	
	1.1*†	18.2	1.7	1.7*	11.8*	-0.9*
	2.1*†	19.7	1.4	1.5*	10.7*	0.0*
	3.2*†	21.4	1.5	1.5*	11.8*	-0.3*
	4.2*†	20.1	-1.1	0.9*	9.4*	0.3*
	5.3*†	24.2	3.7	1.4*	10.1*	0.1*
Reis and Combs (2000)	0	21.8			13.9	
	5.0	26.8	1.00	1.00	12.7	0.24
	10.0	30.4	0.72	0.86	9.77	0.41
Delaby *et al.* (2001)						
Experiment 1	0	21.8				
	1.8	24.2	1.36			
	3.6	26.5	1.31			
	5.3	27.4	0.51	1.06		
Experiment 2	0	22.0				
	2.6	24.1	0.80			
	5.4	27.1	1.09	0.94		
Experiment 3	0	22.7				
	2.6	25.8	1.17			
	5.3	28.4	0.98	1.07		
Pulido and Leaver (2001)						
Experiment 1	0	22.2			13.9	
	2.6	23.7	0.57		11.3	0.99
	5.2	22.7	-0.38	0.10	8.1	1.11
Experiment 2	0.0	24.0			16.5	
	5.2	28.4	0.84	0.84	13.6	0.55
Sayers *et al.* (2000)	5.0	31.7			13	
	9.9	34.8	0.64	0.64	10.2	0.57
Wales *et al.* (1999)	0					
	5.0		1.09	1.09		0.35

* Results presented as OM, † OM estimated as 920g kg^{-1} FW (continued over)

Table 2.14 Effect of concentrate allowance on milk yield response and herbage intake (continued)

	Concentrate (kg DM d^{-1}) (* OM)	Milk yield (kg d^{-1})	Marginal efficiency (kg milk kg concentrate^{-1})	Overall efficiency (kg milk kg concentrate^{-1})	Herbage intake (kg d^{-1})	Substitution (kg herbage kg concentrate^{-1})
Robaina *et al.* (1998)						
Year 1	0.0					
	5.0		0.70	0.70		0.45
Year 2	0					
	5.0		0.95	0.95		0.45
Dillon *et al.* (1997)						
Year 1	0.0	24.2			13.85	
	1.8	25.8	0.89		13.25	0.33
	3.5	26.0	0.12	0.51	12.75	0.31
Year 2	0	24.0			15.3	
	1.8	25.0	0.56		15.15	0.08
	3.6	26.6	0.89	0.72	14.95	0.10
Wilkins *et al.* (1995)	0.0	24.1				
	3.5	25.8	0.49	0.49		
Wilkins *et al.* (1994)	0	22.9				
	1.8	25.4	1.37			
	3.5	26.0	0.35	0.88		
Hoden *et al.* (1991)	0.5*	22.4			16.7*	
	3.7*	25.0	0.81*	0.81	16.1*	0.17*
Meijs and Hoekstra (1984)						
Year 1	0.8*				12.9*	
	2.8*				12.5*	0.18*
	3.9*				12.0*	0.30*
Year 2	0.8*				13.4*	
	3.2*				12.5*	0.35*
	5.6*				11.3*	0.43*

* Results presented as OM

Milk yield responses to concentrate supplementation are usually accompanied by a steady increase in milk protein concentration, and a reduction in milk fat concentration (Peyraud and Delaby, 2001; Reis and Combs, 2000; Schwarz *et al.*, 1995). An increase in milk protein content indicates an improved energy status of the cow, while a reduction in milk fat can occur as a consequence of a dilution effect of milk volume and reduction in the acetic to propionic acid ratio in the rumen (Peyraud and Delaby, 2001; Peyraud and Gonzalez-Rodrigez, 2000). From their review of experiments, Delaby and Peyraud, (unpublished, as cited in Peyraud and Delaby, 2001) report a mean increase in milk protein of 0.23 ± 0.32 g kg^{-1} milk kg^{-1} concentrate DM; and a reduction in milk fat content of 0.29 ± 0.53 g kg^{-1} milk kg^{-1} concentrate DM.

Efficiency of supplementation and substitution rates are dependant upon multiple interactions between the animal's milk production potential and nutritional requirements; and herbage availability, sward structure and potential herbage intake; as well as concentrate allowance and concentrate type (Delaby *et al.*, 2001; Pulido and Leaver, 2001).

2.8.2.1 Concentrate allowance

When increasing amounts of concentrate are fed, marginal efficiency of milk production generally declines (for example, Delaby *et al.*, 2001; Robaina *et al.*, 1998; Wilkins *et al.*, 1994) and substitution rate increases (Meijs and Hoekstra, 1984; Pulido and Leaver, 2001). From the experiments presented in Table 2.14, there is a slight negative relationship between efficiency of supplementation and concentrate level (Figure 2.28), and a positive association between substitution rate and concentrate level (

Figure **2.29**). Variability in results between studies however is high.

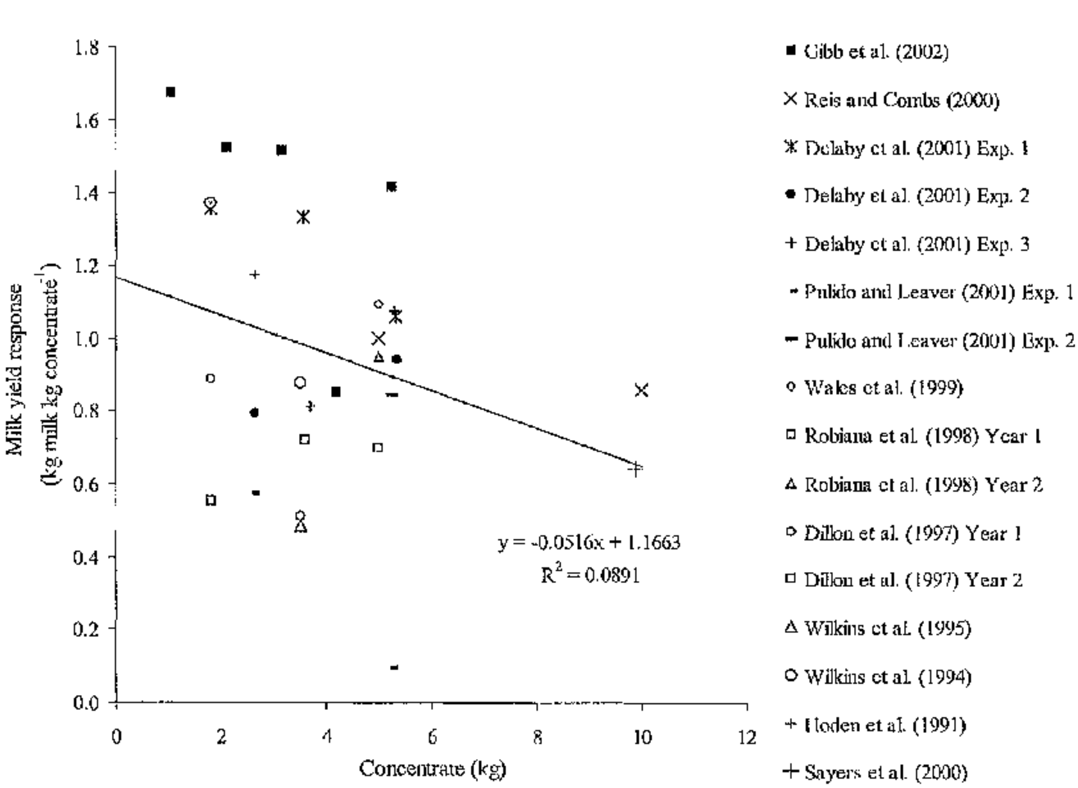


Figure 2.28 Effect of concentrate intake on milk yield response (from results of experiments presented in Table 2.14)

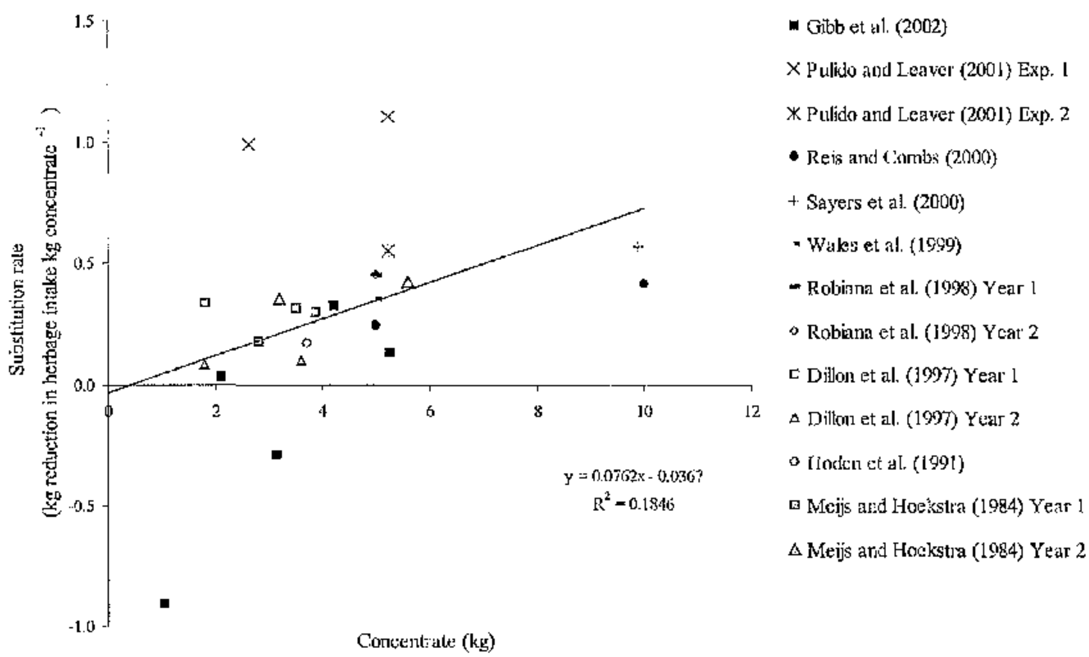


Figure 2.29 Effect of concentrate intake on substitution rate (from results of experiments presented in Table 2.14)

A reduction in herbage intake with concentrate supplementation is generally mediated through a reduction in grazing time (Leaver, 1985; Peyraud and Gonzalez-Rodrigez, 2000). Some studies have reported that grazing time declines by between 10 and 22 minutes kg^{-1} concentrate DM intake (Combellas and Hodgson, 1979; Kibon and Holmes, 1987; Sarker and Holmes, 1974).

More recently, Pulido and Leaver (2001) found the effect of concentrate on herbage DM intake was a consequence of changes in both grazing time and rate of intake. Feeding concentrate reduced the intake drive of animals by decreasing the duration and intensity of grazing. In Experiments 1 and 2 respectively, reductions in grazing time were 3.8 and 11.0 minutes kg^{-1} concentrate DM d^{-1}, and substitution rates were 1.12 and 0.55. The higher substitution rate reported in their first experiment was explained by a large reduction in rate of intake of 1.82 g DM $minute^{-1}$ kg^{-1} increase in concentrate DM intake, compared to 1.01 g DM $minute^{-1}$ in their second experiment. An increase in concentrate allowance from 5 to 10 kg DM cow^{-1} d^{-1} by Sayers *et al.* (2000) reduced grazing time by 18.2 minutes kg^{-1} concentrate DM d^{-1}, and reduced total number of bites by 1018 bites kg^{-1} concentrate DM, but had no effect on DM intake $bite^{-1}$.

Effects of increasing concentrate level on marginal efficiency of supplementation and herbage intake however are not always observed. Gibb *et al.* (2002b) for example, reports a linear increase in milk production when concentrate offered to continuously grazed cows was increased to 6 kg FW d^{-1}. Substitution of herbage for concentrate was very limited and there was no effect of increasing concentrate level on bite mass, bite rate, intake rate, total grazing time and temporal pattern of grazing activity over the day, or ruminating behaviour. Effects of variables other than simply concentrate allowance are therefore important in determining responses to supplementation.

2.8.2.2 Milk production potential and milk yield level

Responses to supplementation have been shown to increase with increasing milk yield, or potential milk production and genetic merit. Higher responses observed in experiments conducted in more recent years (Peyraud and Delaby, 2001) for example, coincide with increases in genetic merit of dairy cows for milk production traits. It seems likely that increased efficiency of concentrate use and reduced substitution rates are associated with the greater nutrient requirements of higher producing animals.

Results from experiments presented in Table 2.14 demonstrate a large amount of variation in efficiency of concentrate supplementation with increasing milk yield level (Figure 2.30). Effects of milk yield potential on efficiency of supplementation as reported in Figure 2.30 however, are compounded by the positive effect of concentrate supplementation on milk yield level.

Milk yield of unsupplemented cows could provide a better indication of a cow's genetic potential for milk production and of potential milk production from pasture alone (Figure 2.31). Variability between experiments however is still high. Within experiments, differences in the relationship between unsupplemented milk yield and efficiency of supplementation are an effect of level of concentrate supplementation.

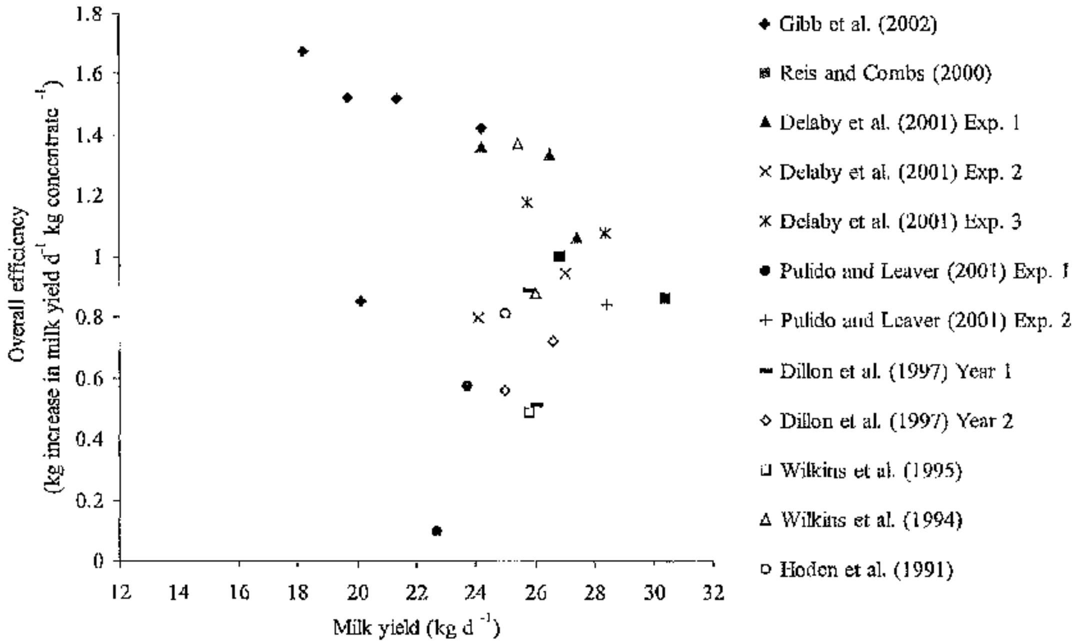


Figure 2.30 Overall efficiency of concentrate supplementation and milk yield

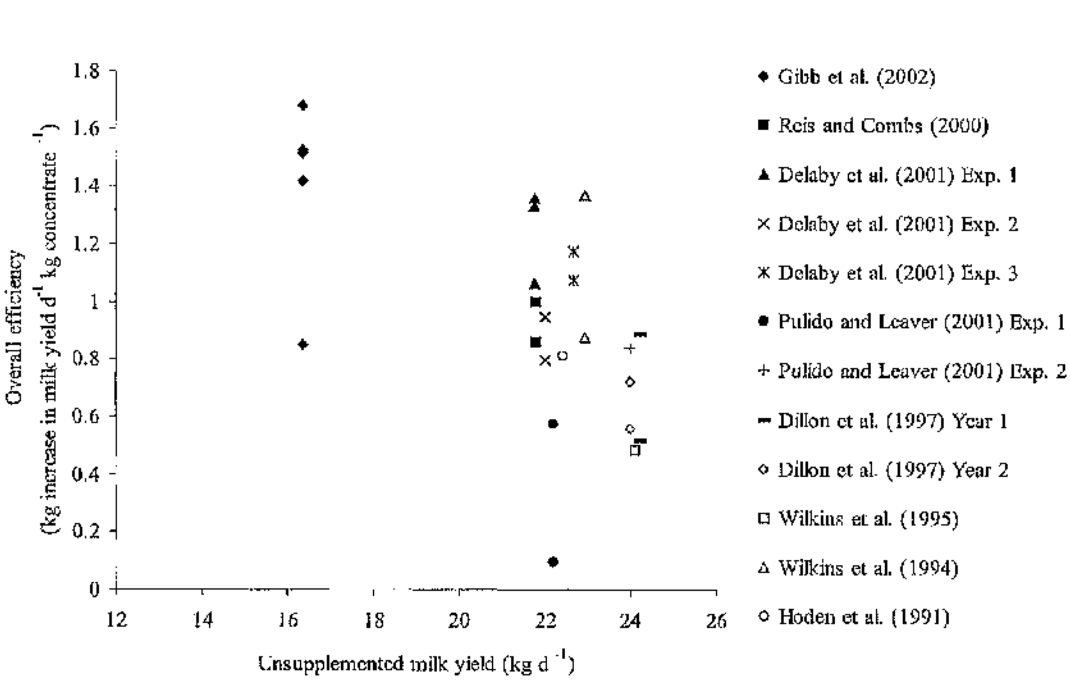


Figure 2.31 Overall efficiency of concentrate supplementation and milk yield of unsupplemented cows

Some studies have used milk yield level at turnout as a measure of milk production potential, and have found increasing efficiency of concentrate supplementation with higher milk yields at turnout (Hoden *et al.*, 1991) (Table 2.15).

Table 2.15 Effect of milk yield at turnout on milk yield response to concentrates (Hoden *et al.*, 1991)

Milk yield at turnout (kg d^{-1})	Milk yield response (kg milk kg concentrate DM^{-1})
25	0.50
30	0.70
35	0.75

Dillon *et al.* (1999) similarly reports improved efficiency of concentrate utilisation from higher genetic index cows. Milk yield response from cows with a peak yield of 34.6 kg d^{-1} was 1.12 kg milk kg^{-1} concentrate DM, compared to 0.92 kg milk kg^{-1} concentrate DM from cows with a peak milk production of 30.6 kg d^{-1}. Mean substitution rate was low for both groups at 0.22. Peyraud *et al.* (1998) on the other hand observed a decline in substitution rate as milk yield at turnout increased and cows were offered 0 or 4 kg concentrate at herbage allowances of 11 or 15 kg OM d^{-1}. Relatively high milk yield responses have also been reported at higher levels of supplementation from higher yielding cows. For example Sayers *et al.* (2000) obtained a marginal efficiency of 0.6 kg milk kg^{-1} concentrate DM, when concentrate allowance increased from 5 to 9.9 kg DM d^{-1}, from cows yielding over 35 kg milk d^{-1} at turnout.

The effect of potential milk production on response to supplementation however is not consistent. Delaby *et al.* (2001) found milk yield at turnout, which ranged from 25 to 40 kg d^{-1}, had no effect on milk yield response or substitution of herbage with increases in concentrates offered up to 4 or 6 kg FW d^{-1}. Pulido and Leaver (2001) similarly report a constant linear response to concentrates from cows yielding between 16.9 and 35.5 kg d^{-1}, and fed up to 6 kg FW concentrate d^{-1}. Increases in herbage intake kg^{-1} increase in milk yield in their experiments were estimated to be between 0.18 and 0.21 kg DM d^{-1}.

Greater responses from higher yielding cows to increasing levels of concentrate supplementation could reflect behavioural constraints on biting rate and grazing time which restrict herbage intake from a sward (Mayne *et al.*, 2000). As milk yield increases, marginal increases in herbage intake tend to decline, and consequently Peyraud *et al.* (1996) have demonstrated that incremental increases in intake from the sward provide only approximately two-thirds of net energy required per kg additional milk produced for high yielding cows. Both Pulido and Leaver (2001) and Delaby *et al.* (2001) also calculate the additional ME supply from increases in herbage intake as milk yield potential increases in their experiments is insufficient to meet the requirement for higher levels of milk production. Therefore when animals are unable to reach their nutritional requirements from herbage and concentrates offered, it is likely that the response to increasing concentrate level will remain linear to a higher level of supplementation, and no interaction between milk yield potential and concentrate level will be apparent. It might also be expected that responses to concentrates will progressively decrease with increasing concentrate level as cows reach their energy and nutrient requirements to support their production potential (Peyraud and Delaby, 2001).

Efficiency of concentrate supplementation can therefore be affected by milk production potential. The evidence suggests that whether or not an effect is observed however, depends upon the interaction between grazing conditions that affect potential intake from the sward and the ability of cows to meet their nutrient requirements from grazing alone.

2.8.3 Herbage allowance and sward structural characteristics

Herbage availability has long been recognised as a major factor influencing the response to concentrate supplementation (Leaver, 1968; Leaver, 1985). Higher milk production responses have been observed at lower levels of herbage allowance (Grainger and Mathews, 1989), at higher stocking rates (Hoden *et al.*, 1991), at lower sward surface heights (Wilkins *et al.*, 1995), and reduced levels of herbage mass (Wales *et al.*, 1999). These effects have been accompanied by lower substitution rates (Meijs and Hoekstra, 1984).

Delaby *et al.* (2001) found milk yield response to increasing levels of concentrate supplementation in their first experiment was dependent upon herbage allowance (Figure 2.32). Response was linear at the lower level of herbage allowance but curvilinear when herbage allowance was increased.

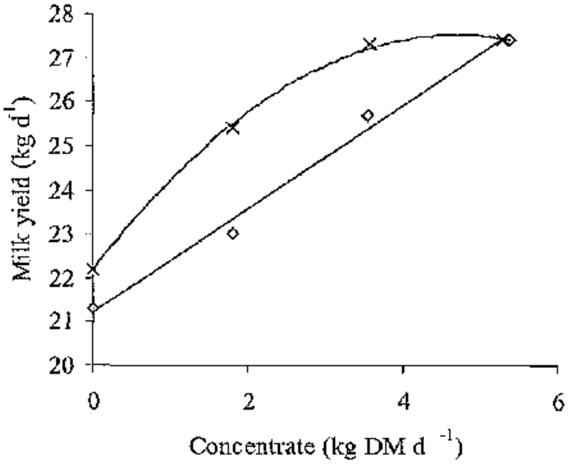


Figure 2.32 Effect of herbage allowance; 12.1 kg DM (◊), and 15.8 kg DM cow $^{-1}$ d^{-1} (x), on milk yield response to concentrate (Delaby *et al.*, 2001)

Meijs and Hoekstra (1984) investigated the interaction between concentrate level, herbage allowance and herbage intake. The model they fitted to their data is presented in Figure 2.33, and it clearly illustrates the large substitution effect that is expected when supplements are offered at a high herbage allowance.

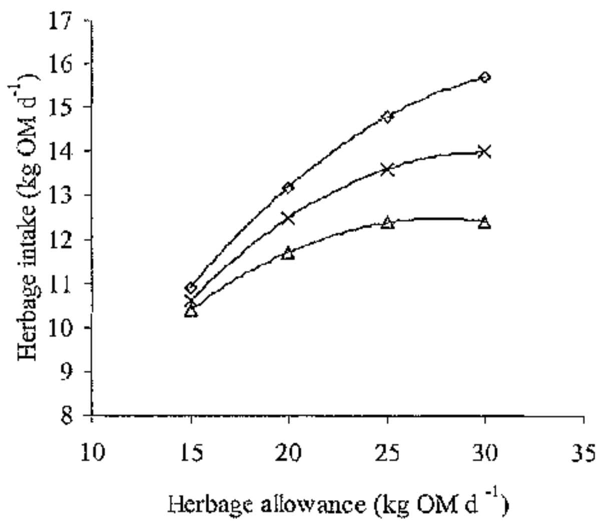


Figure 2.33 Effect of concentrate level, 0.8 (◊), 3.2 (x), 5.6 (Δ) kg DM cow^{-1} d^{-1}; and herbage allowance, on herbage intake (Meijs and Hoekstra, 1984)

Reduced levels of herbage allowance cow^{-1} are associated with higher stocking rate ha^{-1}. Hoden *et al.* (1991) reports an increase in milk yield response from 0.5 to 0.8 kg milk kg concentrate OM^{-1}, when stocking rate was increased from 2.3 to 3.0 cows ha^{-1} on a rotational grazing system.

An effect of sward structure at equal levels of herbage allowance is apparent although is less well documented. Wales *et al.* (1999) offered cows 0 or 5 kg DM concentrate d^{-1} at a low and medium herbage mass per unit area, and found substitution rate increased from 0.20 to 0.42 at the low mass, and from 0.34 to 0.44 at a higher herbage mass. Efficiency of supplementation at the two herbage allowances declined from 1.38 to 0.95 and from 1.07 to 0.97 kg milk kg^{-1} DM concentrate at the low and medium levels of herbage mass respectively.

When sward height was reduced from 6 to 4.5 cm, Wilkins *et al.* (1995) reports an increase in milk yield response from 0.31 to 0.85 kg milk kg^{-1} concentrate DM. Rook *et al.* (1994a) however has found reduced herbage intake and higher substitution of herbage for concentrates, when concentrates were offered to cows grazing very short swards of 4 cm compared to 6 cm or 8 cm. Unsupplemented animals on the shortest sward grazed for longer, however this effect was reversed when concentrates were offered. These authors suggested that the relatively high substitution rate of 0.42 on the shortest sward occurred when animals were unwilling to invest substantial effort in grazing once a threshold level of energy intake was reached.

Efficiency of concentrate use can also be affected by herbage quality, and in particular digestibility (Grainger and Mathews, 1989). Improved herbage quality of swards containing a high proportion of clover may explain a reduced efficiency of supplementation from cows grazing higher clover swards (Wilkins *et al.*, 1994). Higher responses to concentrate supplementation have been achieved in summer compared to spring (Gleeson, 1981; Stakelum, 1986a; Stakelum, 1986b; Stakelum, 1986c) which might be associated with a reduction in both herbage availability and quality. Similar responses have been achieved on both rotational and continuous grazing systems (Arriaga-Jordan and Holmes, 1986b).

At a high herbage allowance, a reduction in the acetic to propionic ratio in the rumen can be more pronounced if cows have access to a leafier diet that is more rapidly fermented (Peyraud and Gonzalez-Rodrigez, 2000). The decline in milk fat content therefore tends to be greater with supplementation at higher herbage allowances when cows can select a leafier, higher quality diet.

There is generally better agreement between studies in predicting effects of concentrate supplementation on herbage intake at low levels of herbage allowance, however much more variation exists between studies at higher herbage allowances (Mayne, 1991). This reflects effects of other factors such as herbage digestibility, supplement type, season, concentrate level and milk production potential of the animals.

2.8.4 Interaction between sward and animal factors

The negative correlation observed between herbage allowance or herbage availability and response to supplementation (Delaby *et al.*, 2001; Wales *et al.*, 1999), would suggest that efficiency of supplementation is related to potential herbage intake from the sward. Herbage intake of unsupplemented cows could be used to indicate potential herbage intake. In a review of Australian studies conducted with cows grazing high quality pasture, Grainger and Mathews (1989) demonstrate a significant positive correlation between substitution rate (*SR*) and herbage intake of unsupplemented cows (*PI*, kg DM cow^{-1} d^{-1} 100 kg live weight^{-1}) (Equation 2.3):

$$SR = -0.445 + 0.315\, PI \qquad (2.3).$$

Consequently, in periods of low herbage availability when potential herbage intake is low, provision of supplementary feeds will result in low substitution rates and so an increase in total nutrient intake and hence milk production.

Effects of measures of herbage availability and potential intake, milk production potential, and response to concentrate supplementation can be summarised in terms of the difference in energy intake compared to energy requirements, or energy balance. The evidence suggests response to concentrate is higher for example, if a cow is in negative energy balance due to high nutrient demands or low intake potential from the sward, or a combination of both of these factors (Peyraud and Delaby, 2001). Delagarde and Peyraud (unpublished, as cited by Peyraud and Delaby, 2001) summarised responses presented in 48 grazing experiments when the net energy balance of unsupplemented cows was calculated from measurements of herbage intake, herbage digestibility and milk yield. Substitution rate was poorly related to concentrate level ($r^2 = 0.02$), but primarily a function of net energy balance (*EB*), in MJ day^{-1}, of the unsupplemented cows ($r^2 = 0.32$), as follows (Equation 2.4):

$$SR = 0.32 + 0.01\ EB \qquad (\text{rsd} = 0.19,\ n = 48) \qquad (2.4).$$

According to this relationship, substitution rate is reduced when cows are in lower net energy balance. A substitution rate of 0.1 for example, is estimated when energy balance is –21 MJ d^{-1}, increasing to 0.6 when energy balance is 28 MJ d^{-1}.

Efficiency of supplementation is similarly closely related to the proportion of the animal's requirements that are met from herbage alone. In a review of 95 experiments, Delaby and Peyraud (unpublished, as cited by Peyraud and Delaby, 2001) characterised the severity of grazing conditions by calculating the difference between actual milk yield of unsupplemented cows and their expected milk yield. It was assumed that the greater the difference between actual and expected milk yield, the more adverse the grazing conditions. A good relationship was observed between the difference between expected and actual milk yield and milk yield response to concentrates ($r^2 = 0.69$). This compares to a linear but much more variable positive relationship between milk yield response and concentrate allowance ($r^2 = 0.27$). From their calculations, efficiency of supplementation is estimated to be only 0.3 when energy requirements are met for pasture alone, increasing to 0.9 when grazing conditions are less favourable.

Neaves *et al.* (1996) estimated substitution rate from measurements of herbage intake prior to concentrates being offered, and concentrate intake. These variables could provide an indication of potential herbage intake from a sward, as well as the animals nutritional requirements and energy balance. A regression equation was derived from 9 experiments when high starch concentrates were fed and the DM digestibility of pasture exceeded 0.7 (Equation 2.5):

$$SR = 0.313\ (PI + CI/2) - 0.48 \qquad (2.5)$$

where PI = pasture intake prior to concentrates being offered (kg DM 100 kg^{-1} live weight) and CI = concentrate intake (kg DM 100 kg^{-1} live weight). This relationship was valid for values of $PI + CI/2$ of between 1.5 and 4.0 (Neaves *et al.*, 1996).

Energy balance is affected by herbage intake, which explains lower substitution rates, and higher milk yield responses observed in experiments when herbage availability is reduced (Delaby *et al.*, 2001; Meijs and Hoekstra, 1984). Absence of an effect of increasing concentrate allowance on herbage intake and grazing behaviour observed by Gibb *et al.* (2002b) when cows grazed swards maintained at a height of 7 to 8 cm, could therefore be a consequence of potential intake which is insufficient to meet the animals nutritional requirements.

Animal production responses to concentrate, and substitution of herbage can therefore be affected by potential for milk production and milk yield level (Dillon *et al.*, 1999; Hoden *et al.*, 1991). However, whether or not an effect of supplementation on milk production or herbage intake is observed, is dependant upon interactions between concentrate allowance, grazing conditions, and the ability of cows to meet their nutritional requirements from grazing (Delaby *et al.*, 2001; Peyraud and Delaby, 2001; Pulido and Leaver, 2001).

2.8.5 Type of concentrate supplement

Milk production from grazing cows can be limited by the low energy content of grass resulting in a low energy compared to protein supply to the animal, and the imbalance in supply of rumen fermentable carbohydrate and RDP (Reis and Combs, 2000). Concentrates can increase energy and protein intake of grazing cows, as well as improve synchrony of their supply to the rumen and animal. Concentrate type can therefore interact with concentrate allowance, and also animal and sward factors, to determine responses of grazing cows to supplementation. In particular, animal performance and intake can be affected by concentrate energy source and the level and type of protein supply (Gibb *et al.*, 2002a; Sayers *et al.*, 2000).

2.8.5.1 Concentrate energy source

Results from some experiments that demonstrate effects of concentrate energy source on milk production and herbage intake are presented in Table 2.16.

Table 2.16 Effects of concentrate energy source on milk production and herbage intake

	Concentrate					Animal Performance			Herbage intake
	Energy source	kg DM d^{-1}	Starch (g kg DM^{-1})	Sugar (g kg DM^{-1})	NDF (g kg DM^{-1})	Milk yield (kg d^{-1})	Fat (g kg^{-1})	Protein (g kg^{-1})	kg d^{-1}
Gibb *et al.* (2002a)									
Experiment 1	$DC^{\S}$	$6.11^{\dagger}$	29.9	98.5^{α}	267.6	23.3	36.8a	30.9	13.3^{*}
	HP^{Ω}	$6.02^{\dagger}$	37.6	124.5^{α}	220.9	21.1	40.2a	31.8	11.1^{*}
	Starch	$6.72^{\dagger}$	81.7	65.5^{α}	172.8	21.0	25.7b	33.4	9.1^{*}
Experiment 2	$DC^{\S}$	$7.92^{\dagger}$	29.9	98.5^{α}	267.6	23.2	34.8a	32.9	11.5^{*}
	HP^{Ω}	$7.75^{\dagger}$	37.6	124.5^{α}	220.9	19.8	35.9a	33.1	9.8^{*}
	Starch	$7.79^{\dagger}$	81.7	65.5^{α}	172.8	19.3	27.3b	34.3	7.6^{*}
	Fibre	$7.38^{\dagger}$	27.1	244.0^{α}	301.5	20.5	36.5a	33.0	9.1^{*}
Sayers *et al.* (2000)	Starch	5.0	470	74^{α}	146	31.6	36.6	33.7	12.6
	Fibre	5.0	62	216^{α}	244	31.7	39.4	33.0	13.4
	Starch	10.0	470	74^{α}	146	34.6	29.9	35.5	9.5
	Fibre	10.0	62	216^{α}	244	35	36.2	33.4	10.9
Khalili and Sairanen (2000)	Starch	3.5	$600^{\#}$		245	19.7	38.5	34.2	
	Fibre	3.5	$366^{\#}$		350	21	37.6	34.9	
Fisher *et al.* (1996)	Starch	4.4				23.7	39.4	30.3	12.6
	Fibre	4.4				24.7	40.7	30.3	13.5
Schwarz *et al.* (1995)	Fibre ($MSBP^{\Phi}$)	5.53		227	328	20.8	39.7	33.1	12.1
	Starch (maize)	4.77	631		247	22.4	38.1	33.0	12.6
	Starch (cereal)	5.40	411		255	22.9	39.5	32.9	11.8

* Results presented as OM; † Fresh weight; $^{\alpha}$ Water soluble carbohydrate; $^{\#}$ Starch plus sugar; § DC, Standard dairy concentrate;

$^{\Omega}$ HP, High protein concentrate, $^{\Phi}$ MSBP, Molassed sugar beet pulp

(Continued over)

Table 2.16 Effects of concentrate energy source on milk production and herbage intake (continued)

	Concentrate					Animal Performance			Herbage intake
	Energy source	kg DM d^{-1}	Starch (g kg DM^{-1})	Sugar (g kg DM^{-1})	NDF (g kg DM^{-1})	Milk yield (kg d^{-1})	Fat (g kg^{-1})	Protein (g kg^{-1})	kg d^{-1}
Valk *et al.* (1990)									
Equal concentrate DM	Starch	6.2	468	22	257	28.4	39.2	34.8	11.2
	Fibre	6.2		100	465	25.8	41.5	34.3	10.9
Equal concentrate ME	Starch	7.0	567	42	103	31.6	37	32.7	12.2
	Fibre	6.7		119	372	30.9	41.9	33.2	12.0
Meijs (1986)									
Herbage intake experiments	Starch	5.5*	267	94	268				11.5
	Fibre	5.3*	26	73	478				12.6
Milk production experiment	Starch	5.5*	275	83	277	25.6	39.6	34	9.9
	Fibre	5.4*	36	66	461	26.9	41	33.7	10.5
van Vuuren *et al.* (1986)	Starch	0.9	258	104	259	19.3	41	33	
	Starch	6.1	258	104	259	20	38	35	
	Fibre	6.3	15	79	495	18.9	41	33	

* Results presented as OM; † Fresh weight; α Water soluble carbohydrate; # Starch plus sugar; § DC, Standard dairy concentrate;

Ω HP, High protein concentrate, Φ MSBP, Molassed sugar beet pulp

Energy supplements provide an opportunity to improve the balance between the high quantities of rumen degradable N found in herbage, compared to rumen fermentable energy supply (Beever *et al.,* 1986). Improved synchrony of energy and N supply could potentially increase microbial capture of ruminally degradable N, and reduce ruminal ammonia concentrations (Kolver *et al.*, 1998; Reis and Combs, 2000; van Vuuren *et al.,* 1986). However, these effects are minimal and effects of synchrony of energy and N supply with grazing cows are difficult to prove. High inputs of quickly fermentable substrates such as starch on the other hand, can increase concentrations of VFA and lactate in the rumen, and so reduce rumen pH (Sutton *et al.*, 1987). This in turn can reduce cellulolytic activity of microbes in the rumen, resulting in a lower rate of breakdown of fibrous particles and reduced digestibility of forage (Arriaga-Jordan and Holmes, 1986a; Russell and Wilson, 1996). As a result, increased rumen fill with non-fermented residues can restrict intake of more food.

It is important therefore to consider not only the quantity of supplementary energy, but also the type of carbohydrate supply. Improved milk yield responses to concentrate supplementation have been reported when the concentrate contains a source of energy which is higher in fibre and lower in starch (Fisher *et al.*, 1996; Khalili and Sairanen, 2000; Meijs, 1986; Schwarz *et al.*, 1995). Increased levels of milk production with a higher fibre concentrate have been accompanied by increases in milk fat content (Fisher *et al.*, 1996; Meijs, 1986), but lower milk protein concentrations (Gibb *et al.*, 2002; van Vuuren *et al.*, 1993).

Substitution rate can also be lower when a more fibrous energy source is offered (Fisher *et al.*, 1996; Gibb *et al.*, 2002; Schwarz *et al.*, 1995). Herbage intake experiments conducted by Meijs (1986), demonstrated mean substitution rate was reduced to 0.21 compared to 0.45 kg herbage OM kg^{-1} concentrate OM, by feeding the high fibre compared to high starch supplement. Fisher *et al.* (1996) and Kibon and Holmes (1987) also reported an increase in herbage intake when a high starch concentrate was replaced with a higher fibre concentrate. Similarly, Gibb *et al.* (2002a) found offering cows 8 kg FW d^{-1} of a high starch concentrate reduced herbage intake, compared to a more fibrous concentrate or a standard dairy concentrate. In their experiments, the high starch concentrate reduced total grazing time d^{-1} but had no effect on short-term intake rate, bite rate, or bite mass. Despite a reduction in herbage intake, treatment had no effect on total ruminating time, which indicates an increased ruminative requirement for cows offered the high starch supplement. Gibb *et al.* (2002a) suggest this could be a consequence of a requirement for the animals to increase production of saliva to ameliorate rumen acidity caused by a starchy supplement.

More recently, Sayers *et al.* (2000) reports a significantly higher herbage intake with a high fibre compared to high starch supplement and, with the exception of the period from 1 May to 5 June, the high starch concentrate produced a higher substitution rate than the high fibre supplement over the season. This increase in herbage and total DM intake was not accompanied with an increase in milk yield, however increased energy intake could have contributed to improved milk composition.

Greater responses from more fibrous energy sources however have not always been found. A higher milk yield response (Schwarz *et al.*, 1995; van Vuuren *et al.*, 1986) accompanied by increased herbage intake (Valk *et al.*, 1990) has been reported for higher starch concentrates. The effects of concentrate energy source can be affected by degradability of the starch sources in the concentrate. Cereal grains for example, provide rapidly degradable starch which is more than 90 percent ruminally fermentable, compared to maize starch which has a lower rumen degradability of between 70 and 80 percent (Orskov, 1986). The less degradable maize starch used by Schwarz *et al.* (1995) and Valk *et al.* (1990) and less degradable starch in the mixture of ingredients used by van Vuuren *et al.* (1986) could explain some of the beneficial effects of the higher starch concentrates observed in these studies. A negative effect of a high starch supplement may therefore not be apparent if less rapidly fermentable starchy ingredients are used, and a starchy concentrate may actually improve rumen conditions by providing a better energy supply than much less degradable fibrous ingredients. Reis and Combs (2000) for example, report no effect of supplementation of grazing cows with up to 10 kg DM d^{-1} of a maize based concentrate, on rumen pH or digestibility of fibre. The difference between starch and fibre energy sources is also lower when the fibrous concentrate is based on sugar beet pulp or citrus pulp which are sources of rapidly fermentable pectin, and hence there is less difference in total starch plus sugar content (Peyraud and Delaby, 2001).

In terms of milk composition, readily fermentable starch is generally considered to reduce the acetate to propionate ratio, and hence milk fat, to a greater extent than high fibre concentrates or those containing less fermentable starch (Peyraud and Delaby, 2001; Schwarz *et al.*, 1995).

Energy source has limited effects on milk production or herbage intake when only moderate amounts of concentrate are fed. Peyraud and Delaby (2001) suggest the nature of the energy source does not necessarily cause enough digestive perturbations to affect animal performance when less than 5 kg DM concentrate d^{-1} is offered. Information regarding effects of offering high levels of concentrate to high yielding grazing cows is limited but Sayers *et al.* (2000) found an increase in milk fat and depression in milk protein with a higher fibre concentrate fed to cows yielding above 30 kg milk d^{-1}. This effect was more evident as proportion of supplement in the diet increased, and concentrate intake increased from 5 to 9.9 kg DM cow d^{-1}. Cows offered the higher feed level in this experiment however had their concentrate allowance split into three feeds and it might be speculated that this would reduce effects of a high starch concentrate on rumen conditions (Russell and Wilson, 1996).

Sward characteristics and herbage availability could interact with the response to different concentrate types. Supplementation has larger effects on rumen digestion when herbage allowance is high (Peyraud and Delaby, 2001), and so effects of concentrate energy source could also be greater when herbage availability is high. The level of concentrate required to affect rumen fermentation is expected to be lower when the content of soluble material in herbage, and in particular sugar and N, is high (Meijs, 1986). It might be expected therefore that the higher the leaf content, and higher the quality and digestibility of herbage selected by the cow, the greater the effect of highly-fermentable starch on ruminal digestion and milk fat content (Peyraud and Delaby, 2001). Compared to cows grazing pasture, zero-grazed animals have less opportunity for selection of herbage of higher quality than the average of that on offer (Stakelum, 1986b). Lower digestibility and a lower rapidly fermentable carbohydrate content of herbage consumed by zero-grazed cows could explain the positive effect of supplementation with a rapidly degradable cereal-based starch concentrate, compared to a fibrous concentrate, on their milk production (Schwarz *et al.*, 1995).

The evidence suggests therefore that the effect of different carbohydrates on milk production and herbage intake is dependent upon level of concentrate feeding and herbage availability, which affects the ratio of herbage to concentrate in the diet. Additionally, effects of concentrate energy source are dependent upon the composition of herbage on offer, and quality of herbage selected by the cow. Starchy concentrates however are generally more likely to cause inappetence and a disruption to grazing activity and reduction in daily herbage intake.

2.8.6 Protein supplementation

When cows are grazing high quality pasture, milk production is most often limited by energy intake compared to protein supply (Kolver *et al.*, 1998; Mayne *et al.*, 2000; Peyraud and Delaby, 2001). Responses to additional protein however have been obtained when pasture quality is poor, cows are in early lactation or high yielding, or when there are high levels of grain supplementation (Neilsen *et al.*, 2002; Kellaway and Porta, 1993 as cited by Hongerholt and Muller, 1998).

It has been calculated that duodenal protein supply to dairy cows from grazed pasture is adequate to meet requirements for up to 25 kg milk d^{-1} (Beever and Siddons, 1986). Neilsen *et al.* (2002) reported a reduction in milk yield from 27.0 to 25.2 kg d^{-1} when cows were offered a low protein supplement containing 110 g CP kg^{-1} DM, compared to a supplement containing 170 g CP kg^{-1} DM. High yielding and early lactation cows were most sensitive to this reduction in CP level and so they suggest N utilisation can be improved by varying the supplement CP concentration according to yield and stage of lactation. Hongerholt and Muller (1998) suggest high yielding dairy cows, producing 35 to 40 kg milk d^{-1} in early lactation, require diets that contain 16 to 18 percent CP on a DM basis, and total dietary protein supply should contain around 37 to 38 percent RUP.

A source of RUP in the diet is important to supply post-ruminal protein and amino acids to complement microbial protein supply (Beever *et al.*, 2000). Since a large proportion of protein in herbage is rapidly degradable in the rumen, protein supplements, and in particular those high in RUP, could enhance production. Hongerholt and Muller (1998) reviewed four studies which all involved feeding high

RUP supplements to grazing cows yielding between 9.6 to 18 kg milk d^{-1}. Supplementation with protected casein increased milk yield by between 0.5 and 2.4 kg d^{-1}, while RUP supplements increased milk protein concentration in three of the studies. O'Mara *et al.* (2000) also found supplements of RUP can increase milk and protein yields. When cows were offered 1.25 kg d^{-1} of beet pulp, or concentrates based on either fishmeal or protected soya, milk yields were 17.3, 18.0, and 18.6 kg d^{-1} respectively (O'Mara *et al.*, 2000). O'Mara (1991) offered grazing cows 0.5 kg d^{-1} of either a barley, beet pulp or maize gluten concentrate, with or without a feed additive designed to reduce dietary protein degradability. The additive gave a significantly higher milk and milk protein yield despite the low level of supplement offered, and therefore appears to have increased supply of RUP to the animal and improved dietary N utilisation. Herbage and microbial protein become less likely to satisfy requirements with increasing levels of milk production. Hongerholt and Muller (1998) fed a high or low RUP concentrate at a rate of 1 kg per 4 kg milk d^{-1}, to grazing cows yielding 39.8 kg milk d^{-1} at the start of experiment. Mean daily milk yields for all cows did not differ significantly between treatments; 34.2 and 35.5 kg d^{-1} for the low and high RUP concentrates respectively. Multiparous cows however tended to yield more milk and milk protein when fed the high RUP concentrate, 36.2 compared to 34.5 kg milk d^{-1}, and 1.06 kg compared to 0.98 kg protein d^{-1}. Concentration of plasma urea was unaffected by treatment. This experiment therefore tends to suggest a slight positive effect of feeding higher levels of RUP to high yielding cows.

Others however report limited effects of supplementary protein on milk production. Gibb *et al.* (2002a) found no advantage in providing a source of highly digestible RUP and increasing total concentrate CP content above 180 g kg^{-1} FW, on either milk production, herbage intake, or grazing behaviour, suggesting cows already had a sufficient protein supply. Tesfa *et al.* (1995) offered rotationally grazing cows concentrates at a rate of 0.3 kg concentrate kg $milk^{-1}$. A basic dairy concentrate (control) contained 12.4 percent CP, and other supplements were formulated by addition to the control of either 0.9 percent urea, 12 percent rapeseed meal, or heat treated concentrate plus 12 percent heat treated rapeseed meal. No significant differences were observed in energy corrected milk yields, which were 27.4, 26.9, 27.1, and 27.7 kg d^{-1} for the four treatments respectively. Milk protein concentration tended to be higher on the urea treatment compared to either of the rapeseed meal treatments. It is possible that heat treatment of concentrate in this experiment lowered rumen available energy below what is required for optimal protein synthesis by rumen microbes, and additional protein may have been used as an energy source.

Response to protein supplementation can be affected by the CP content of herbage. Increases in both milk production (Delaby *et al.*, 1996) and herbage intake (Delagarde *et al.*, 1999) have been reported when herbage CP is reduced, for example when N fertilisation is low, or during summer grazing. Delaby *et al.* (1996) described milk yield response when an increasing supply of MP was provided by replacing 3 kg wheat with protected soya bean meal. On a highly fertilised sward and when CP content was greater than 160 g kg DM^{-1}, protein supplementation slightly increased milk yield. On a sward with a lower level of N fertilisation however when herbage CP content was less than 130 g kg DM^{-1}, milk production response was much greater.

It is possible that an improved nutrient supply to the rumen and the animal, by increasing RUP or reducing the amount of surplus N in the rumen, may improve voluntary herbage intake. Hongerholt and Muller (1998) found cows fed a high RUP mixture also tended to have a higher DM intake. Replacement of a carbohydrate concentrate by protected soya bean meal has increased herbage intake on a low N sward (Delagarde *et al.*, 1999). In their study, Delagarde *et al.* (1999) reported herbage intake increased by 0.8 kg DM kg^{-1} concentrate DM when cows grazed swards of less than 140 g CP kg^{-1} DM. Herbage digestibility, rumen ammonia, VFAs, and blood urea concentrations were increased. Protein supplementation therefore promoted herbage intake when herbage CP concentration was low by improving rumen digestion due to the input of N (Table 2.17). In contrast, supplementing cows with protected soya bean meal did not affect herbage intake on swards with a CP concentration higher than 160 g kg^{-1} DM (Delagarde *et al.*, 1997).

Table 2.17 Effect of energy and protein supplementation on herbage intake and digestion on a low CP sward (adapted from Delaby *et al.*, 1999, and cited by Peyraud and Delaby, 2001)

	No concentrate	Cereal-based concentrate	Soya-bean meal
Concentrate intake (kg DM d^{-1})	0	2.8	2.8
Grass intake (kg DM d^{-1})	14.6	14.9	17.2
Herbage digestibility	0.77	0.76	0.79
Rumen VFA (mmoles l^{-1})	99	101	111
NH_3 (mg l^{-1})	11	11	21
Protein flowing into duodenum (kg d^{-1})	2.2	2.5	3.5
Milk yield (kg d^{-1})	19.6	22.0	24.8

Protein supplementation can therefore increase milk production by alleviating a shortfall in MP supply, and also by increasing nutrient intake through promotion of herbage intake. This effect is particularly evident when sward CP content is low, and with higher producing animals.

2.8.7 Concentrate supplementation strategies

Supplementation of grazing cows to achieve efficient and economically viable production responses is dependent upon interactions between many variables. Herbage allowance and availability affect responses to supplementation and so prediction of potential herbage intake and milk production from a sward could assist in determining appropriate levels and types of supplementation for grazing cows. Leaver (1982) for example, used sward height as an indicator of when concentrates should be offered to continuously grazed cows. Concentrates were introduced when sward height fell below 9, 7, or 5 cm at a rate of 1 kg d^{-1} for each 0.2 cm decline below these threshold levels. Mean concentrate intakes for the 3 treatments respectively were 3.3, 1.7 and 1.4 kg d^{-1}; and mean daily milk yields were 17.7, 16.0, and 15.0 kg.

Recommendations for levels of concentrate supplementation which take into consideration potential milk production from grass as well as milk production potential of the cow, or target milk yield, have been proposed by Mayne *et al.* (2000) (Table 2.18).

Table 2.18 Suggested concentrate feeding levels for high yielding dairy cows in early and late season offered moderate herbage allowance (20 kg DM cow^{-1} d^{-1} assessed above 3.5 cm, equating to residual sward height in rotational grazing of 8 cm) (Mayne *et al.*, 2000)

	Early season target milk yield (kg cow^{-1} d^{-1})			Late season target milk yield (kg cow^{-1} d^{-1})	
	25.0	35.0	40.0	25.0	35.0
Potential milk yield from grass (kg d^{-1})†	27.0	29.4	30.9	20.0	24.5
ME required from supplement (MJ d^{-1})‡	0	28.0	45.5	25.0	52.5
Supplement feed level required (kg cow^{-1} d^{-1}) §	0	4.5	7.0	4.0	8.5

† Assumes increase in herbage intake of 0.125 kg DM kg^{-1} milk; ‡ ME required for milk production of 5.0 MJ kg^{-1} milk; § substitution rate 0.4 kg herbage DM kg^{-1} supplement DM, ME concentration of herbage and supplement 12.0 MJ kg^{-1} DM

Components of a decision support model for supplementing concentrates to grazing cows are summarised in Figure 2.1 (Neaves *et al.*, 1996).

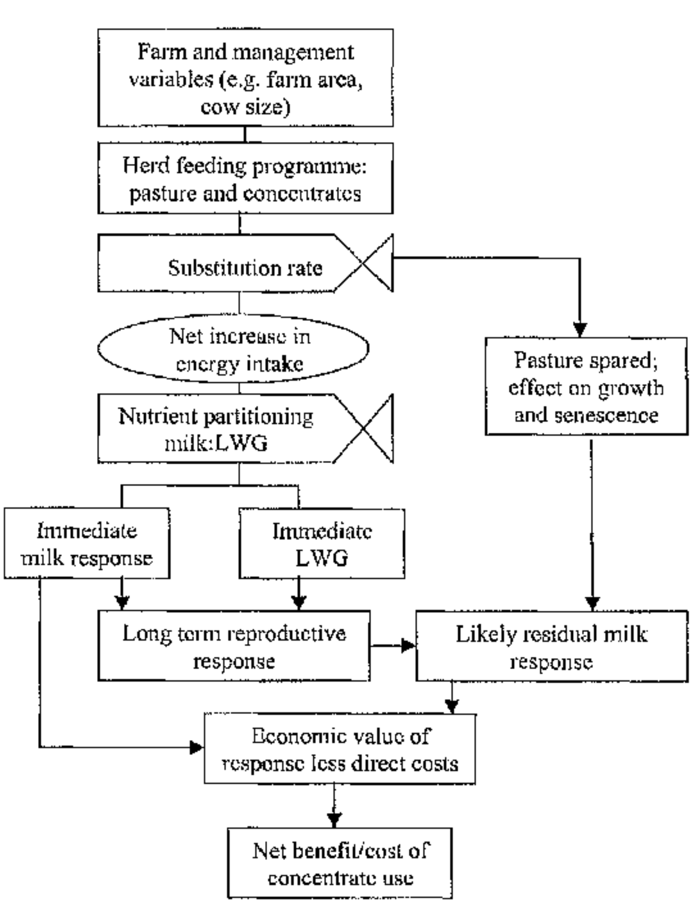


Figure 2.34 Components of a decision support model for the feeding of concentrates to lactating cows grazing pasture (Neaves *et al.*, 1996)

As well as direct and immediate effects of supplementation on herbage intake and milk production, effects of supplementation on live weight and body condition (Delaby *et al.*, 2001); which can affect health, welfare, and fertility (Pryce *et al.*, 2001), must be taken into account. There can also be residual milk yield responses to concentrate supplementation (Ferris *et al.*, 1999a). The value of herbage that is spared as a result of substitution for concentrate should also be considered, and reduced intake from a sward could also potentially affect herbage growth and production, and alter sward characteristics (Lemaire and Chapman, 1996). Overall, the net benefit or cost of supplementation must consider the economic value of these responses less direct costs of supplementation.

2.9 CRITICAL SUMMARY OF THE LITERATURE AND RATIONALE FOR FURTHER WORK

Milk production from grazed pasture is dependant upon herbage intake, the nutritional value of herbage selected, and the animal's genetic merit and milk production potential (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000). Sward and animal behavioural characteristics however restrict herbage intake, and these are major factors limiting milk production from grazed pasture (Pulido and Leaver, 2001; Rook, 2000).

Potentially high yielding dairy cows have increased energy and nutrient requirements to support higher levels of milk production. With increasing genetic merit for milk production there is also a change in nutrient partitioning towards milk production at the expense of liveweight gain, and increased tendency for body tissue mobilisation to support higher energy requirements (Agnew *et al.*, 1998; Buckley *et al.*, 2000b; Veerkamp *et al.*, 1994). The major challenge when managing potentially high yielding dairy cows at pasture is therefore to achieve high enough levels of intake to enable them to reach their production potential, and to avoid a shortfall in energy requirements being made up from excessive mobilisation of body reserves.

Levels of herbage intake of up to 20.7 kg DM d^{-1} have been recorded (Buckley and Dillon, 1998), which suggests grazed herbage is theoretically capable of supporting 38 kg milk d^{-1} (assuming ME requirements for maintenance 70 MJ d^{-1}, and milk 5.2 MJ kg^{-1}; and herbage ME content of 12.0 MJ ME kg DM^{-1}, AFRC, 1993). Under ideal spring grazing conditions others report grazed pasture has potential to support between 27 and 33 kg milk d^{-1} (Mayne, 2001; Peyraud and Gonzalez-Rodrigez, 2000). Such high levels of performance however are rarely observed in practice. Cows require supplementation if they are to sustain levels of milk production above what is possible from grazed herbage alone. Concentrate supplements of a high nutrient density provide the most appropriate form of supplementation for high genetic merit, high yielding cows if they are to achieve high levels of DM intake (McGilloway and Mayne, 1996). There is limited information available in the literature however to enable development of grazing management and supplementation strategies for high yielding cows producing in excess of approximately 30 kg milk d^{-1}.

Milk production response to concentrate supplementation is variable. The majority of evidence demonstrates that higher milk yield responses are achieved from cows with higher milk production potential (Dillon *et al.*, 1999), and when herbage allowance is low (Meijs and Hoekstra, 1984). As the level of concentrate fed increases, response to additional increments of concentrate will decline and reach a plateau as the animal meets its energy and nutrient requirements (Delaby *et al.*, 2001). Response is therefore dependent upon the difference between herbage intake potential of the sward and the animal's nutrient requirements to support its potential level of production. Further research is required however to quantify effects of sward characteristics on herbage intake and examine their interactions with supplementation.

Additionally, the type of concentrate offered can affect milk production responses to supplementation. High inputs of rapidly degradable carbohydrate can disrupt the rumen environment and reduce activity of rumen microbes (Arriaga-Jordan and Holmes, 1986a). This can lower the rate of passage of material through the rumen, and potentially restrict further herbage intake. Different energy sources however have been fed to grazing animals with varying results (Gibb *et al.*, 2002a; Schwarz *et al.*, 1995). There could be an effect of the quantity and type of ingredients fed, and interactions with sward factors; in particular herbage quality and potential herbage intake, and animal factors such as nutritional requirements. While energy tends to be limiting to animal performance at grazing, there can be production responses to protein supplementation. In particular, high producing animals with high protein requirements can increase their milk production when provided with an additional source of RUP (Hongerholt and Muller, 1998). Effects of concentrate formulation for supplementation of high yielding cows therefore requires further investigation.

It is well recognised that herbage intake increases with higher levels of herbage allowance (Greenhalgh *et al.*, 1966; Le Du *et al.*, 1979; Stakelum, 1986b; Stakelum, 1986c). More recent evidence highlights the importance of sward structural characteristics on herbage intake, and especially sward surface height (Gibb *et al.*, 1997; Pulido and Leaver, 1997; Rook *et al.*, 1994a), sward density (Mayne *et al.*, 1997; McGilloway *et al.*, 1999), and green leaf mass (Parga *et al.*, 2000). Cows can alter aspects of their grazing behaviour according to sward characteristics and their intake requirements, to support their production potential. In particular, they can increase grazing time and bite rate to compensate for low bite mass (Gibb *et al.*, 1999; McGilloway *et al.*, 1999). Grazing time and bite rate however reach a plateau at between 9 and 10 hours d^{-1}, and approximately 60 bites min^{-1} (Phillips and Leaver, 1986; Rook and Huckle, 1996; Rook *et al.*, 1994). High yielding cows are more likely to reach these behavioural constraints as they attempt to meet their high intake requirements. Bite mass is therefore a particularly important determinant of herbage intake and milk production from grazed pasture when the aim is to achieve high levels of herbage intake. Further exploration of interactions between bite mass, sward structure and animal characteristics, is required to quantify potential levels of herbage intake from a sward.

Descriptions of sward characteristics known to affect bite mass could improve prediction of herbage intake from a sward. In particular, little attempt has been made to describe the vertical distribution of herbage mass through the sward and to examine effects of this distribution on intake. Evidence suggests cows bite to a depth equal to a constant proportion of sward surface height (Barrett *et al.*, 2000; Wade *et al.*, 1989). Sward surface height and the vertical distribution of mass within the sward are therefore expected to have a significant effect on bite mass. Information regarding the vertical distribution of herbage mass could therefore be utilised to predict potential bite mass and herbage intake from a sward at specified bite dimensions.

Mean measurements of sward structure, such as average sward height and bulk density, can conceal variability across the grazed area. Spatial heterogeneity in sward structure and the selection behaviour of cows between patches of different structure, is in particular likely to have a significant influence on mean bite mass and intake from a sward (Schwinning and Parsons, 1999; Swain, 2000). The impact of spatial heterogeneity in sward structure on aspects of grazing behaviour therefore requires further investigation. Progress in understanding sward and animal interactions is dependent upon methodologies to measure grazing behaviour and components of herbage intake. Automatic behaviour recording equipment is now relatively well established for recording the temporal pattern of grazing activity, grazing times and bite rates (Laca and Wallis De Vries, 2000; Rutter, 2000; Rutter *et al.*, 1997). Methods of obtaining detailed measurements of grazing behaviour and intake, and in particular bite mass, within patches of a grazed sward however require further development to investigate and quantify sward-animal interactions.

Overall, there is a need for further investigation of interactions between milk production from pasture and sward characteristics, supplementation, grazing behaviour, and herbage intake. The main objective of the following study is to contribute to the development of strategies to achieve high levels of milk production from dairy cows at pasture, which optimise the contribution of grazed herbage and make efficient use of concentrate supplements.

Specific aims of the study are:

1. To investigate effects of different concentrate supplementation strategies on milk production, grazing behaviour and herbage intake.
   a) To study effects of offering high levels of concentrate to grazing cows during the late summer period, when milk production response might be enhanced as a consequence of deteriorating herbage and sward quality.
   b) To investigate effects of supplementation of high yielding cows with different energy sources, and the potential of reducing dietary protein degradability to improve response to supplementation, over the grazing season.

2. To investigate the effects of sward structure on herbage intake.

a) To make detailed measurements of vertical distribution of herbage mass from swards under different simulated grazing systems; and to examine relationships between sward height, mass, and the vertical distribution of mass in the sward.

b) To predict effects of vertical distribution of herbage mass on bite mass from these descriptions of sward structure and estimates of bite dimensions.

3. To examine interactions between sward structure and animal behaviour with grazing cows.

a) To explore potential to develop a methodology to make detailed measurements of grazing activity and herbage intake within patches of a grazed sward using a combination of sward and grazing behaviour measurements, and recordings of the animals spatial location.

b) To estimate mean bite mass from a grazed sward using this methodology, within different time periods over the day.

CHAPTER 3.0 EXPERIMENT 1

Effects of supplementing grazing dairy cows with high levels of concentrates over the late summer and housing period, on animal performance, herbage intake and grazing behaviour

3.1 INTRODUCTION

Under ideal grazing conditions, grazed grass can support up to between 27 and 33 kg milk d^{-1} in spring, declining to 25 kg milk d^{-1} in autumn (Mayne, 2001; Mayne *et al.*, 2000). When potential levels of milk production exceed this level, or where optimal sward conditions are not available, concentrate supplementation can enable grazing cows to perform closer to their production potential. Animal production responses to concentrate supplementation at pasture however are extremely variable (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000). Milk production response is highly dependant upon the effect of concentrates on herbage intake, and in particular the rate of substitution of herbage for concentrate (Pulido and Leaver, 2001). Substitution rate and milk production responses to supplementation are affected by interactions between the animal's nutritional requirements, and hence production potential, as well as its potential energy and nutrient intake from the sward (Peyraud and Delaby, 2001). A lower substitution rate and greater milk yield response to supplementation is expected from cows that are unable to meet their intake requirements from herbage alone (Delaby *et al.*, 2001). Efficiency of concentrate supplementation for milk production for example, is greater from cows with a high milk production potential (Dillon *et al.*, 1999; Hoden *et al.*, 1991; Peyraud *et al.*, 1998), and when sward characteristics do not enable them to meet their intake requirements from grazing (Gibb *et al.*, 2002b; Meijs and Hoekstra, 1984).

High responses to supplementation of above 1 kg milk kg^{-1} concentrate dry matter (DM) have been achieved when cows have been offered up to 5.4 kg d^{-1} concentrate DM (for example, Delaby *et al.*, 2001; Gibb *et al.*, 2002b; Wales *et al.*, 1999; Wilkins *et al.*, 1994). Few experiments are reported when higher levels of concentrate have been offered, although Sayers *et al.* (2000) and Reis and Combs (2000) have found relatively high efficiencies of up to 0.86 kg milk kg^{-1} concentrate DM, when grazing cows were fed up to 10 kg DM concentrate d^{-1}.

Potential herbage intake and the nutritional value of herbage in the sward generally decline as the grazing season progresses. A decrease in herbage growth rate (Orr *et* *al.*, 1988) can result in a reduction in herbage availability and herbage allowance, which can restrict herbage intake and so increase efficiency of supplementation (Grainger and Mathews, 1989; Meijs and Hoekstra, 1984). Sward characteristics associated with late season swards, such as a decline in sward height and an increase in the proportion of stem, can limit potential bite mass and reduce herbage intake (Gibb *et al.*, 2002b; Peyraud and Gonzalez-Rodrigez, 2000). An increase in heterogeneity and the proportion of infrequently grazed patches in the sward, which are associated with later season grazing (Connell and Baker, 2002), can similarly reduce mean bite mass and herbage intake potential (Connell and Baker, 2002; Givens *et al.*, 1993; Swain, 2000). Progression of the season, increasing herbage maturity, and greater sward structural heterogeneity is also associated with a decline in nutritional quality of herbage (Beever *et al.*, 2000). In particular, a reduction in herbage digestibility and ME content will reduce the nutritional value of herbage consumed from later season swards (Givens *et al.*, 1993).

Lower potential milk production from pasture later in the season could therefore be associated with larger milk yield responses to supplementation (Peyraud and Delaby, 2001). Furthermore, although marginal efficiency of supplementation declines when increasing amounts of concentrate are fed (Delaby *et al.*, 2001), responses to higher levels of concentrates could be apparent in late season when potential nutrient intake from the sward is reduced. Towards the end of the grazing season, the transition from the grazing to housing period can place further stress on animals as they adapt to a new nutritional and management regime. Additional concentrate supplementation over this period could help avoid negative effects on animal performance.

This experiment was conducted to highlight factors that affect the efficiency of responses to concentrate supplementation, and to set the context for further work. Specific objectives of the study were;

- To investigate effects of offering high levels of concentrates to lactating, grazing dairy cows in late summer, on animal performance and grazing behaviour.
- To examine responses in animal performance to increasing the amount of concentrate offered over the housing period.

3.2 MATERIALS AND METHODS

3.2.1 Experimental design

The experiment was conducted over a 9-week period from 13 August to 14 October 1999. Treatments were applied according to a continuous factorial design and the experiment was split into two stages, during which cows were fed different levels of concentrate.

3.2.2 Animals and treatments

Forty-eight multiparous Holstein-Friesian cows on average 65 ± s.e.m. 1.8 days in milk, yielding 36.8 ± 0.65 kg milk d^{-1}, and with a mean Profitable Lifetime Index (PLI) value of £64 ± 2.9 were used in the experiment. Average lactation number of the cows was 3.8 ± 0.29, and animals had a mean live weight of 610 ± 6.9 kg, and condition score of 2.16 ± 0.05. Cows were blocked into groups of 6 on the basis of milk yield in the week prior to the start of the experiment, days in milk, and lactation number, and then allocated at random from groups to one of 6 treatments.

Prior to commencing the experiment, cows were continuously grazed as a single group and offered 5.3 kg DM d^{-1} of a cereal-based dairy concentrate split between morning and afternoon milkings.

Stage 1 of the experiment began on 13 August for 5 weeks, and Stage 2 continued for 4 weeks from 17 September to 14 October. Treatment groups were offered different levels of concentrates according to **Table 3.1**.

Table 3.1 Concentrate offered per treatment, T1-T6 (kg FW cow^{-1} d^{-1})

	Concentrate treatment					
	T1	T2	T3	T4	T5	T6
Stage 1	6	6	9	9	12	12
Stage 2	6	8	9	11	12	14

During Stage 1, cows were fed 6, 9, or 12 kg fresh weight (FW) concentrate d^{-1} and grazed separately in these 3 concentrate treatment groups. For the duration of Stage 2, cows were housed overnight. Concentrate was increased by 2 kg FW d^{-1} for one of the treatments in each of the three main groups of Stage 1 (T2, T4, and T6), and silage was offered *ad libitum* overnight. Cows were grazed and housed in 3 separate groups as in Stage 1.

Concentrate amounts of 8 kg FW d^{-1} or less were fed to individual cows through the parlour, split equally between morning and afternoon milkings at approximately 07:00 and 14:30 h. Cows offered more than 8 kg concentrate d^{-1} had concentrate split equally between three meals all fed through the parlour, at morning and afternoon milkings, and at 11:00 h when cows were not milked.

3.2.3 Concentrate composition

Ingredient composition of the concentrate fed is detailed in Table 3.2.

Table 3.2 Ingredient composition of concentrate fed

	g kg^{-1} FW
Wheat	230
Maize yellow	151
Citrus pulp	61
Rapeseed	150
Soya extraction 49 %	168
Soyabean hulls	120
Molasses	63
Dairy blend mixer and spray	33
Minerals and vitamins	24

3.2.4 Grazing

The grazed swards were predominantly perennial ryegrass (*Lolium perenne*), on free draining, sandy loam soils. Cows were continuously grazed and the 3 separate groups of animals were rotated daily in a random order around paddocks in the grazed area. The grazed area was increased from 8.8 to 18.0 ha over the course of the experiment when herbage growth rate declined, so as to maintain sward surface height above the target height of 9 cm. An additional paddock was added to the grazing area on 23 August, and a further paddock added on 30 August.

3.2.5 Animal measurements

Milk yield of all cows was measured twice daily by flow meters at milking. Milk samples were collected weekly at two consecutive milkings to be analysed for fat, protein, and lactose content using an infrared milk analyser (Foss-Electric Milkoscan

203). All cows were weighed and condition scored (Lowman *et al.*, 1973) weekly after the afternoon milking.

Individual amounts of concentrate fed and refused were weighed at each milking. FW and DM of silage offered to each of the three groups was measured daily and silage refusals were weighed twice weekly to calculate intake per group. Herbage intakes for individual cows were estimated for Stage 1 of the Experiment by energy balance according to ME requirements as stated by AFRC (1993). Intake calculations were based on energy requirements for maintenance and milk production considering milk fat, protein, and lactose concentrations. Energy supply from concentrates; and either energy supply from liveweight loss or energy requirements for liveweight gain, depending on whether the animal was gaining or losing live weight, were also included in the calculations (AFRC, 1993).

Grazing behaviour of the three initial groups of cows was observed for 24 hours starting at 09:00 h on 2 September. Cows were observed for 15 seconds in every 10 minute period during daylight hours; or every 15 minutes in darkness, and their behaviour was recorded as either grazing, ruminating, milking, drinking or other.

3.2.6 Sward measurements

Sward surface height of each paddock was measured twice weekly using the HFRO sward stick (Barthram, 1986). Approximately 40 heights were taken in each paddock with the operator walking in a 'W' pattern across the paddock and taking a reading every 20 paces.

3.2.7 Herbage, concentrate and silage analysis

Simulated grazing samples were hand plucked weekly from paddocks and bulked for weekly analysis. Silage samples were taken and analysed weekly. Concentrate samples were collected weekly and bulked to one sample for chemical analysis per month. Concentrate DM was recorded weekly.

3.2.8 Statistical analysis

The results were analysed for statistically significant effects with Genstat 5, Release 4.1 (Lawes Agricultural Trust, 1998) using one way analysis of variance in randomised blocks, with concentrate level as treatment and allocation groups as block. Milk yield at allocation was used as a covariate for milk yield. Milk composition figures for the month prior to start of the experiment, as recorded by the Scottish Milk Recording Agency, were covariates for milk composition and yield of constituents.

Milk yield persistency over the two experimental periods was calculated by linear regression of daily milk yield on time, and results were analysed by analysis of variance. Liveweight change and condition score change for individual cows were similarly calculated by regression, and results analysed by analysis of variance.

3.3 Results

3.3.1 Herbage, concentrate and silage analysis

Chemical analysis of concentrate fed over the course of the experiment and mean results from fresh herbage samples in Stages 1 and 2 of the experiment, are presented in Table 3.3. Weekly herbage analysis results are presented in Figure 3.1.

Table 3.3 Mean chemical analysis of concentrate, and fresh herbage in Stages 1 and 2 (g kg^{-1} DM, unless stated otherwise)

	Concentrate		Herbage			
			Stage 1		Stage 2	
	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.
DM (g kg^{-1} FW)	853	2.4	223	15.1	189	24.9
Crude protein (CP)	216	0.9	176	14.8	231	24.6
Metabolisable energy (ME) (MJ kg^{-1} DM)	13.6	0.10	10.2	0.12	10.2	0.41
Water soluble carbohydrate (WSC)	133	6.3	85	6.9	48	4.1
Starch	286	9.9	-	-	-	-
Neutral detergent fibre (NDF)	191	2.9	563	7.7	582	13.9
Acid detergent fibre (ADF)	142	4.0	-	-	-	-
Acid hydrolysis ether extract (AHEE)	61	1.2	-	-	-	-
Neutral cellulose gaminase degradability (NCGD) (% DM)	73	13.4	-	-	-	-
Organic matter (OM)	-	-	915	10.1	868	22.4
DM digestibility (%)	-	-	68	0.9	68	2.7

Concentrate was on average 853 g kg^{-1} DM, and so concentrate levels of 6, 9, and 12 kg FW were equal to approximately 5.1, 7.7, and 10.2 kg DM respectively. Herbage DM ranged from a minimum of 157 g kg^{-1} FW on 30 September, to a maximum of 271 g kg^{-1} FW on 9 September. CP concentration increased over the experiment from 145 g kg^{-1} DM on 19 August to 268 g kg^{-1} DM on 7 October, before falling suddenly to 161 g kg^{-1} DM on 14 October. Herbage ME concentration ranged from 9 to 10.8 MJ kg^{-1} DM. WSC content declined from 88 to 56 g kg^{-1} DM over the Experiment while NDF concentration was slightly higher later in the season, increasing from 568 to 620 g kg^{-1} DM. A decline in herbage ME content and digestibility between 7 and 14 October was associated with an increase in NDF concentration.

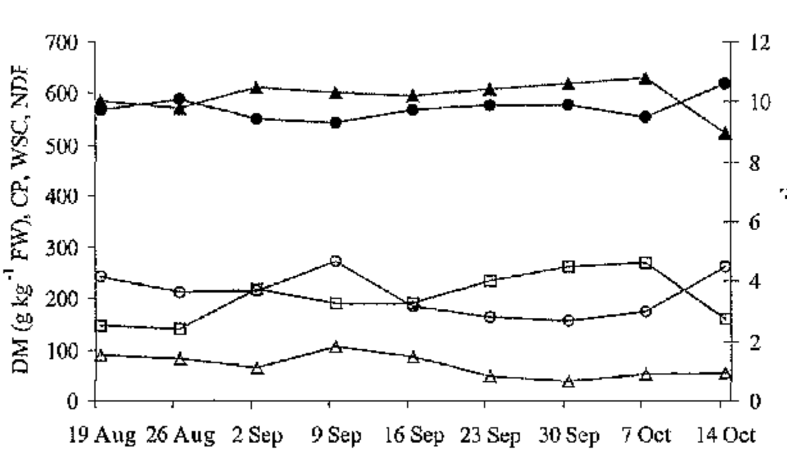


Figure 3.1 Weekly herbage analysis results DM ○, CP □, WSC Δ, NDF •, ME ▲ (g kg^{-1} DM, unless stated otherwise)

Chemical analysis of silage fed in Stage 2 is presented in Table 3.4.

Table 3.4 Mean chemical analysis of silage (g kg^{-1} DM, unless stated otherwise; Near Infra Red Spectroscopy (NIR) predictions)

	Mean	s.e.m.
DM (g kg^{-1} FW)	255	4.3
CP	154	0.6
CP degradability	0.76	0.003
ME (MJ kg^{-1} DM)	10.8	0.06
Fermentable metabolisable energy (FME) : ME	0.67	0.006
Intake factor (cattle)	101	1.4
Sugar content	26	4.0
NDF	504	0.3
DM digestibility (%)	68	0.3
pH	4.2	0.05
Ammonia (g N kg^{-1} total N)	75	4.0

3.3.2 Sward surface height

Mean sward surface height in Stage 1 was 9.6 ± 0.08 cm. Sward height in Stage 2 was on average 11.9 ± 0.13 cm. Mean sward height per measurement period (Figure 3.2) reached a minimum of 7.7 cm on 30 August, and a maximum of 13.3 cm on 30 September and 4 October. Variability in sward height measurements was higher in Stage 2, and increased towards the end of the experiment. Frequency distribution of sward height measurements for weeks 5 and 8 of the experiment is presented in Appendix 1.

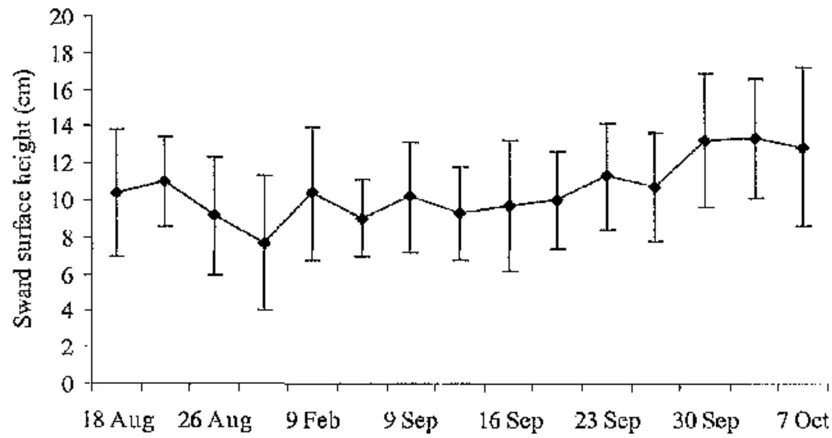


Figure 3.2 Mean sward surface height of grazed areas per recording (bars indicate standard deviation of individual sward height measurements)

3.3.3 Animal performance, Stage 1

Mean performance data from cows on each concentrate treatment during Stage 1, and statistical significance of effects of concentrate level, are presented in Table 3.5. Mean daily milk yield per week per concentrate treatment is presented in Figure 3.3.

Milk yield was significantly greater with increasing levels of concentrate supplementation, and increased from 28.8 to 31.4 and 33.6 kg d^{-1} when concentrate was increased from 6 to 9 kg and 9 to 12 kg FW respectively ($P < 0.05$). Milk yield persistency over the experimental period was not affected by concentrate treatment ($P > 0.05$). Concentrate level did not have an effect on milk composition ($P > 0.05$), although there was a slight positive association between protein concentration and amount of concentrate fed. Concentration of fat tended to decrease as more concentrates were fed which would be expected with an increase in total milk yield.

As a consequence of increased milk volume however, protein and lactose yields were higher when concentrate level was increased (6-9 kg, $P < 0.05$). Fat yield showed a slight positive association with level of concentrate fed but this effect was not statistically significant ($P > 0.05$).

Cows offered 12 kg FW concentrate d^{-1} gained on average 0.69 kg live weight d^{-1} which was significantly more than those offered the lower levels of supplementation ($P < 0.05$). The highest concentrate fed group also showed a slight increase in condition while those fed 6 and 9 kg FW d^{-1} lost condition over the first stage of the experiment, although these effects were not significant ($P > 0.05$).

Table 3.5 Effect of concentrate level on animal performance, Stage 1

	Concentrate level (FW d^{-1})[†]					
	6 kg	9 kg	12 kg			
Treatments	T1 T2	T3 T4	T5 T6	s.e.d.	s.e.m.	P value
Milk yield (kg d^{-1})	28.8^{a}	31.4^{b}	33.6^{c}	1.048	0.741	<0.001
Milk yield persistency (kg d^{-1})	-0.197	-0.148	-0.153	0.390	0.0276	0.391
Milk composition (g kg^{-1})						
Fat	37.0	33.9	33.3	1.61	1.37	0.059
Protein	31.8	32.5	32.7	0.61	0.43	0.319
Lactose	45.4	45.3	45.6	0.37	0.26	0.678
Yield of constituents (g d^{-1})						
Fat	1046	1059	1080	54.2	38.3	0.817
Protein	894^{a}	1022^{b}	1063^{b}	37.0	26.1	<0.001
Lactose	1279^{a}	1434^{b}	1491^{b}	60.3	42.6	0.004
Live weight						
Mean at start (kg)	602	615	611	15.6	11.0	0.696
Liveweight change (kg d^{-1})	0.24^{a}	0.15^{a}	0.69^{b}	0.149	0.107	0.002
Condition score						
Mean at start	2.16	2.14	2.18	0.11	0.076	0.945
Change per week	-0.038	-0.008	0.001	0.0205	0.0145	0.059

[†] Means with different superscripts in this and subsequent tables differ significantly $P < 0.05$

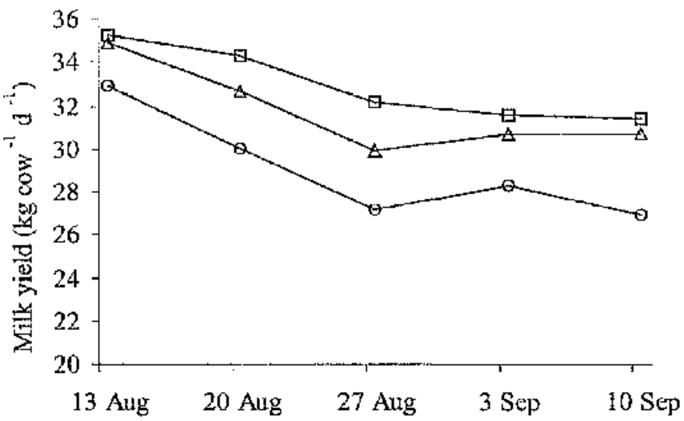


Figure 3.3 Effect of concentrate treatment; 6 kg (○), 9 kg (Δ) and 12 kg (□) FW cow^{-1} d^{-1}, on mean daily milk yield week^{-1}

3.3.4 Concentrate and herbage intake, Stage 1

Grazed herbage intake, as estimated by energy balance calculations (AFRC, 1993), was reduced with increasing concentrate intake (Table 3.6). As a consequence, there was no significant difference in total DM intake between treatments ($P > 0.05$), although total DM intake tended to be greatest for the 12 kg concentrate FW d^{-1} treatment group ($P = 0.051$).

Table 3.6 Mean concentrate intake and herbage intake (AFRC, 1993) Stage 1

	Concentrate level (FW d^{-1})			s.e.m.	P value
	6 kg	9 kg	12 kg		
Concentrate (kg DM d^{-1})	5.1^{a}	7.7^{b}	10.2^{c}	0.02	< 0.001
Herbage (kg DM d^{-1})	13.3^{a}	10.4^{b}	9.7^{b}	0.46	< 0.001
Total intake (kg DM d^{-1})	18.4	18.1	19.9	0.49	0.051

3.3.5 Energy balance, Stage 1

ME requirements for maintenance and milk production, and ME supply from concentrates and herbage, estimated from animal performance data (AFRC, 1993) are presented in Table 3.7. Two measurements of energy balance were made from these data. The first describes ME requirements for maintenance plus milk production less ME supply from concentrates (MJ d^{-1}); while the second calculation includes estimated ME supply from herbage (MJ d^{-1}) (Table 3.7).

Table 3.7 Effect of concentrate treatment on mean ME requirements, ME supply and energy balance (MJ ME cow^{-1} d^{-1}), Stage 1 (AFRC, 1993)

	Concentrate level (FW d^{-1})			s.e.m.	*P* value
	6 kg	9 kg	12 kg		
ME requirements					
Maintenance	60.2	61.1	61.3	0.79	0.666
Milk production	136.9^{a}	145.0^{ab}	152.7^{b}	3.87	0.019
ME supply					
Concentrate	69.5^{a}	104.3^{b}	138.5^{c}	0.24	<0.001
Herbage	135.0^{a}	106.0^{b}	102.0^{b}	3.82	<0.001
Energy balance					
(ME maintenance + milk) - (ME concentrate)	127.6^{a}	101.8^{b}	75.5^{c}	4.04	<0.001
(ME maintenance + milk) - (ME concentrate + herbage)	8.4^{a}	5.3^{a}	22.5^{b}	3.16	0.001

As milk yield level increased with increasing concentrate level, ME requirements to support milk production were raised. ME supply from concentrate increased with increasing concentrate level, while substitution of herbage for concentrate reduced herbage ME intake. Total ME intake from herbage plus concentrates however was increased from 204.5 to 240.5 MJ cow^{-1} d^{-1}. The proportion of ME requirements for maintenance and milk production which were supplied by concentrates was high and increased from 0.35 to 0.65 as concentrate supplementation increased from 6 to 12 kg d^{-1} FW.

On average, an increase in live weight of cows on each concentrate treatment (Table 3.5) indicates cows were in positive energy balance.

3.3.6 Milk yield response and substitution rate, Stage 1

The greatest milk yield response to supplementation was achieved when concentrate was increased from 6 to 9 kg d^{-1}, and this resulted in an increase in milk yield of 0.86 kg per kg concentrate FW, and 1.01 kg per kg concentrate DM. Milk yield response to supplementation above 9 kg concentrate FW d^{-1} was smaller at 0.71 and 0.83 kg extra milk per kg concentrate FW and DM respectively.

A reduction in herbage DM intake of 1.12 kg per kg increase in concentrate DM intake is estimated when concentrate supplementation increased from 6 to 9 kg FW d^{-1}. This indicates an almost direct DM substitution of herbage for concentrates. Further increases in concentrate supplementation from 9 to 12 kg FW d^{-1} resulted in a reduction in herbage intake of 0.28 kg DM kg^{-1} additional concentrate DM intake. This is equivalent to an overall substitution of herbage of 0.77 kg herbage DM when concentrate level was increased from 6 to 12 kg FW d^{-1}.

3.3.7 Grazing behaviour, Stage 1

Time spent grazing was reduced by 36 and 39 minutes kg^{-1} DM concentrate when supplementation was increased from 6 to 9 and 9 to 12 kg concentrate FW d^{-1} respectively (Table 3.8). Part of this effect however could be attributed to a reduction in potential grazing time by feeding the 9 kg and 12 kg groups at 11:00 h when they were removed from grazing for approximately 30 minutes. Mean rate of herbage intake as calculated from estimated herbage intake divided by grazing time was not found to vary between concentrate treatments.

Table 3.8 Grazing and ruminating behaviour, 2-3 September 1999 (cow^{-1} d^{-1})

	Concentrate treatment FW d^{-1}			s.e.m.	s.e.d.	*P* value
	6 kg	9 kg	12 kg			
Grazing (minutes)	666^{a}	574^{b}	475^{c}	15.3	21.7	<0.001
Ruminating (minutes)	406^{a}	523^{b}	478^{c}	13.2	18.7	<0.001
Herbage intake rate (kg DM h^{-1})	1.20	1.11	1.27	0.073	0.103	0.321

A positive linear relationship is observed between grazing time and estimated herbage intake ($r^2 = 0.20$) (Figure 3.4).

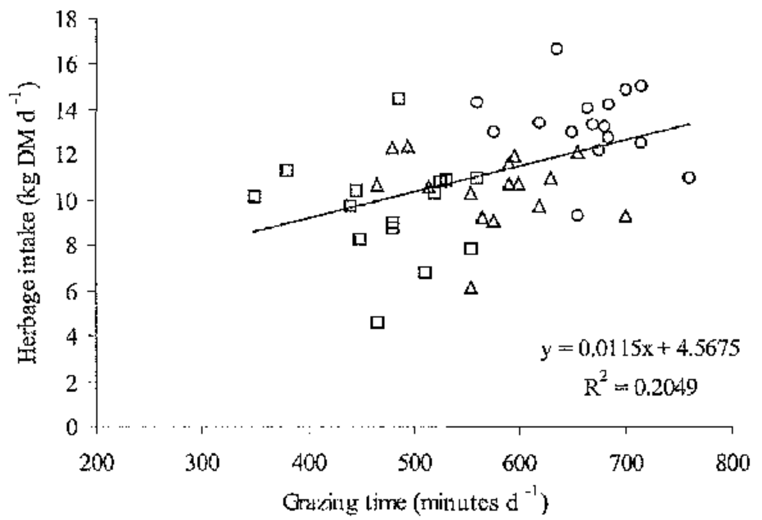


Figure 3.4 Relationship between grazing time and estimated herbage intake (concentrate treatment 6 kg (○), 9 kg (Δ) and 12 kg (□) FW cow^{-1} d^{-1})

Grazing time declined at higher levels of concentrate ME intake (grazing time = - 2.7117 concentrate ME intake + 854.93, $r^2 = 0.65$). A positive linear relationship also exists between grazing time and energy requirements for maintenance and production less energy supply from concentrates (r^2 = 0.39) (Figure 3.5). A better relationship however is observed between grazing time and the proportion of energy requirements for maintenance and milk production which were met from concentrate ME intake (r^2 = 0.57) (Figure 3.6).

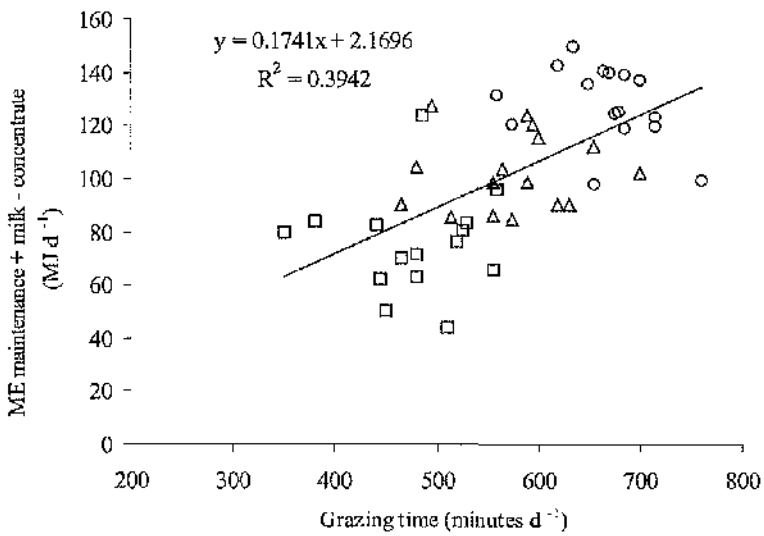


Figure 3.5 Relationship between grazing time and ME requirements for maintenance and milk production less ME supply from concentrates (concentrate treatment 6 kg (○), 9 kg (Δ) and 12 kg (□) FW cow^{-1} d^{-1})

Inclusion of both concentrate intake and estimated herbage intake in the energy balance calculation (Table 3.7) shows an increase in grazing time as the maintenance plus milk production ME requirement compared to ME supply from concentrate plus herbage increases, and hence energy balance declines (Figure 3.7).

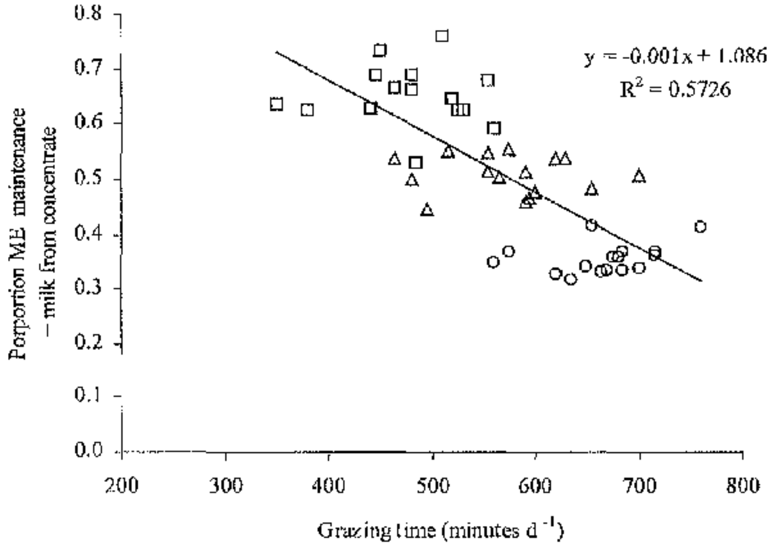


Figure 3.6 Relationship between grazing time and proportion ME requirements for maintenance and milk production supplied from concentrates (concentrate treatment 6 kg (○), 9 kg (Δ) and 12 kg (□) FW cow^{-1} d^{-1})

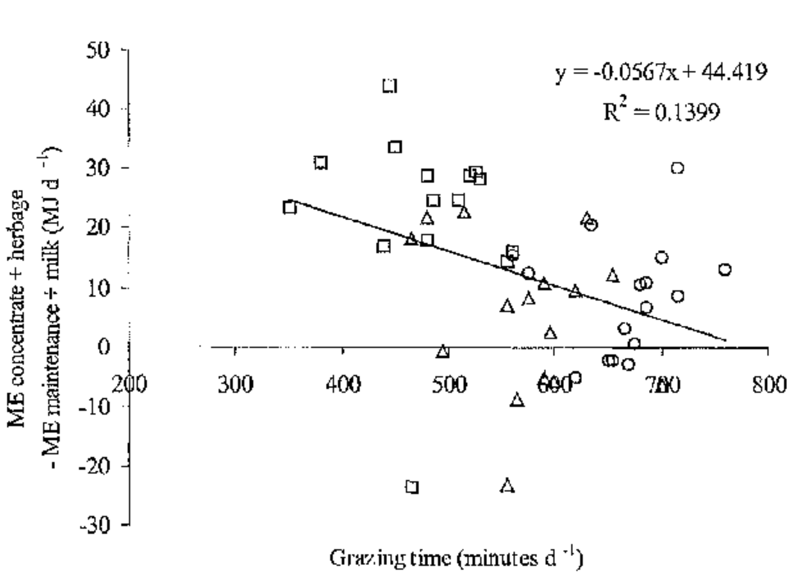


Figure 3.7 Relationship between grazing time and ME supply from concentrates plus herbage less ME requirements for maintenance and milk production (concentrate treatment 6 kg (○), 9 kg (Δ) and 12 kg (□) FW cow^{-1} d^{-1})

3.3.8 Animal performance, Stage 2

One animal on Treatment 6 suffered from poor health and had to be removed from the trial in Stage 2 of the experiment. Results from this animal have hence been omitted from analysis of results in Stage 2. Mean performance data from cows on each concentrate treatment in Stage 2, and significance of effects of concentrate level, are presented in Table 3.9.

Table 3.9 Effect of concentrate treatment on animal performance, Stage 2

	Concentrate level (FW d^{-1})							
	6 kg	8 kg	9 kg	11 kg	12 kg	14 kg		
Treatment	T1	T2	T3	T4	T5	T6	s.e.m.	*P* value[†]
Milk yield (kg d^{-1})	26.7	27.8	30.2	29.8	31.4	28.7	1.013	0.025[‡]
Milk yield persistency (kg d^{-1})	0.059	0.066	-0.022	-0.020	-0.074	-0.067	0.0294	0.004[§]
Milk composition (g kg^{-1})								
Fat	39.3	38.0	35.9	36.3	35.5	33.5	0.1542	0.152
Protein	33.9	33.1	33.2	34.3	32.5	35.3	0.0696	0.051
Lactose	45.1	44.6	44.7	44.8	44.0	44.8	0.0508	0.674
Yield of constituents (g d^{-1})								
Fat	1002	1112	1112	1071	1107	932	55.3	0.125
Protein	893	957	1006	1025	1009	973	36.1	0.141
Lactose	1189	1296	1364	1343	1381	1243	58.4	0.169
Live weight								
Start Stage 2 (kg)	624	599	628	622	636	622	15.71	0.757
Change (kg d^{-1})	0.49	0.83	0.72	0.49	0.56	0.95	0.173	0.286
Condition score								
Start Stage 2	2.09	1.91	2.19	2.03	1.97	2.21	0.1417	0.633
Change $week^{-1}$	0.021	0.055	0.027	0.043	0.053	0.088	0.0297	0.086

[†] No significant differences at $P < 0.05$ were observed between means of treatments 1 and 2, 3 and 4, or 5 and 6; [‡] least significant difference, $P < 0.05$ (l.s.d.) = 2.914; [§] l.s.d. = 0.0845

Increasing concentrate level by 2 kg d^{-1} FW (1.7 kg d^{-1} DM) did not affect mean milk yield over Stage 2 of the experiment, and no significant differences were observed between Treatments 1 and 2, 3 and 4, or 5 and 6 ($P > 0.05$). Mean results between Treatment groups however indicate a trend for higher milk yield when concentrate was increased from 6 to 8 kg d^{-1}FW, and a detrimental effect on milk production when concentrate level was increased by 2 kg FW d^{-1} above 9 kg or 12 kg FW d^{-1}. No differences in either milk composition or yield of constituents were observed between treatments ($P > 0.05$).

An increase in concentrate level by 2 kg did not affect milk yield persistency over Stage 2, and no significant differences in persistency were observed between Treatments 1 and 2, 3 and 4, or 5 and 6 ($P > 0.05$). An increase in milk yield persistency however was observed over this period for Treatments 1 and 2. Milk yield for the remaining Treatments declined over Stage 2 and a greater decline in persistency was observed for the highest levels of concentrate fed.

There were no significant differences between treatments in live weight or condition score at the beginning of Stage 2 and concentrate treatment had no effect on liveweight or condition score change over Stage 2 ($P > 0.05$).

3.3.9 Concentrate and silage intake, Stage 2

Mean concentrate and silage intake per Treatment is presented in Table 3.10. Silage intake was estimated per group for the three concentrate treatment groups of Stage 1.

Table 3.10 Effect of concentrate treatment on silage and concentrate intake cow^{-1}

	Concentrate level (FW d^{-1})								
	6 kg	8 kg	9 kg	11 kg	12 kg	14 kg			
Treatment	T1	T2	T3	T4	T5	T6	s.e.m.	l.s.d.	P value
Concentrate intake (kg DM d^{-1})	5.12	6.82	7.68	9.38	10.12	11.87	0.036	0.104	<0.001
Silage intake (kg DM d^{-1})†	9.31	9.31	9.17	9.17	7.39	7.39			

† Group means of Treatments 1 and 2, 3 and 4, 5 and 6

Silage DM intake was lower with higher concentrate intake however total DM intake of silage plus concentrates was greater with increasing levels of concentrate fed.

3.3.10 Energy requirements and energy supply from concentrates and silage, Stage 2

Mean ME requirements to support the observed levels of animal performance and ME supply from concentrates and silage per Treatment, as estimated using energy balance calculations (AFRC, 1993), are presented in Table 3.11.

Table 3.11 Mean ME requirements and ME supply per Treatment (MJ ME cow^{-1} d^{-1}) Stage 2 (AFRC, 1993)

	Concentrate level (FW d^{-1})							
	6 kg	8 kg	9 kg	11 kg	12 kg	14 kg		
Treatment group	T1	T2	T3	T4	T5	T6	s.e.m.	*P* value
ME requirements								
Maintenance	61.8	60.9	62.1	61.6	62.1	62.3	1.53	0.968
Milk production	127.1	139.6	142.4	144.2	147.7	128.7	7.59	0.069
ME supply								
Concentrate	69.6^{a}	92.8^{b}	104.4^{c}	127.6^{d}	137.5^{e}	161.5^{f}	0.69	<0.001
Silage	100.5^{a}	100.5^{a}	99.0^{b}	99.0^{b}	79.8^{c}	79.8^{c}	0.00	<0.001
Energy balance								
(ME maintenance + milk) - (ME concentrate)	119.2	107.6	100.1	78.2	72.4	29.5	7.45	<0.001†
(ME maintenance + milk) - (ME concentrate + silage)	18.7	7.1	1.1	-20.8	-7.4	-50.3	7.45	<0.001†

† l.s.d. 15.12 MJ ME

Silage intakes were not measured for individual cows and are presented as averages for Treatments 1 and 2, 3 and 4, and 5 and 6. However it appears that silage intake decreased as concentrate supplementation increased, and that the majority of ME requirements to support the observed levels of production were met from concentrates and silage, especially for cows offered the higher levels of supplementation.

3.4 Discussion

3.4.1 Concentrate supplementation in late season (Stage 1)

3.4.1.1 Milk production, herbage intake and grazing behaviour responses

A high milk yield response of 1.01 kg and 0.83 kg milk kg^{-1} DM concentrate intake was observed when concentrate supplementation was increased from 5.1 to 7.7, and 7.7 to 10.2 kg DM d^{-1} (equivalent to 6 to 9 and 9 to 12 kg FW concentrate d^{-1}) respectively. Others have similarly demonstrated high efficiencies of concentrate supplementation above 1 kg milk kg^{-1} concentrate DM (for example, Delaby *et al.*, 2001; Gibb *et al.*, 2002b; Wales *et al.*, 1999; Wilkins *et al.*, 1994). Milk yield responses to supplementation of this magnitude reported in these and other studies however, have generally most often only been obtained from grazing cows when offered up to 5.4 kg DM d^{-1} of concentrate. Few experiments have investigated effects of supplementation with significantly more than 6 kg FW concentrate d^{-1}. Reis and Combs (2000) however achieved a milk production response of 0.86 kg milk kg^{-1} concentrate DM when grazing cows were fed 10 kg DM concentrate d^{-1}. Similarly, although Sayers *et al.* (2000) do not report milk production from unsupplemented animals to calculate overall efficiency of supplementation, they do demonstrate a relatively high response of 0.64 kg milk kg^{-1} concentrate DM when concentrate supplementation is increased from 5.0 to 9.9 kg DM d^{1}.

An increase in concentrate level in the present experiment resulted in a reduction in estimated herbage intake. Substitution of herbage for concentrate was high at 1.01 and 0.77 kg kg^{-1} DM when concentrate offered was raised from 6 to 9 kg and 9 to 12 kg FW d^{-1} respectively. Total ME intake however increased as a result of the higher ME content of herbage compared to concentrate, which can help explain the high milk yield response to increasing concentrate level.

Despite a lower marginal efficiency of concentrate supplementation for milk production reported by Sayers *et al.* (2000) compared to the present experiment, these authors also report a lower substitution rate of 0.57. This could be related to differences in herbage ME content and intake from the sward. Sayers *et al.* (2000) conducted their experiment from 1 May to 25 September. Mean herbage ME content is therefore expected to be higher and this is suggested from WSC results, which were on average 161 g kg^{-1} DM, compared to 85 g kg^{-1} DM in the current study. A lower DM substitution rate would therefore be required to have the same effect on total ME intake when herbage ME content is lower. A high substitution rate of 1.06, similar to that of the present experiment, however was reported by Sayers *et al.* (2000) when cows were offered a starch based concentrate late in the season from 21 August to 25 September.

Estimates of average daily herbage intake cow^{-1} $treatment^{-1}$ ranged from 9.7 to 13.3 kg DM. Under ideal grazing conditions however, intakes of over 20 kg DM have been reported (Buckley and Dillon, 1998). Mean grazing time was high at approximately 11 h d^{-1} for cows offered 6 kg FW concentrate d^{-1}. It has previously been suggested that grazing time reaches a plateau at between 9 and 10 h d^{-1} (Rook *et al.*, 1994). Although grazing time was measured only over a single 24-hour period in the experiment and there may be variability in grazing behaviour between days, it seems that herbage intake of cows could have been limited by time available to graze and sward conditions could have restricted voluntary herbage intake.

Grazing time was positively associated with estimated herbage intake ($r^2 = 0.20$). Measurements of grazing time were significantly reduced with increasing concentrate level, which supports the high estimates of substitution of herbage for concentrate as concentrate level was increased. Grazing time was substantially reduced, by on average 36 and 39 minutes kg concentrate DM^{-1} when supplementation was increased from 6 to 9 kg and 9 to 12 kg concentrate FW d^{-1} respectively. This is higher than results reported by others who have reported a reduction in grazing time of up to 18 minutes kg^{-1} concentrate DM (Sayers *et al.*, 2000). It would be expected that grazing time would be reduced by longer at higher levels of supplementation and when substitution rates are higher. Pulido and Leaver (2001) demonstrate that high substitution rates observed in their experiments occurred as a consequence of a reduction in rate of intake as well as grazing time, however no effect of concentrate treatment on rate of herbage intake was observed in the current study.

Removal of cows which were supplemented with 9 or 12 kg FW d^{-1} from pasture for approximately 30 minutes d^{-1} for an additional concentrate feed at 11 am could also have reduced time available for grazing and so could explain some of the reduction in grazing time with increasing supplementation. This could also have contributed to the large substitution rates observed in the study, and the higher level of substitution when supplementation was increased from 6 to 9 kg, compared to 9 to 12 kg FW d^{-1}.

On average, animals gained live weight over Stage 1, which suggests they were in positive energy balance. Animals offered the highest concentrate level gained significantly more live weight. A greater proportion of the additional ME intake of this treatment appears to have been diverted to liveweight gain which may explain the lower milk yield response despite a lower substitution rate when concentrate level was increased from 9 to 12 kg, compared to 9 to 12 kg FW d^{-1}.

3.4.1.2 Effect of milk yield level and milk production potential

A greater milk yield response to supplementation and reduced substitution rate is associated with increasing milk production potential and genetic merit of grazing cows (Dillon *et al.*, 1999; Hoden *et al.*, 1991; Peyraud and Delaby, 2001). This could partially explain the high efficiency of supplementation observed in the current study compared to experiments conducted with lower yielding cows (Dillon *et al.*, 1997; Pulido and Leaver, 2001). Few studies report results from cow yielding above 30 kg milk d^{-1} however those who have used higher yielding animals have shown greater efficiencies of supplementation to higher levels of concentrate (Reis and Combs, 2000; Sayers *et al.*, 2000). Greater milk production responses are expected as milk production potential increases and cows are unable to support their intake requirements from grazed grass alone (Peyraud and Delaby, 2001). Whether or not an effect of increasing supplementation is observed will therefore depend upon the interaction between milk production potential of the cow, potential intake from the sward and the level of concentrates offered.

3.4.1.3 Sward characteristics

Current recommendations for continuously grazed, high yielding cows suggest sward heights of 7-8 cm April to June, 8-10 cm July to August, and 10-12 cm September to October (Mayne *et al.*, 2000). Peyraud and Gonzalez-Rodrigez (2000) propose an optimal range of pre-grazing sward heights of between 10 and 12 cm. Mean sward surface heights per measurement period in this experiment ranged from 7.7 to 13.3 cm, averaging 9.6 cm in Stage 1, and so mean sward heights were generally within the recommended ranges. Variability between sward height measurements however was high, and is expected to be greater than earlier in the season (McBride *et al.*, 2000). An increases in variability in sward height over the grazed area, and increased sward structural heterogeneity, reduces mean bite mass (Swain, 2000). Sward height also gives little indication of other aspects of sward structure known to affect bite mass and herbage intake, and in particular sward density and leafiness (Mayne *et al.*, 1997; Parga *et al.*, 2000).

Herbage intake rate was on average 1.19 kg DM h^{-1}, and this is low compared to other experiments reported in the literature in which cows have grazed at similar sward heights (for example, Gibb *et al.*, 1999; McGilloway *et al.*, 1999; Pulido and

Leaver, 2001). A good relationship between intake rate and bite mass is evident from results in the literature (Barrett *et al.,* 2001; Orr *et al.*, 2001). A high grazing time and relatively low herbage DM intake and intake rate therefore suggests that, in the current experiment, cows were achieving a low mean bite mass from the sward.

3.4.1.4 Concentrate level and composition

Marginal efficiency of supplementation for milk production declined with increasing concentrate level, which is expected when animals approach their energy requirements to meet their potential level of milk production (Delaby *et al.*, 2001). Few studies have offered cows levels of concentrates at grazing that are comparable with the current experiment. Reis and Combs (2000) do however report a decline in marginal efficiency from 1.00 to 0.72 kg milk kg^{-1} DM when concentrate level was increased from 0 to 5 kg and 5 to 10 kg DM respectively.

It is possible that high inputs of a high starch, cereal-based concentrate had a disruptive effect on the rumen environment, reducing microbial activity and lowering the rate of breakdown of material in the rumen (Arriaga-Jordan and Holmes, 1986; Sutton *et al.*, 1987). The concentrate formulation contained a high proportion of starchy ingredients, such as wheat and maize. A starch content of 286 g kg^{-1} DM was comparable with the starch level that has been demonstrated to have a disruptive effect on intake and milk production compared to more fibrous energy sources, (for example, Gibb *et al.*, 2002 and Meijs, 1986). Effects of a rapidly degradable energy source on the rumen environment are expected to be greater when the ratio of concentrate to herbage in the diet is high (Sayers *et al.*, 2000), which is likely in the current experiment. Effects however could be less when cows are grazing in late season, and herbage is less digestible and contains a lower concentration of rapidly available energy (Schwarz *et al.*, 1995). Splitting the concentrate offered between 3 feeds d^{-1} for animals offered 9 or 12 kg d^{-1} FW could also have reduced effects of high inputs of rapidly degradable carbohydrate on the rumen environment.

3.4.1.5 Interaction between animal, sward and concentrate factors

The effect of supplementation on herbage intake and milk yield response is dependant upon the ability of the cow to meet its intake requirements from herbage and concentrate (Delaby *et al.*, 2001; Pulido and Leaver, 2001). The evidence suggests that autumn swards are capable of supporting no more than 25 kg milk d^{-1} (Mayne, 2001). In the current experiment, a low potential DM and energy intake from the late season sward that is unable to meet requirements to support the animals' milk production potential, could be responsible for the high milk production responses to high levels of supplementation which were measured.

Grazing time can be used to give an indication of herbage intake that is independent from energy balance estimates (AFRC, 1993) of herbage intake. Positive linear relationships between grazing time and ME requirements for maintenance and milk production less ME supply from concentrates, and the proportion of these ME requirements met from concentrate are observed. These results suggest substitution rate will be higher when the cow reaches its potential level of milk production and a larger proportion of these energy requirements are met from concentrates and herbage. Milk yield response is therefore dependent upon sward characteristics that determine herbage intake potential from the sward, and the level of concentrate, in comparison to the cow's intake requirements to support its potential level of milk production. Sward characteristics that determine herbage intake are therefore important in determining milk production responses to supplementation.

3.4.2 Concentrate supplementation over the housing period (Stage 2)

3.4.2.1 Milk production response, silage intake and energy balance

Increasing the level of concentrate offered to cows by 1.7 kg DM d^{-1} when they were housed overnight had no significant effect on animal performance. Mean milk yield persistency (kg d^{-1}) for the duration of the experimental period however was slightly improved after housing. Some of this effect could be attributed to the slightly lower milk yield level of later lactation cows. The difference in persistency however was particularly apparent between Stages 1 and 2 of the experiment for Treatments 1 and 2, which were fed 6 or 8 kg FW d^{-1} respectively in Stage 2, and milk yield actually increased slightly over Stage 2 for these treatments. It seems that nutrient status of cows on the lowest concentrate level treatment was improved after housing when they were offered *ad libitum* silage. These cows may have been unable to meet their requirements to support their potential levels of milk production from herbage and concentrates offered in Stage 1. The high grazing times of cows fed the lowest concentrate level in Stage 1 supports this theory.

Silage intakes were only measured as group totals for the three concentrate levels as fed in Stage 1 of the experiment. Results however suggest a reduction in silage DM intake as concentrate level was increased. Silage was offered to cows *ad libitum* and so it is expected that substitution of herbage for both concentrates and silage would be high. Calculation of energy requirements (AFRC, 1993) and energy supply suggest that virtually all of the cow's ME requirements for maintenance and production are met from concentrates and silage. Cows therefore had little requirement for grazing. Cows could reduce intakes of both herbage and silage as concentrate offered was increased. Increasing concentrate level therefore appears to have had limited effect on total energy intake and hence upon level of milk production for these animals.

3.5 CONCLUSION

High milk production responses can be achieved from grazing cows offered high levels of concentrate supplements late in the season. A higher efficiency of concentrate supplementation for milk production can be expected later in the season when herbage quality is poorer, and when herbage availability declines to reduce potential bite mass and herbage intake from the sward.

Grazing time is positively related to estimates of herbage intake. Both grazing time and herbage intake are reduced when concentrate level increases. Grazing time and hence herbage intake are positively related to the proportion of the cow's energy requirements for maintenance and milk production which are met from concentrate intake. Substitution of herbage for concentrate can be high although a greater reduction in herbage DM intake is required to have the same effect on total ME intake when herbage ME content is lower. Disruption of the rumen environment by high inputs of a high starch, cereal-based concentrate could contribute to high substitution rate (Arriaga-Jordan and Holmes, 1986). Herbage intake can also be limited by time available for grazing. This is more likely to occur when herbage availability is reduced later in the season and when cows are unable to meet their nutrient requirements from the herbage and concentrates on offer. Removal of animals from pasture can therefore reduce herbage intake by reducing time available for grazing.

An increase in concentrate level over the housing period is expected to have limited effects on animal performance when cows are offered supplementary silage and concentrates that supply a large proportion of their energy requirements for maintenance and milk production. A positive response to increasing concentrate level may have been observed if cows were in negative energy balance, for example due to higher potential for milk production and increased nutrient demand, or lower potential nutrient intake from pasture and supplementary forages.

CHAPTER 4.0 EXPERIMENT 2

Animal performance and herbage intake of high yielding dairy cows fed different concentrate energy sources and an additive formulated to reduce the rate of dietary protein degradation in the rumen

4.1 INTRODUCTION

Production responses to concentrate supplementation can be affected by composition of the concentrate (Gibb *et al.*, 2002a; Schwarz *et al.*, 1995). Concentrate composition determines supplementary energy intake and protein supply and can affect the rate of substitution of herbage, which affects total intake (McGilloway and Mayne, 1996).

Energy supplements can increase total metabolisable energy (ME) supply to the animal, increase energy supply to rumen microbes, and improve synchrony of supply of rumen fermentable energy and the rapidly available nitrogen (N) from herbage (Beever *et al.*, 1986). Results from Experiment 1 however, indicate substitution of herbage for concentrates can be significant when grazing cows are offered high levels of supplementation with a starch-based concentrate. High inputs of quickly fermentable substrates, such as starch, can increase concentrations of volatile fatty acids (VFAs) and lactate in the rumen and so lower rumen pH (Sutton *et al.*, 1987). In turn, this can reduce activity of rumen microbes, and so decrease the rate of breakdown and passage of material through the rumen which can restrict further herbage intake (Arriaga-Jordan and Holmes, 1986). It could therefore be more appropriate to offer grazing cows a less rapidly degradable source of energy. Higher milk yields have been reported for example, when high fibre compared to high starch concentrates are fed to grazing cows (Khalili and Sairanen, 2000), and others have found these higher levels of production are supported by increased herbage intake (Fisher *et al.*, 1996; Gibb *et al.*, 2002a; Meijs, 1986).

Greater effects of concentrate energy source might be expected when the ratio of concentrate to herbage in the diet increases (Sayers *et al.*, 2000; Schwarz *et al.*, 1995). Effects of concentrate energy source could therefore be particularly important for high genetic merit cows when it is necessary to offer high levels of concentrates for them to achieve their potential level of milk production. Similarly, there could be an interaction between concentrate composition and herbage quality, which affects the total level and availability of fermentable energy and N in the rumen (Schwarz *et al.*, 1995). Results from experiments that have fed different energy sources however are inconclusive and the extent of the effect of energy source on animal performance and substitution rate has been variable.

Further studies have investigated effects of protein supplementation of grazing cows. Responses to improved protein supply may be expected from higher yielding cows when metabolisable protein (MP) requirements are in excess to MP supplied from microbial protein alone (Leng and Nolan, 1984; Neilsen *et al.*, 2002). While fresh herbage has a high crude protein (CP) content (Beever *et al.*, 2000), the majority of this protein is rapidly degradable in the rumen (Beever *et al.*, 1986). Milk production responses and a trend for higher dry matter (DM) intake have been observed when protein supplements with low rumen degradability were fed to high yielding grazing cows (Hongerholt and Muller, 1998). Additives have been formulated to reduce the degradability of dietary protein and so improve synchrony of supply of ruminally available energy and N for microbial protein synthesis, and improve the supply of RUP to the cow. Some studies however have detected no effects of feeding higher quantities of protein supplements with low rumen degradability on milk production or pasture utilisation (Tesfa *et al.*, 1995).

Results from experiments investigating both concentrate energy source and protein supplementation are therefore inconclusive. Furthermore, data from cows yielding above 30 kg milk d^{-1}, which have been fed different concentrate types at pasture is limited. This experiment was designed to test the hypotheses that concentrate energy source affects herbage intake and milk production of potentially high yielding, grazing cows; and that there are benefits of inclusion of an additive formulated to reduce the degradability of dietary protein available to cows which have high protein requirements.

Specific objectives of the Experiment were;

- To investigate the effects of concentrate energy source, either high starch or high fibre; on animal performance, herbage intake and grazing behaviour.
- To investigate the effects of an additive designed to reduce protein degradability, on animal performance, herbage intake and grazing behaviour.

4.2 MATERIALS AND METHODS

4.2.1 Experimental design

The experiment was conducted over a 16-week period from 1 May to 20 August 2000. Effects of two different concentrate energy sources, and inclusion of an additive designed to reduce dietary protein degradability, were studied by feeding either a high starch (HS) or high fibre (HF) concentrate, with (AD+) or without (AD-) inclusion of the additive. Treatments were applied according to a continuous factorial design with 4 treatments, each replicated with 12 cows.

4.2.2 Animals and treatments

Forty-eight multiparous Holstein-Friesian cows on average 62 ± 2.4 days calved, and with an average milk yield of 38.9 ± 0.70 kg d^{-1}, were used in the experiment. Cows had a mean liveweight of 611 ± 8.1 kg and condition score (Lowman *et al.*, 1973) of 2.1 ± 0.07. Animals were blocked into groups of four cows on the basis of days in milk, milk yield in the week prior to start of the experiment, and lactation number. Cows were allocated to treatments at random from blocks.

Prior to commencing the experiment, cows were offered grass silage plus 5.3 kg DM d^{-1} of a cereal-based dairy concentrate, and 2.1 kg DM d^{-1} of distillery grains. Cows were given increasing access to pasture from 3 hours d^{-1} on 20 March to 24 hours d^{-1} from 23 April.

During the experiment cows were fed 6 kg fresh weight (FW) d^{-1} of one of the four concentrate formulations. All concentrate was fed in the parlour and split equally between morning and afternoon milkings, at approximately 06:00 and 16:00 h.

Ingredients in the different concentrates were similar but their proportions were varied to provide a high starch and high fibre concentrate (Table 4.1). Concentrates were formulated to contain equal quantities of CP and ME. To ensure similar types of protein and protein degradability, the total quantity of rapeseed plus soya extract was similar between diets. The ratio of maize to wheat was also equal to maintain a similar ratio of fast to slow fermenting starch plus sugar between concentrates.

Table 4.1 Ingredient composition of concentrates fed (g kg $^{-1}$ FW)

	HS	HF
Wheat	250	84
Maize yellow	198	80
Wheatfeed	65	78
Citrus pulp	37	65
Oatfeed	-	3
Rapeseed	150	150
Palm kernel expeller	96	150
Soya extraction 48 %	81	66
Soyabean hulls	-	200
Molasses	56	56
Dairy blend mixer and spray	30	29
Minerals and vitamins	36	31

Cows grazed swards of predominantly perennial ryegrass (*Lolium perenne*), on free draining, sandy loam soils. Animals were continuously grazed in their separate treatment groups and groups were rotated daily in a random order around the grazing area. The target sward surface height was 10 to 12 cm, and the grazed area was increased over the duration of the experiment from 11.2 to 15.0 hectares to maintain the target height. All paddocks were mechanically topped once over the course of the experiment, between 29 June and 21 July, to maintain sward height within the target range. Paddocks were topped to 11 cm when mean sward surface height exceeded 14 cm.

The sward received fertiliser applications at a rate of 50 kg N ha^{-1} in mid-March, mid-April and at 3-weekly intervals from 7 May 2000.

4.2.3 Measurements

Milk yield was measured twice daily for all cows. Milk samples were collected weekly on two consecutive milkings and analysed for fat, protein and lactose concentration (FOS Electric Milkoscan 650 or S4000) and urea concentration (Sigma Chemical Company Test Kit No. 640). Cow live weight and condition score (Lowman *et al.*, 1973) were recorded weekly after the afternoon milking.

Individual amounts of concentrate fed and refused were weighed at each milking. Intake of grazed herbage was estimated for all cows from 22-26 May, 19-23 June, 17-21 July and 14-18 August, using the *n*-alkane technique of Mayes *et al.* (1986), as modified by Dillon and Stakelum (1988). Cows were dosed twice daily after milking with paper pellets containing 300 mg of C_{32} (*n*-dotriacontane), for 12 days. Faecal samples were collected once daily after the afternoon milking on the last 5 days of each 12-day period. Samples from each cow were bulked for analysis. Grass samples were obtained from each paddock on days 7, 8, 9, 10 and 11 of each of the 12-day measurement periods, by observing a grazing cow and hand-plucking herbage from an area adjacent to that being grazed. This operation was repeated with different cows until a sample of approximately 300 g FW of herbage had been collected from each paddock. Samples of concentrates fed were also taken on these days. Herbage and concentrate samples were bulked to give one sample for analysis from each treatment group for each measurement period. The C_{32} and C_{33} (*n*-tritricontane) contents of pellets, herbage, concentrates and faeces, were analysed according to Mayes *et al.* (1986), and an estimate of herbage intake was calculated for each cow from each measurement period (Equation 4.1):

$$HI = (\frac{F_i}{F_j} * ((D_j + IC * C_j) - (D_i + IC * C_i))) / ((H_i + D_i) - (\frac{F_i}{F_j} * H_j)) \qquad (4.1)$$

where *HI* is herbage intake (kg DM d^{-1}); *H*, *C*, and *F*, are concentrations (mg kg^{-1} DM) of C_{33} (*i*) or C_{32} (*j*) in herbage, concentrate, and faeces respectively; D_i and D_j are the amounts of C_{33} and C_{32} respectively in dosed pellets (mg d^{-1}); and *IC* is concentrate intake (kg DM d^{-1}).

Herbage intakes for individual cows were also estimated by energy balance calculations according to ME requirements stated by AFRC (1993). The energy balance technique was applied using data recorded in weeks 4, 8, 12 and 16, to coincide with *n*-alkane intake recording periods. Intake calculations were based on energy requirements for maintenance and milk production considering milk fat, protein, and lactose concentrations. Energy supply from concentrates; and either energy supply from liveweight loss or energy requirements for liveweight gain, depending on whether the animal was gaining or losing live weight, were also included in the calculations (AFRC, 1993).

Studies of grazing behaviour were carried out for 24 hours during each of the herbage intake estimation periods. Cows were observed for 15 seconds every 10 minutes in daylight, and every 15 minutes in darkness, and their behaviour was recorded as grazing, ruminating, milking, drinking or other.

Sward surface height of each paddock was measured twice weekly using the HFRO sward stick (Barthram, 1986). Approximately 40 recordings were taken from each paddock with the operator walking in a 'W' pattern across the paddock and taking a reading every 20 paces.

Simulated grazing samples were hand plucked from paddocks weekly at mid day for DM calculation and chemical analysis. Concentrate samples were taken weekly and bulked on a monthly basis for chemical analysis. Concentrate DM was measured weekly. Concentrate and herbage samples were analysed by the neutral cellulose gaminase degradability (NCGD) and acid hydrolysis ether extract (AHEE) techniques (MAFF, 1985). ME (MJ kg^{-1} DM) was calculated as ME = NCGD * 0.14 + AHEE * 0.25 (MAFF, 1993). CP content was estimated using indo-phenol blue colorimetry following micro-Kjeldahl digestion of samples.

4.2.4 Statistical analysis

Results were analysed for statistically significant effects using Genstat 5, Release 4.1 (Lawes Agricultural Trust, 1998). The data were analysed for concentrate energy type and additive effects, and for interaction of the two treatments. Mean milk yield, milk composition and yield of constituents, per week and for the experimental period overall, were analysed by two way analysis of variance using concentrate energy source and inclusion of the additive as treatments, and allocation groups as block. Milk yield and milk composition data at allocation were used as covariates for milk yield and milk composition respectively. Liveweight change and condition score change for each cow was calculated by regression and analysed by analysis of variance.

4.3 Results

4.3.1 Concentrate and herbage analysis

Concentrate was on average 877 g kg^{-1} DM and so offering cows 6 kg concentrate FW d^{-1} was equivalent to 5.3 kg DM^{-1}. Chemical analyses of concentrates were similar except for neutral detergent fibre (NDF) content which was on average 106 g kg^{-1} DM higher for the HF compared to HS supplement; and starch content which was on average 117g kg^{-1} DM higher for HS than HF (Table 4.2). Total starch plus WSC offered to cows per day was therefore equal to 2.20 kg and 1.58 kg for the HS and HF treatments respectively. There was no interaction between energy source and additive treatment for chemical composition of concentrates ($P < 0.001$).

Herbage analysis (Table 4.2, Figure 4.1) shows a high DM content over the course of the experiment of on average 217 g DM kg^{-1} FW. CP content was highest in week 2 at 254 g kg^{-1} DM. CP content declined to 187 g kg^{-1} DM in week 12, and then increased slightly towards the end of the experimental period. Herbage ME fell steadily over the season from 11.7 to 10.1 MJ kg^{-1} DM. Water soluble carbohydrate (WSC) concentration was high at the start of the season, reached maximum of 115 g kg^{-1} on 20 July, and then fell significantly to 45 g kg^{-1} DM in week 16. NDF increased over the season from 468 to 586 g kg^{-1} DM, with the greatest increase observed after week 12. DM digestibility declined gradually over the course of the experiment.

Table 4.2 Mean chemical analysis of concentrates and fresh herbage (g kg^{-1} DM, unless stated otherwise)

	Concentrate treatment								Herbage	
	HS		HF		AD-		AD+			
	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m
DM (g kg^{-1} FW)	873	2.2	880	2.1	875	2.1	878	2.5	217	8.1
CP	188	3.2	182	3.1	189	3.1	181	1.6	214	5.1
ME (MJ kg^{-1} DM)	13.4	0.06	13.2	0.06	13.4	0.06	13.2	0.07	11.0	0.11
WSC	116	4.2	117	4.2	124	1.9	110	2.4	87	4.5
Starch	299	6.4	182	6.4	235	23.2	246	22.5	-	-
NDF	192	7.6	298	7.6	242	21.5	249	20.2	518	7.7
AHEE	63	1.4	68	1.4	68	1.2	63	1.3	-	-
NCGD (% DM)	84	0.4	82	0.4	83	0.4	83	0.6	-	-
OM	-	-	-	-	-	-	-	-	951	4.1
DM digestibility	-	-	-	-	-	-	-	-	0.71	0.007

AHEE, Acid hydrolysis ether extract; NCGD, Neutral cellulose gaminase degradability

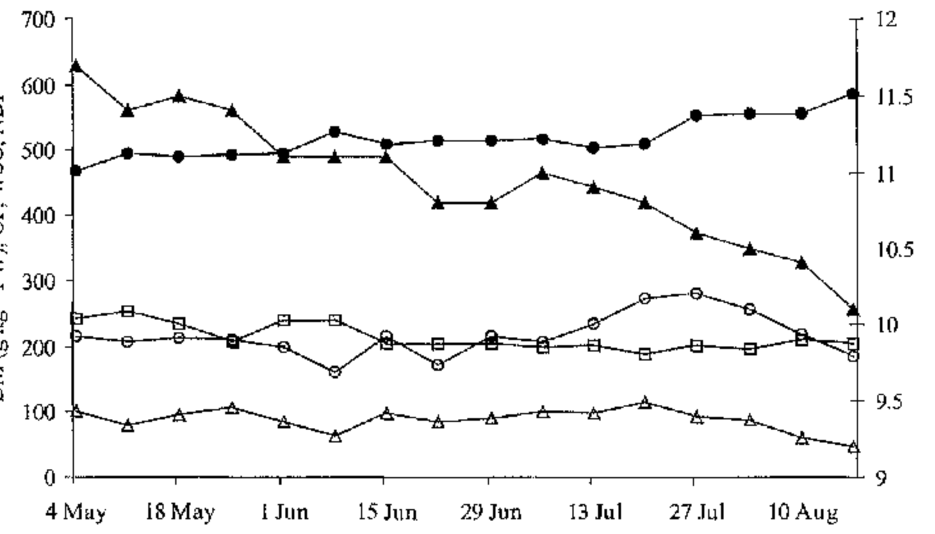


Figure 4.1 Weekly herbage analysis results (g kg^{-1} DM, unless stated otherwise); DM ○, CP □, WSC Δ, NDF ●, ME ▲

4.3.2 Sward surface height

Mean sward surface height over the experiment was 12.2 ± 0.05 cm. Mean sward height per measurement remained above 10 cm other than in week 15 when it fell to 9.4 cm (Figure 4.2). Mean sward height fluctuated most widely over the first four weeks and fell slightly after week 11. Variability between individual sward height measurements per week was highest mid-season and the greatest standard deviation in sward height measurements was observed between 19 June and 20 July (Figure 4.2). Frequency distribution of height measurements for weeks 4, 8, 12 and 16 of the Experiment is presented in Appendix 2.

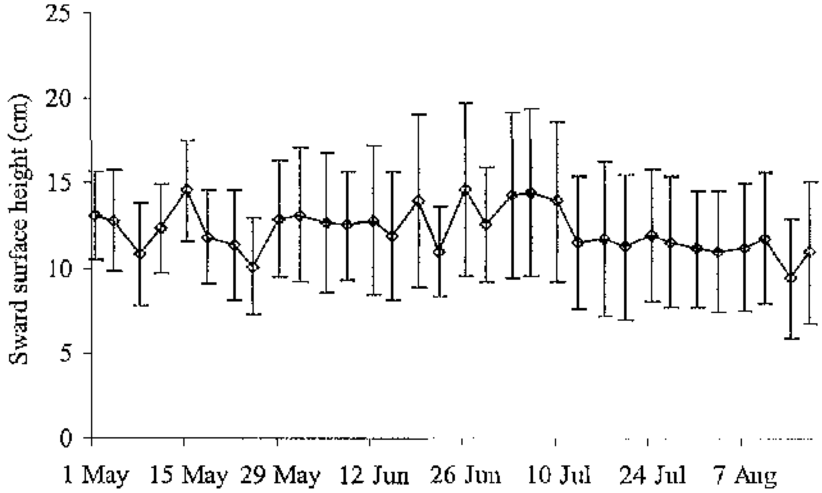


Figure 4.2 Mean sward surface height of grazed paddocks per week (bars indicate standard deviation of individual height recordings)

4.3.3 Animal performance

Means of treatment groups, and the statistical significance of effects of energy type and inclusion of the additive on animal performance, are detailed in Table 4.3. Graphs of mean weekly milk yield are presented in Figure 4.3 (energy source) and Figure 4.4 (additive).

Concentrate energy source had no significant effect on milk yield for the experimental period overall (P > 0.05). Milk yields however, tended to be slightly higher for the HS concentrate and this effect increased over the grazing season ($P <$ 0.05 in weeks 12 and 16). Concentrate energy source had no significant effect on fat concentration. Fat yield therefore tended to be higher for cows fed the HS concentrate towards the end of the experiment as a direct result of increased milk yield. Effect of concentrate energy source on concentration and yield of milk protein and lactose was not significant ($P > 0.05$). Although there was no significant difference in urea concentration between treatments for the experimental period overall, weekly analyses demonstrate a tendency for lower milk urea concentration from the HS treatment, and this effect was significant in weeks 4, 8, 15 and 16 ($P <$ 0.01).

Table 4.3 Mean milk yield, milk composition, yield of constituents, urea concentration and production, liveweight change and condition score change

	†Energy source (SF)		Additive (AD)			*P* value		
	HS	HF	AD-	AD+	s.e.m.	SF	AD	SF*AD
Milk yield (kg d^{-1})	33.9	33.3	32.9^{a}	34.4^{b}	0.56	0.279	0.015	0.916
Milk composition (g kg^{-1})								
Fat	36.6	37.1	37.5	36.2	1.07	0.725	0.301	0.801
Protein	33.1	33.1	33.0	33.2	0.41	0.898	0.511	0.465
Lactose	46.3	46.0	45.9	46.4	0.28	0.255	0.119	0.205
Yield of constituents (g d^{-1})								
Fat	1201	1195	1176	1220	41.2	0.959	0.311	0.838
Protein	1086	1065	1034^{a}	1117^{b}	26.8	0.473	0.006	0.701
Lactose	1528	1492	1459^{a}	1561^{b}	42.5	0.422	0.029	0.802
Milk urea								
Mg kg^{-1}	346	343	346	343	5.4	0.689	0.733	0.342
Mg d^{-1}	12054	11796	11522^{a}	12327^{b}	336.0	0.467	0.043	0.621
Liveweight change (kg d^{-1})	0.36	0.27	0.23^{a}	0.40^{b}	0.063	0.130	0.008	0.410
Condition score change (units $week^{-1}$)	0.006	0.005	0.004	0.006	0.0047	0.777	0.726	1.000

† Means with different superscripts in this and subsequent tables differ significantly $P < 0.05$.

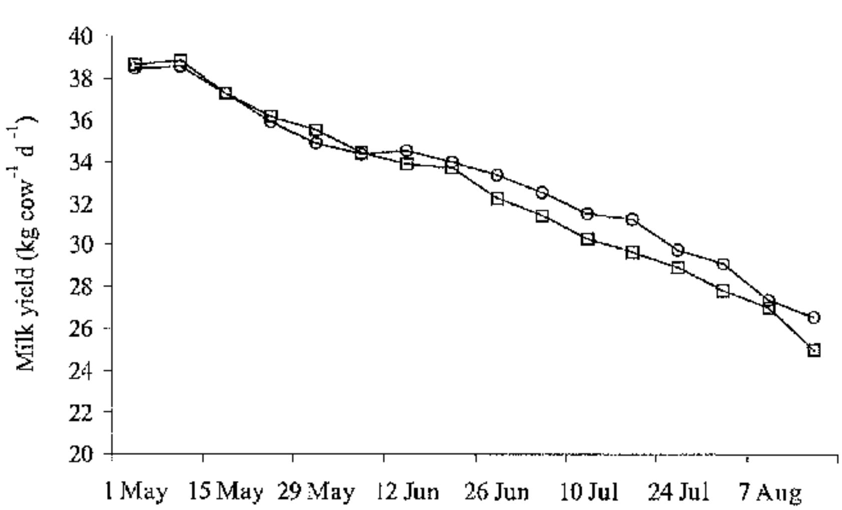


Figure 4.3 Effect of concentrate energy source, HS (○) and HF (□), on mean weekly milk yield

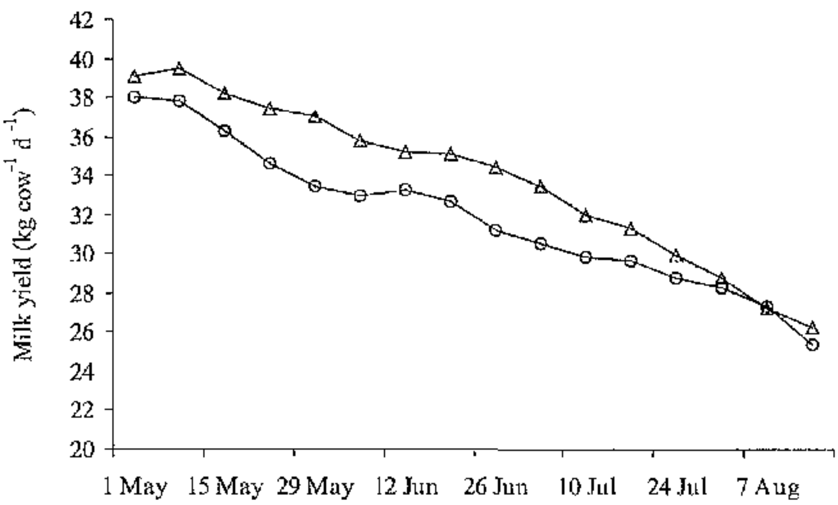


Figure 4.4 Effect of inclusion of additive, AD+ (Δ) AD- (○), and on mean weekly milk yield

Inclusion of the additive had a positive effect on milk yield ($P < 0.05$). Over the first 12 weeks of the experiment, milk yield of the AD+ treatment cows was on average 2.4 kg d^{-1} higher than the AD- treatment. In the final four weeks however, this positive effect was reduced to on average 0.61 kg milk cow^{-1} d^{-1} and was not statistically significant ($P > 0.05$). The additive tended to have a negative effect on fat concentration and this effect was significant in weeks 1, 3, 4, and 5 ($P < 0.05$). Fat yield from the AD+ treatment cows however was higher because increased milk yield compensated for a slight reduction in milk fat concentration. There was a slight tendency for the additive treatment to give a higher milk protein concentration ($P <$ 0.05 in week 16). An interaction between treatments was observed in week 2 ($P =$ 0.015), week 3 ($P = 0.014$), and week 4 ($P = 0.002$), when higher milk protein concentration was evident for the HS AD- and HF AD+ treatments. For the experimental period overall, additive treatment had a positive effect on yields of milk protein ($P < 0.001$) and lactose ($P < 0.05$), which was a result of the positive effect of the additive on milk yield. There was a tendency for milk urea concentration to be slightly lower for the additive treatment and this effect was significant in weeks 5, 7, 14, and 15 ($P < 0.05$). Overall, total urea production per day however was slightly greater for the AD+ treatment ($P < 0.05$) as a consequence of increased milk volume.

On average, animals gained live weight and condition over the experiment. Concentrate energy source had no significant effect on live weight or condition score change. Additive however had a positive effect on live weight ($P < 0.01$), and animals fed the additive gained on average 0.17 kg live weight d^{-1} more than the control group. Inclusion of the additive had no significant effect on condition score.

4.3.4 Herbage intake

Herbage intakes per treatment group over the intake measurement periods as estimated using the *n*-alkane method, are presented in Table 4.4.

Table 4.4 Herbage intake estimated by *n*-alkane method (kg DM cow^{-1} d^{-1})

	Energy source		Additive			*P* value		
	HS	HF	AD-	AD+	s.e.m.	SF	AD	SF*AD
22 May - 26 May	16.7	16.5	16.4	16.8	0.63	0.767	0.524	0.574
19 June - 23 June	16.8	16.6	15.5^a	17.9^b	0.64	0.633	0.001	0.002
17 July - 21 July	18.3	17.7	17.0^a	20.0^b	0.71	0.404	0.013	0.202
14 August - 18 August	19.2	17.8	18.0	19.0	0.90	0.097	0.285	0.367

n-Alkane estimates of herbage intake were slightly higher for the HS concentrate for each measurement period. Difference in herbage intake between HS and HF treatments increased as the season progressed, although effects of energy source were not significant ($P > 0.05$). *n*-Alkane estimates of herbage intake were highest for additive fed cows for each measurement period. This effect was significant ($P < 0.05$) for the estimates made in June and July when herbage DM intake was on average 2.4 and 3.0 kg cow^{-1} d^{-1} higher respectively for the additive compared to control treatment.

Herbage intakes as estimated by energy balance (AFRC, 1993) are presented in Table 4.5.

Table 4.5 Herbage intake estimated by energy balance (AFRC, 1993) (kg DM cow^{-1} d^{-1})

	Energy source		Additive			*P* value		
	HS	HF	AD-	AD+	s.e.m.	SF	AD	SF*AD
22 May - 26 May	15.0	15.8	15.4	15.4	0.64	0.211	0.971	0.245
19 June - 23 June	14.6	15.0	14.5	15.0	0.67	0.621	0.481	0.866
17 July - 21 July	14.8	14.3	13.4^a	15.6^b	0.57	0.368	<0.001	0.697
14 August - 18 August	12.6^a	11.3^b	11.5	12.5	0.56	0.015	0.085	0.797
Mean 22 May – 18 August	14.5	14.4	14.1	14.8	0.46	0.921	0.126	0.609

Herbage intakes for each measurement period per treatment were lower when estimated by energy balance compared to the *n*-alkane method. Unlike *n*-alkane estimates, energy balance estimates indicate a slightly higher herbage intake from the HF concentrate in the first 2 measurement periods, although differences between treatments were not significant ($P > 0.05$). Over the last 2 measurement periods, energy balance calculations estimate a positive effect of the HS treatment on herbage intake, and this is significant in the period from 14-18 August ($P < 0.05$). Energy balance calculations indicate improved herbage intake with the additive treatment in all but the first measurement period (17-21 July, $P < 0.001$).

Overall, there was a positive linear relationship between estimates of herbage intake using the energy balance and *n*-alkane methods, and r^2 values ranged from 0.31 to 0.45 for the four intake recording periods (Figure 4.5).

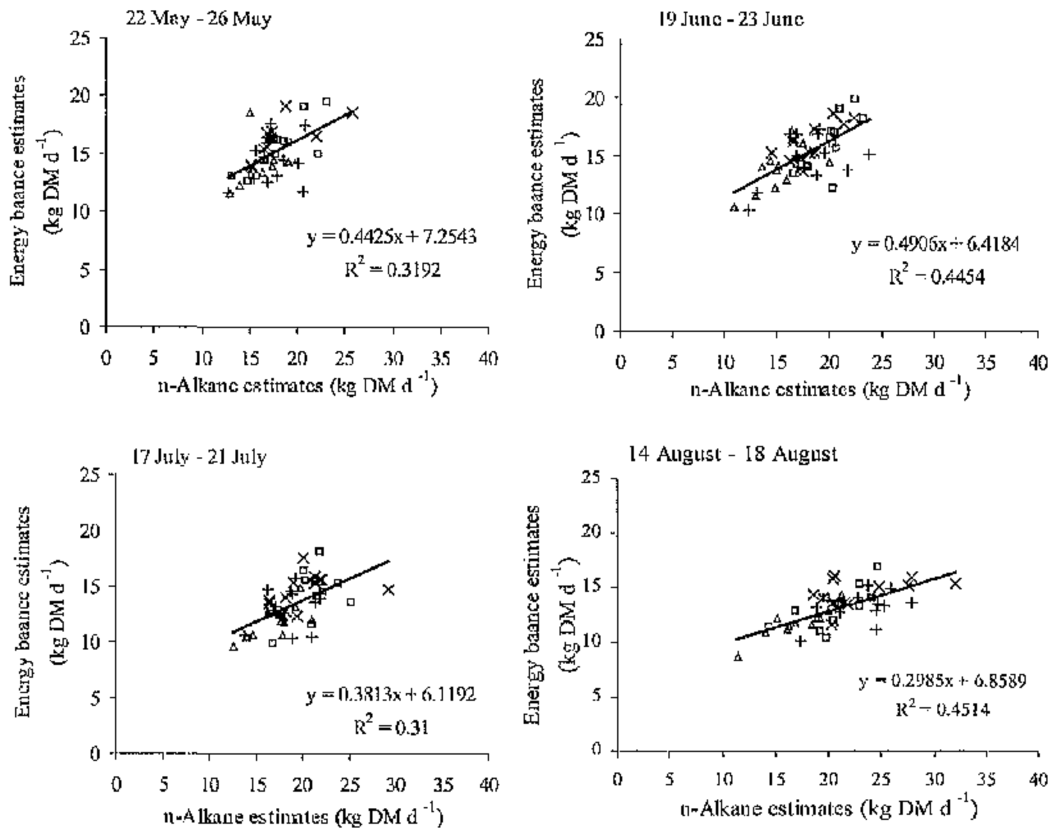


Figure 4.5 Relationship between estimates of herbage intake using energy balance (AFRC, 1993) and *n*-alkane (Mayes *et al.*, 1986) methods for treatments HSAD- (+), HFAD- (x), HSAD+ (Δ), HFAD+ (□), per recording period

4.3.5 Grazing and ruminating behaviour

Time spent grazing was on average 17, 75, and 43 minutes cow^{-1} d^{-1} greater for the HF compared to HS treatment for the May, June and July observations respectively, and this effect was significant in for the June and July observations (P < 0.001) (Table 4.6). In the final observation period in August however, grazing time was greater for the HS treatment (P < 0.05). During May and June observations, cows fed AD- spent longer grazing and this effect was significant in May (P < 0.05). In July and August, cows offered the additive spent longer grazing and this effect was statistically significant for the July recordings (P < 0.05). A significant interaction between concentrate treatment group and behaviour is observed in a number of instances. This could suggest differences in sward conditions between paddocks, or differences in recording between observers.

Cows fed the HS concentrate spent more time ruminating in May (P < 0.05) and July (P < 0.01), while cows fed the HF concentrate spent more time ruminating in weeks June and August (P < 0.001) (Table 4.6). An increase in grazing time between energy sources and additive or control treatments was most often accompanied by a reduction in ruminating time.

Table 4.6 Grazing and ruminating behaviour of cows (minutes cow^{-1} d^{-1})

		Energy source		Additive			*P* value		
		HS	HF	AD-	AD+	s.e.m.	SF	AD	SF*AD
25 – 26 May	Grazing	533	550	562	521	13.6	0.339	0.039	0.002
	Ruminating	473	429	444	457	13.2	0.013	0.484	<0.001
22 – 23 June	Grazing	489	564	536	517	9.9	<0.001	0.183	0.223
	Ruminating	455	549	484	521	10.3	<0.001	0.01	0.218
20 – 21 July	Grazing	532	575	537	570	9.0	<0.001	0.015	<0.001
	Ruminating	523	483	504	502	11.2	0.009	0.912	0.593
17 – 18 August	Grazing	588	530	547	570	16.4	0.010	0.320	0.010
	Ruminating	436	489	459	467	9.8	<0.001	0.558	<0.001

Estimated rates of herbage intake from *n*-alkane estimates of herbage intake (Table 4.4) and grazing behaviour observations (Table 4.6) demonstrate some significant effects of concentrate treatment (Table 4.7). Rate of herbage intake was higher for cows offered the high starch compared to high fibre concentrate in June and July measurement periods (P < 0.01, and P <0.01 respectively), and cows offered the additive had a higher rate of intake in May, June and July (P < 0.001 in June).

Table 4.7 Herbage intake rate estimated from *n*-alkane measurements of herbage intake and grazing behaviour observations (Table 4.6) (kg DM h^{-1} cow^{-1})

	Energy source		Additive			*P* value		
	HS	HF	AD-	AD+	s.e.m.	SF	AD	SF*AD
25 - 26 May	1.92	1.82	1.79	1.95	0.088	0.260	0.930	0.058
22 - 23 June	2.08	1.78	1.76	2.09	0.083	<0.001	<0.001	0.101
20 - 21 July	2.08	1.85	1.91	2.02	0.084	0.008	0.229	0.360
17 - 18 August	1.98	2.01	2.00	2.00	0.131	0.804	0.955	0.187

4.4 Discussion

4.4.1 Grazing and herbage intake

Herbage intakes of up to 20.7 kg d^{-1} have been reported for high yielding cows offered a high herbage allowance (Buckley and Dillon, 1998), and it seems grazed herbage may have the potential to meet requirements for levels of production up to between 27 and 33 kg milk d^{-1} (Mayne, 2001; Mayne *et al.*, 2000). Over the course of the present experiment, it was aimed to provide cows with a high herbage allowance and to avoid restriction of herbage intake by sward factors. Sward surface height was generally maintained between 10 to 12 cm, which is within the recommended range of sward heights to allow high levels of herbage intake (Peyraud and Gonzalez-Rodrigez, 2000).

Estimates of mean herbage intake per treatment group reached a maximum of 20 kg DM cow^{-1} d^{-1} although there were some higher estimates of intake for individual cows within treatments. These results appear high compared to maximum herbage intakes reported previously (Mayne, 2001). Furthermore, in the present experiment, it would have been expected that intake would decrease as the experiment progressed, corresponding to a decline in sward quality later in the season (Beever *et al.*, 2000; Parsons and Chapman, 2000), and lower energy requirements of later lactation cows. *n*-Alkane results however contradict this theory and estimated herbage intakes per treatment increased as the experiment progressed.

n-Alkane estimates of herbage intake were consistently higher than those estimated form energy balance calculations (AFRC, 1993) and there was a positive linear relationship between the two measurements. Others, for example Fisher and Dowdeswell (1995), have similarly reported higher estimates of herbage intake using the *n*-alkane procedure compared to energy balance relationships. Both methods have possible sources of error for herbage intake estimation. A limitation of the energy balance system is that it relies on accurate measurement of liveweight change. Live weight is dependent upon the level of gut fill. Weighing animals at the same time each day can reduce these effects of variability in gut fill on measurements of liveweight change. However, estimation of the composition of liveweight change to obtain an accurate estimation of energy balance is difficult. Additionally, energy balance calculations do not take into consideration differences in efficiency of energy and nutrient utilisation between treatments. For example, there could have been greater efficiency of energy and N utilisation when the additive was included in the diet due to improved synchrony of energy and N availability in the rumen, as well as increased RUP supply.

The most likely source of error in the *n*-alkane procedure is in obtaining a sample of herbage that has representative *n*-alkane concentrations to that of the diet consumed by the animal (Dove and Mayes, 1996). For cattle grazing homogenous pastures, it is considered satisfactory to collect herbage samples by hand (Mayes and Duncan, 1999; Vulich *et al.*, 1993). Differences in *n*-alkane concentrations however exist between plant parts, species and varieties (Dove and Mayes, 1996; Laredo *et al.*, 1991). In this experiment, as the season progressed and sward quality and structure became more heterogeneous, cows would have greater opportunity to select a diet that differed in *n*-alkane composition compared to a sample collected by hand. This could explain larger differences in estimates of intake between the *n*-alkane and energy balance techniques towards the end of the experiment. Therefore while comparisons may be made between treatments within each of the measurement periods, comparing estimates of herbage intake over time could be less reliable. It is also possible that concentrate treatment influenced composition of herbage selected, and therefore caused differences in *n*-alkane composition of diet compared to sampled herbage. For example, an increase in herbage intake when additive is included in the concentrate could increase the proportion of stem in the diet if animals grazed deeper into the sward (Delagarde *et al.*, 2000b). Only a single sample of herbage for each treatment group was analysed for *n*-alkane concentrations. Variability in the diet selected by individual animals is therefore not taken into consideration, which could affect the accuracy of estimates of individual intakes.

Over each of the intake and grazing behaviour recording periods, no significant interactions between grazing time and herbage intake were observed ($r^2 < 0.001$). In the final observation period in August however, grazing time was greater for the HS treatment ($P < 0.05$) and this is correlated with a higher *n*-alkane estimate of herbage intake ($P = 0.097$). In weeks 12 and 16, cows offered the additive spent longer grazing. This effect was statistically significant in week 12 ($P < 0.05$) which is correlated with higher estimates of herbage intake. A tendency for higher estimates of daily herbage intake from the higher starch concentrate and inclusion of the additive, were associated with higher estimates of rate of herbage intake. This could indicate an effect of concentrate treatment on bite rate or bite mass.

4.4.2 Concentrate energy source

Results from the present study demonstrate that concentrate energy source has a limited effect on milk production and this is in agreement with others, for example, Fisher *et al.* (1996), Gibb *et al.* (2002a), and Sayers *et al.* (2000). These studies however have tended to suggest slightly improved animal performance with higher fibre concentrates, and some experiments report significant beneficial effects of feeding less rapidly fermentable energy sources (Khalili and Sairanen, 2000; Meijs, 1986; Schwarz *et al.*, 1995). The current experiment actually demonstrates a slight positive effect of the HS concentrate on milk production and herbage intake. In agreement with these results van Vuuren *et al.* (1986) and Valk *et al.* (1990) have also reported slight positive effects of a higher starch supplement on milk production. In the present study, the trend towards higher milk production from the HS compared to HF concentrate appears to have been supported by higher herbage intake and rate of intake, and this difference between treatments increased as the season progressed. Valk *et al.* (1990) similarly reports increased herbage DM intake with a higher starch concentrate.

It is possible that the HS concentrate increased supply of fermentable energy to the rumen and improved the balance between rapidly available rumen N from herbage and fermentable energy (Beever *et al.*, 2000; Kolver *et al.*, 1998). Others who similarly report beneficial effects of a higher starch supplement, have found improved efficiency of microbial protein synthesis and increased duodenal amino acid flow from a high starch concentrate than from either grass alone, or when a more fibrous supplement was fed (van Vuuren *et al.*, 1993). A tendency for improved animal performance and higher herbage intake with the HS concentrate may therefore have resulted from increased microbial activity and breakdown of cellulose, and improved microbial protein flow to the small intestine. A reduction in excess N as a result of improved N use for microbial growth and improved efficiency of N utilisation, is supported by results which demonstrate a significantly lower milk urea concentration towards the end of the experimental period from animals fed the HS concentrate.

Variation in types of starch fed between studies may explain some differences in results. It appears that a negative effect of a high starch concentrate on animal performance has been reported when ingredients used have been based on the most rapidly degradable sources of carbohydrate, for example barley grain (Fisher *et al.*, 1996; Khalili and Sairanen, 2000). A higher starch concentrate has had less of an effect on intake or milk production when less rapidly degradable sources of starch such as maize (Schwarz *et al.*, 1995; Valk *et al.*, 1990), or a mixture of ingredients (van Vuuren *et al.*, 1986), have been fed. The HS concentrate in the present study was formulated to contain a mixture of ingredients including some less rapidly degradable sources of starch, such as maize. There was therefore less likelihood of this concentrate providing such a rapidly available energy supply to cause disruption to the rumen environment, compared to a high starch concentrate which was, for example, entirely cereal based.

Differences in total starch plus sugar content of supplementary concentrates have also varied between studies. The starch content of concentrates fed by Sayers *et al.* (2000), who reports a slight positive effect of higher fibre on milk production and a significant positive effect of higher fibre on intake, for example, was 470 and 62 g kg^{-1} DM for starch and fibre supplements respectively. This difference in starch content is significantly greater than the difference in starch levels between HS and HF concentrates in the present study, which contained 299 and 182 g starch kg^{-1} DM respectively. Total starch plus sugar content in the experiment by Sayers *et al.* (2000) was 544 and 278 g kg DM^{-1} for starch and fibre supplements respectively, while the difference in total starch plus WSC in the present study was again lower at 415 for HS and 299 g kg^{-1} for HF treatments. Equivalent figures for experiments by Khalili and Sairanen (2000) are 600 and 366 g starch plus sugars kg^{-1} DM, and results from Meijs (1986) were 385 and 102 g kg^{-1} DM starch plus sugars, for high starch and high fibre concentrates respectively. Additionally, it might be expected that higher levels of concentrate would elicit greater effects of concentrate energy source. For example, Sayers *et al.* (2000) reported a significantly greater milk fat content and lower milk protein content with a high starch concentrate when cows were offered 10 kg FW concentrate d^{-1}, compared to when they were supplemented with only 5 kg d^{-1}. There could also be an effect of ratio of concentrate to herbage in the total diet (Schwarz *et al.*, 1995) and in the current study, concentrates formed an increasing proportion of the total diet as the season progressed.

Changes in response to energy type over the season and an increase in the positive effect of the HS concentrate over the duration of the current experiment could be associated with herbage quality. A higher ME content and digestibility of herbage early in the season may have increased total ruminally available carbohydrate and amount of quickly fermentable carbohydrate. As a result, the effects of concentrate type may have been more evident, with a lower amount of starch required to cause disruption to rumen fermentation and a reduction in pH. In early season there would therefore be little benefit in increasing amount of ruminally available energy to improve synchrony of supply of ruminally available energy and N to increase microbial activity (Beever *et al.*, 2000). As herbage ME content and digestibility decreased and NDF increased as the season progressed however, an improved supply of quickly degradable carbohydrate from the high starch concentrate may have improved energy supply to rumen microbes and had a positive effect on microbial growth and activity. Lower levels of supplementary starch and sugars may be required to cause a disruption to the rumen environment when supply of quickly fermentable carbohydrate, and in particular WSC concentration, of herbage is high. Sayers *et al.* (2000) for example reported herbage that was higher in WSC at between

152 and 170 g kg^{-1} DM compared to between 72 and 101g kg^{-1} DM in the present study, which could contribute to the slightly negative effect of a high starch supplement which they observed.

Evidence suggests therefore that energy availability and carbohydrate degradability of the whole diet determines responses to different energy sources. Differences in supplementary energy sources, protein types, and levels of concentrate fed; as well as varying herbage availability and quality, can therefore explain some of the differences in results between studies. Evidence suggests therefore that the starch fed in this experiment has not been of the type or level to have a disruptive effect on rumen fermentation. A more rapidly fermentable energy source may have actually had some beneficial effects by providing a more immediate supply of energy to rumen microbes to complement energy available from herbage.

4.4.3 Additive treatment

The additive chosen for this study is described as a sugar mineral complex that binds to dietary protein through association with specific structures within the 2 and 3 dimensional protein structure. As a consequence, the additive is proposed to alter the structure of dietary protein and so reduce its degradability in the rumen. This could improve the synchrony of supply of ruminally available energy and N and possibly increase microbial activity and microbial protein synthesis, as well as reduce rumen ammonia levels and so improve the efficiency of N utilisation (Beever *et al.*, 2000; Delagarde *et al.*, 1999). Inclusion of the additive to concentrate fed in the current experiment increased herbage intake and herbage intake rate; and had significant beneficial effects on animal performance. A reduction in degradability of dietary protein would also increase RUP supply to the animal, which along with potentially higher microbial protein flow to the small intestine, could improve animal performance (Hongerholt and Muller, 1998). Increased microbial activity could also improve digestion of fibre and passage of material through the rumen and so encourage increased herbage intake (Arriaga-Jordan and Holmes, 1986), further supporting higher levels of milk production, as observed in the current experiment.

Milk production response to the additive declined towards the end of the experiment, and in particular from 24 July onwards. It is possible that this was a consequence of a change in sward characteristics and herbage quality, or a reduction in energy and nutrient requirements from later lactation cows. As milk production potential declines, milk production responses to increased supply of RUP are expected to be reduced (Hongerholt and Muller, 1998; Neilsen *et al.*, 2002). Towards the end of the study, mean sward surface height was slightly lower, the sward became more heterogeneous with increased rejected areas and stemmier grass, and herbage quality declined. These changes in sward characteristics are associated with a reduction in bite mass and hence potential herbage intake (McGilloway and Mayne, 1996; Swain, 2000). Cows would therefore have less opportunity to increase their intake of herbage later in the season, even if this was encouraged by supplementation with the additive. Herbage CP concentration decreased over the experiment and it is expected herbage protein degradability would also be lower later in the season (Tamminga and Sudekum, 2000). There would therefore be less benefit in feeding an additive to reduce the rate of protein degradation on the synchrony of supply of ruminally available energy and N. Results of this experiment indicate a tendency towards a positive effect of a more rapidly available, higher starch, energy source later in the season, suggesting energy supply to the rumen became more limiting. Similarly, a reduction in milk urea concentration suggests a more synchronous supply of energy and N to the rumen as the season progressed. Further reduction in herbage protein degradability by the additive may therefore have been of less benefit to improve rumen energy and N supply as the season progressed.

4.5 CONCLUSION

Concentrate energy source had a minimal effect on animal performance under the conditions of the experiment. Milk yield tended to be higher from animals on the HS treatment, and the advantage of a starchy concentrate increased as the season progressed. This effect could be related to changes in sward characteristics and herbage quality over the season. Increased energy supply to the rumen from the starchy concentrate may be a better complement for the higher NDF, and lower ME and WSC content of herbage later in the season. Consequently, microbial activity may be improved leading to better digestion of fibre and slightly improved herbage intake. There could therefore be some benefits of supplementing grazing cows with specific energy sources according to sward characteristics and the composition of herbage selected.

Supplementation of grazing cows with an additive formulated to reduce the rate of dietary protein degradation can have significant beneficial effects on animal performance. Cows fed the additive had higher milk and milk protein yields over the course of this experiment and showed an average advantage in milk yield of 1.5 kg cow^{-1} d^{-1}. Improved levels of milk production were supported by increased estimates of intake rate and daily herbage intake. Other factors not measured in the experiment, such as increased RUP and microbial protein supply, could also be important. The positive effects of inclusion of the additive however were reduced towards the end of the study. It is possible that this was a result of reduced sward and herbage quality, lower nutrient requirements of later lactation cows, or an increase in the proportion of concentrates in the total diet. Higher estimates of daily herbage intake were generally associated with higher estimates of rate of herbage intake and so there could be an effect of concentrate treatment on bite rate or bite mass.

Effects of concentrate composition on herbage intake and animal performance therefore appear to be dependant upon interactions with animal requirements and milk production potential, concentrate level and proportion in the total diet, and potential intake from the sward and the composition of herbage selected.

CHAPTER 5.0 EXPERIMENT 3

Vertical distribution of herbage mass in a perennial ryegrass sward cut to simulate different management practices, and implications for herbage intake of grazing dairy cows

5.1 INTRODUCTION

Herbage intake characteristics of a sward can have major effects on milk production from grazed pasture and animal responses to supplementation (Delaby *et al.*, 2001). Experiments 1 and 2 highlight the importance of interactions between herbage intake and the efficiency of concentrate supplementation for milk production. The evidence suggests potential herbage intake from the sward interacts with responses to increasing levels of supplementation. Efficiency of supplementation for milk production for example, increases as herbage allowance or sward height declines (Delaby *et al.*, 2001; Wilkins *et al.*, 1995), and as sward and herbage quality deteriorates later in the grazing season (Delagarde *et al.*, 2000a; Stakelum, 1986a). Similarly, effects of the composition of concentrate on herbage intake and milk production responses can be determined by the quantity and quality of herbage selected (Meijs, 1986; Schwarz *et al.*, 1995). Concentrate supplementation strategies and the efficiency of milk production from grazing cows could therefore be improved through better understanding of effects of sward characteristics on grazing behaviour and herbage intake.

Bite mass is a major determinant of intake rate from a sward (McGilloway *et al.*, 1999; McGilloway and Mayne, 1996). Cows can compensate for low bite mass by increasing grazing time and bite rate. However these variables reach a plateau at approximately 60 bites minute^{-1}, and 9 to 10 hours d^{-1} (McGilloway *et al.*, 1999; Rook *et al.*, 1994). Bite mass is consequently a particularly important determinant of herbage intake for higher yielding cows which are more likely to reach these behavioural constraints on grazing time and bite rate when they attempt to meet their high intake requirements. Processes that occur at the individual bite site which affect bite mass therefore have important effects on herbage intake over time and at the larger spatial scale (Ungar *et al.*, 2001). Bite mass can be described as a product of bite volume and the bulk density of herbage in that volume (Ungar *et al.*, 2001). A bite can be idealised as rectangular or cylindrical and can be described most simply in terms of bite depth and bite area (Hodgson, 1981; Parsons *et al.*, 1994).

Sward surface height and bulk density are important factors affecting bite dimensions, and hence bite mass, when cows graze green, leafy, vegetative swards (Barrett *et al.*, 2001; Peyraud and Gonzalez-Rodrigez, 2000). It has been demonstrated that bite depth of grazing dairy cows is equal to a constant proportion of sward surface height, regardless of the initial height and whether or not tillers have been grazed previously. Under normal grazing conditions, cows remove approximately one third of tiller height (Barrett *et al.*, 2001; Wade *et al.*, 1989). A greater bite depth of up to one half of tiller height however has been observed when animals have been fasted before grazing (McGilloway *et al.*, 2000).

Cattle have a strong tendency to graze by horizon (Ungar, 1996). Bite mass from a sward is therefore dependant upon herbage DM in the grazed horizon. It is well recognised that bulk density increases with depth of the sward (Clark *et al.*, 1974), however variations in bulk density between horizons of the sward can also arise as an affect of grazing management and time of year (Delagarde *et al.*, 2000b).

Description of the vertical distribution of mass in a sward, combined with knowledge of grazing behaviour, could be used to determine herbage DM in the grazed horizon and to estimate potential bite mass. The relationship between height and the vertical distribution of mass could be described using a similar equation to the well-established relationship between leaf area index and the penetration of solar radiation through leaf canopies of different structure, originally proposed by Monsi and Saeki (1953). The relationship is described by Newton and Blackman (1970) (Equation 5.1):

$$I_L = I_O \, e^{-KL} \tag{5.1}$$

where I_L describes the relationship between leaf area index and penetration of solar radiation through the canopy, I_O is light intensity at top of the stand, K is a constant, and L is leaf area above level of which I_L is measured. The vertical distribution of herbage mass in a sward could therefore similarly be described as (Equation 5.2):

$$Y = M \, e^{-b\,(h)} \tag{5.2}$$

where Y is equal to herbage mass above a specified sward height (h), M is total herbage mass per unit area, and b is a constant. Newton and Blackman (1970) used the constant (K) as a description of light penetration through canopies. In canopies composed of broad-leafed species for example, K was larger and ranged from 0.6 to 0.9, compared to grasses when K values ranged from 0.3 to 0.9. There could similarly be values of the constant b (Equation 5.2) that describe the vertical distribution of herbage mass in a sward according to sward height and total herbage mass. From knowledge of grazing behaviour and bite dimensions, this could help generate a general description of bite mass.

The following study involved cutting a perennial ryegrass sward *(Lolium perenne)* to two residual sward heights at different ages of regrowth to simulate different grazing managements. The experiment was designed to test the hypotheses that there are differences in structural characteristics of the sward according to cutting treatment; that there is a general relationship between sward height, total herbage mass and the vertical distribution of mass; and that differences in sward structure can have an affect on estimated bite mass.

Objectives of the study were;

- To describe changes in sward structure and vertical distribution of herbage mass at different regrowth ages of swards cut to different residual heights.
- To explore whether there is a general relationship that can be used to describe the vertical distribution of herbage mass in a sward.
- To investigate effects of sward structure and the vertical profile of herbage mass in the sward on estimates of bite mass in the uppermost grazing horizon.

5.2 Materials and Methods

5.2.1 Experimental sward

The experiment was carried out on a sward of predominantly perennial ryegrass (*Lolium perenne*), on a sandy loam soil. The sward received fertiliser applications at a rate of 50 kg nitrogen ha^{-1} in mid-March, mid-April, and at 3-weekly intervals from 10 May 2001.

5.2.2 Experimental design and treatments

The experiment was conducted over a 9-week period from 3 May to 5 July 2001. Twenty-four plots of 15 m * 2 m were created and blocked into 3 replicates. Within each block, a plot was randomly allocated to one of 8 treatments (Table 5.1). Swards were cut to target residual heights of either 6 cm or 12 cm, and cut either twice week^{-1} or at intervals of 7, 14 or 21 days. Cut herbage was removed from the sward.

Table 5.1 Experimental treatments

Treatment	Residual sward height (cm)	Frequency of cutting to residual sward height
T1	6	Twice week^{-1}
T2	6	7 days
T3	6	14 days
T4	6	21 days
T5	12	Twice week^{-1}
T6	12	7 days
T7	12	14 days
T8	12	21 days

A lawnmower modified to cut to the required heights was used to cut and lift grass from plots. Plots were all cut to target residual heights of 6 cm or 12 cm on 3 May. Thereafter, according to treatment, plots were cut on the Monday of each week beginning 7 May, and those to be cut twice weekly were cut again on the Thursday of each week.

5.2.3 Sward measurements

Sward measurements and samples were taken weekly for all plots on Monday before any plots were cut. Areas of 1 m * 2 m were designated per week as sampling areas in each plot.

5.2.3.1 Sward surface height

Fifteen sward height measurements were recorded at random in each plot on each measurement day using an HFRO sward stick (Barthram, 1986).

5.2.3.2 Vertical distribution of herbage mass

Vertical distribution of herbage mass in each plot was measured by the stratified clip technique using a herbage gripping device (Barthram, 1992). This instrument had gripping surfaces of 9 cm long and 1 cm deep, and opened to 2.5 cm wide. The instrument was placed into the sward at ground level, the jaws closed and the gripped sample of sward cut at ground level. The sample was lifted out of the sward and turned on edge over a box with a cutting guide so that horizons of the sward could be cut into separate boxes. Samples were cut into 2 cm horizons from ground level to 12 cm, and into 4 cm horizons above 12 cm. The maximum height per sample was recorded. Six samples were taken per plot and bulked into the specified horizons per plot. Fresh weight (FW) of herbage samples in individual horizons for each plot was recorded before samples were dried for 16 hours at 100 °C and dry matter (DM) weighed.

5.2.3.3 Herbage mass

Herbage mass was estimated weekly from the total DM collected in sward gripper samples, assuming a sward gripper sample area of 135 cm^2 per plot.

Herbage mass was also estimated weekly over the final 4 weeks of the experiment by cutting 3 strips of herbage of 1 m * 0.076 m per plot to ground level using battery operated hand shears. FW of herbage cut from each plot was recorded before samples were oven dried and weighed to determine herbage DM ha^{-1}. Residual herbage mass was recorded on 11 June after all treatments were cut to residual sward surface heights. Herbage mass was then estimated over the following 3 weeks by sampling plots weekly prior to any being cut to their residual sward height.

5.2.3.4 Tiller density

Tiller density was determined fortnightly throughout the experiment. Four 20 cm^2 cores were removed at random from each plot on each occasion. The numbers of live, dead and aerial tillers in each core were recorded. A tiller was defined as live if 0.5 or more of leaf and sheath components were green. Tillers were assumed to be dead when 0.8 or more of leaf and sheath components were brown. Tillers with 0.2 to 0.5 of green components were dissected and classified according to the presence or absence of a green growing point (Fisher *et al.*, 1995).

5.2.3.5 Botanical composition

Samples of herbage cut to ground level were taken from each plot and bulked per treatment in week 6 when all treatments were at their maximum age of regrowth. Mechanical separations of herbage samples into leaf, stem and dead material were carried out and DM of each component measured.

5.2.4 Calculations and statistical analysis

5.2.4.1 Sward structure

Measurements of sward surface height, total herbage mass, mean sward bulk density, and DM in individual horizons of the sward were calculated per treatment when swards reached their maximum regrowth ages. Mean sward bulk density was calculated using total mass of herbage DM as recorded from sward gripper samples, and the mean of the HFRO measurements of sward surface height.

Vertical distribution of herbage mass was calculated as mean DM per horizon per treatment per week. Distribution of herbage DM was then described by fitting an exponential relationship to measurements of cumulative herbage mass to residual sward heights of each horizon through the sward (Equation 5.3):

$$Y = M\,e^{-b\,(h)} \qquad (5.3)$$

where Y equals herbage mass (g DM) above residual sward height (h) (cm), M is total herbage mass and b is a constant. The y intercept was fixed as total herbage DM of the sample. This relationship could then be used to calculate total herbage DM above or below specified sward heights.

Differences in the proportion of total herbage mass in the top third of sward height between treatments, calculated using Equation 5.3 results, were examined to provide further comparisons of vertical distribution of mass.

5.2.4.2 Bite mass

Estimates of bite mass from swards created by different cutting treatments were made with a simple model of bite dimensions, where bite volume was assumed to be cylindrical or rectangular, and equal to the product of bite depth and bite area (Parsons *et al.*, 1994). Mean bite mass per treatment per week was estimated from equations describing the vertical distribution of herbage mass, assuming a bite depth of one third and one half of maximum sward height, and a constant bite area of 100 cm^2. A maximum bite depth of up to 4 cm above ground level was applied to calculations. Results from weeks in which swards had reached their maximum regrowth age were subject to one way analysis of variance (Lawes Agricultural Trust, 1998), to examine effects of cutting treatment.

5.3 Results

5.3.1 Weather

Total weekly rainfall, weekly mean of daily minimum and maximum air temperature, and average daily minimum and maximum air temperatures for 4 weeks preceding the experimental period, and for the duration of the experiment, are presented in Figure 5.1.

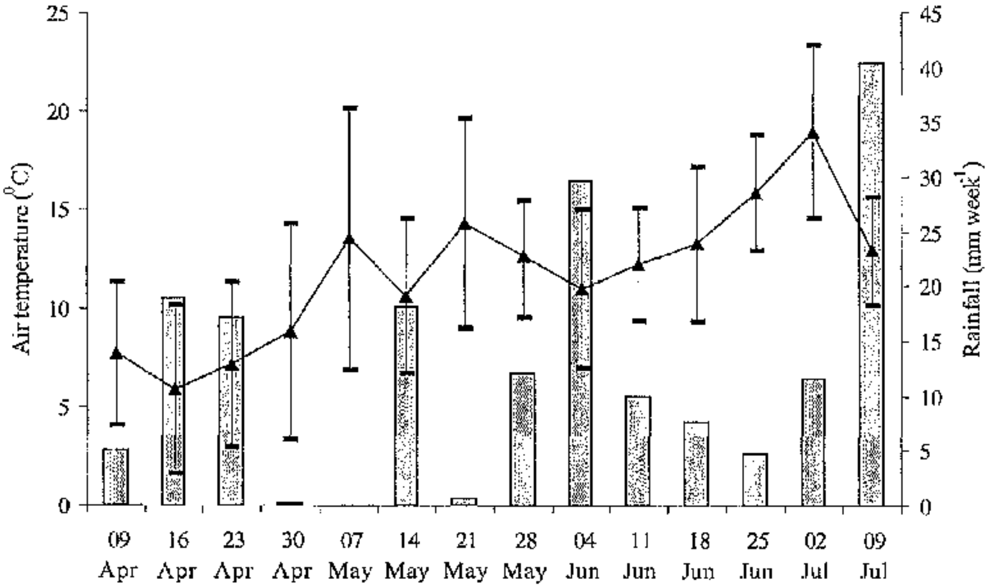


Figure 5.1 Weekly mean of daily minimum and maximum air temperature (▲), average daily minimum and maximum (-) and total weekly rainfall (bars)

5.3.2 Sward characteristics

5.3.2.1 Sward surface height

Mean sward surface heights (± s.e.m.), as measured after all swards were cut to their residual heights at the start of the experiment on 3 May, were 6.7 ± 0.08 cm for Treatments 1 to 4, and 12.9 ± 0.09 cm for Treatments 5 to 8.

Mean sward heights over the course of the experiment, and variation in average sward heights per week per Treatment when swards reached their maximum age of regrowth, are presented in Table 5.2. Results are presented for measurements taken using the HFRO sward stick (Barthram, 1986) and from the maximum horizon heights recorded from sward gripper samples. Mean weekly results per Treatment are presented in Appendices 3 and 4.

Table 5.2 Mean sward height per treatment (cm) when swards at maximum regrowth ages, and s.e.m. between recordings; as measured with sward stick (Barthram, 1986) and from sward gripper samples

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Sward stick								
Mean	9.0	11.8	19.8	27.4	15.1	19.9	27.4	35.2
s.e.m.	0.41	0.48	1.62	1.88	0.48	0.85	2.74	3.44
Sward gripper samples								
Mean	10.0	13.6	22.7	32.0	16.4	22.1	28.3	37.3
s.e.m.	0.27	0.75	1.44	3.36	0.31	1.00	2.40	2.04

Sward surface height increased with increasing regrowth interval, and was higher for swards cut to a target height of 12 cm compared to 6 cm at equivalent ages of regrowth. The coefficient of variation in sward stick measurements generally increased with regrowth intervals of up to 14 d, and was then slightly lower at the maximum regrowth interval.

Sward height measurements from gripper samples were consistently higher than sward stick measurements. Between treatments, this difference in height ranged from 1 cm to 4.6 cm, and averaged 9.7 percent. Greater measurements of height from the gripper results would be expected since these were an average of the maximum height in each sample when samples were laid over the cutting grid; and leaves in the gripper sample were extended before cutting herbage into horizons.

Mean weekly increase in sward height per treatment, calculated from sward stick height measurements (Appendix 3), and variation between mean weekly heights, is presented in Table 5.3. Mean weekly increase in sward height was generally higher with increasing regrowth interval. There was a greater increase in sward height between weeks for swards cut to the higher residual sward height at equivalent regrowth ages, except for swards cut twice per week which showed slightly increased growth when cut to a residual height of 6 cm compared to 12 cm.

Table 5.3 Mean herbage growth per Treatment (cm week^{-1}) calculated from weekly sward stick height measurements, and s.e.m. between recordings

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Mean	4.08	5.07	6.62	6.89	3.90	6.97	7.60	7.42
s.e.m.	0.720	0.481	0.671	0.657	0.844	0.854	1.093	0.728

5.3.2.2 *Herbage mass*

Herbage mass estimated from samples taken using sward grippers when swards were at their maximum ages of regrowth, both to ground level and above 4 cm, are presented in Table 5.4. Details of mean weekly herbage mass per treatment are shown in Appendices 5 and 6. Herbage mass increased with increasing regrowth age, and was higher for swards cut to 12 cm compared to 6 cm at equivalent ages of regrowth.

Table 5.4 Herbage mass (kg DM ha^{-1}) per Treatment to ground level and above 4 cm when swards at maximum regrowth age (kg DM ha^{-1}) calculated from sward gripper samples

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Total herbage mass to ground level								
Mean	4497	4853	5483	7144	7575	7779	7914	9370
s.e.m.	291.7	164.9	247.0	482.1	370.9	185.2	427.2	573.8
Herbage mass above 4 cm								
Mean	807	1311	2323	4157	3767	4306	4822	6333
s.e.m.	40.9	83.3	350.7	627.9	190.9	142.7	308.6	663.3

Comparison of methods for estimating total herbage mass in weeks 7, 8, and 9, demonstrate estimates of herbage mass to ground level made from sward gripper samples were on average 1.126 times greater than estimates from cut strips of herbage (Table 5.5). Herbage mass for all treatments in Weeks 7, 8, and 9 was on average 2899 kg DM ha^{-1} when estimated from cut strips of herbage, compared to 6548 kg DM ha^{-1} for the sward gripper estimates. Relative differences between treatments per week for each measurement method however were generally similar.

Table 5.5 Herbage mass to ground level (kg DM ha^{-1}) in weeks 7, 8, and 9 estimated from sward gripper measurements and cut strips of herbage (s.e.m. between plots per treatment)

Residual height		6 cm				12 cm			
Cutting frequency		Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Estimated herbage mass from cut strips									
Week 7	Mean	2206	1665	1985	1563	3301	3072	3298	2826
	s.e.m.	243.1	75.9	169.1	62.9	287.5	280.6	143.5	135.9
Week 8	Mean	2409	2268	2481	2996	3765	3531	3977	4054
	s.e.m.	92.4	129.3	194.7	528.9	378.0	62.1	200.4	473.1
Week 9	Mean	2197	2335	1996	2982	3510	3649	3306	4197
	s.e.m.	112.4	104.1	206.5	300.1	266.4	389.6	194.1	56.4
Estimated herbage mass from gripper samples									
Week 7	Mean	6519	5457	4309	4148	8790	7617	7222	7173
	s.e.m.	952.5	665.8	691.0	267.1	948.9	461.8	675.9	713.8
Week 8	Mean	4728	4321	5963	4815	8494	8012	7830	6568
	s.e.m.	321.7	1013.2	333.3	279.6	582.2	497.1	587.8	661.3
Week 9	Mean	4531	5802	5444	7013	7728	8259	7049	9358
	s.e.m.	543.6	303.4	256.6	507.0	647.6	611.2	590.4	326.6

5.3.2.3 Sward density

Mean sward bulk density between treatments declined with increasing age of regrowth (Table 5.6). There was no difference in bulk density to ground level between swards cut to different residual sward heights at equivalent regrowth intervals. Bulk density of herbage above 4 cm however was greater for swards cut to 12 cm compared to 6 cm.

Herbage mass to ground level recorded from sward gripper samples and HFRO sward surface height for all treatments in weeks 1 to 9 were positively correlated (Figure 5.2).

Table 5.6 Bulk density of herbage to ground level and above 4 cm when swards at maximum regrowth ages (kg DM m^{-3}), calculated from sward gripper samples and sward height (Barthram, 1986)

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Bulk density to ground level								
Mean	5.16	4.20	2.81	2.61	5.08	3.98	3.00	2.68
s.e.m.	0.548	0.264	0.198	0.084	0.358	0.196	0.395	0.098
Bulk density above 4 cm								
Mean	1.69	1.72	1.45	1.76	3.45	2.76	2.12	2.04
s.e.m.	0.159	0.113	0.104	0.145	0.240	0.130	0.175	0.017

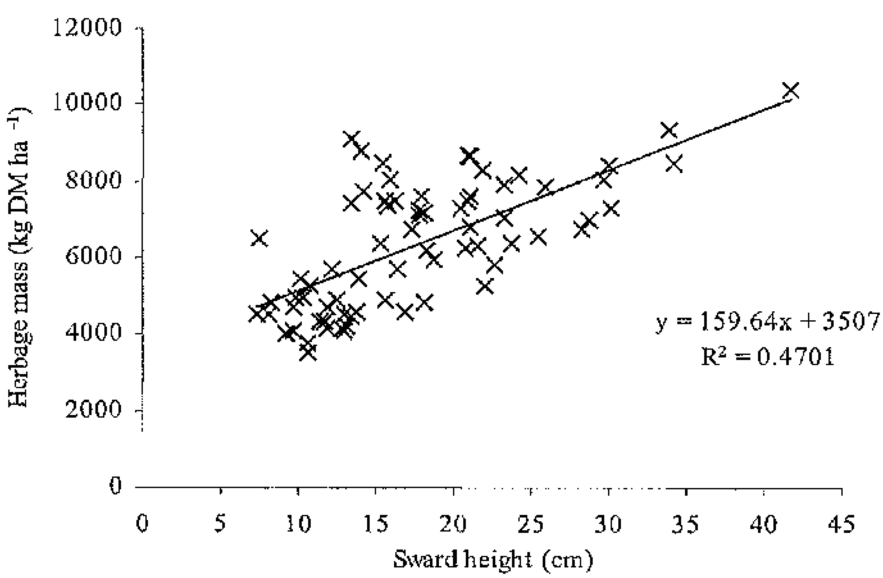


Figure 5.2 Relationship between sward surface height and herbage mass

5.3.2.4 Tiller density

Total tiller density (Table 5.7) increased for treatments cut to a residual sward height of 6 cm twice per week. Swards cut every 21 days showed a reduction in tiller density over the experiment, while total tiller density of swards cut to 12 cm and either every 7 or 14 days, tended to show a reduction in tiller density over time.

Table 5.7 Total tiller density (tillers 20 cm^{-2}) per treatment per week (s.e.m. between plots)

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Week 1	24.4	34.9	31.8	35.7	22.2	32.1	25.7	27.7
s.e.m.	4.32	4.17	4.71	6.84	4.78	7.04	4.26	4.30
Week 3	37.9	44.1	25.8	35.9	26.7	19.9	21.9	23.4
s.e.m.	8.93	10.92	5.33	6.40	6.29	4.08	4.62	4.33
Week 5	28.5	40.3	29.5	25.9	25.7	26.6	24.8	18.4
s.e.m.	5.74	4.75	5.85	3.10	4.80	3.97	5.14	4.82
Week 7	30.4	21.8	30.9	20.3	18.3	23.6	18.8	18.0
s.e.m.	5.65	2.98	5.09	3.95	2.49	3.88	3.75	4.35
Week 9	44.8	27.3	34.3	19.8	21.3	24.6	20.3	11.8
s.e.m.	4.42	3.81	4.75	4.27	3.88	4.63	5.51	2.76

5.3.2.5 Botanical composition

Proportion of live leaf in the sward tended to increase as regrowth age increased, and was greater for swards cut to residual sward heights of 6 cm compared to 12 cm at equivalent regrowth ages (Table 5.8). Treatments cut to 12 cm comprised a greater proportion of stem. The ratio of live leaf to stem was higher for swards cut to the lower sward height and also generally increased with regrowth age. Plots cut to 6 cm at 21 day intervals contained a particularly high proportion of leaf to stem.

Table 5.8 Proportion of total DM comprising live leaf, dead leaf, stem, and other plant material; plus ratio live leaf : stem DM (week 6)

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Grass								
Live leaf	0.52	0.54	0.53	0.77	0.37	0.43	0.43	0.46
Dead leaf	0.17	0.10	0.12	0.04	0.16	0.12	0.16	0.09
Stem	0.30	0.33	0.32	0.18	0.43	0.45	0.41	0.40
Ratio live leaf : stem	1.71	1.64	1.63	4.17	0.85	0.95	1.03	1.13
Other plant material	0.01	0.03	0.03	0.01	0.03	0.00	0.00	0.05

5.3.2.6 Vertical distribution of herbage mass

Herbage mass and bulk density increased from the top to the base of the sward. Differences between treatments are presented in Table 5.9 and Figure 5.3. Mean weekly herbage DM per horizon per treatment is detailed in Appendices 7, 8, and 9.

Table 5.9 Mean vertical distribution of herbage per treatment when at maximum regrowth ages (g DM 135 cm^{-2})

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Horizon height (cm)								
0-2	3.60	3.25	2.90	2.72	3.16	2.92	2.57	2.70
2-4	1.39	1.53	1.37	1.31	1.99	1.77	1.61	1.40
4-6	0.73	0.93	0.99	1.04	2.06	1.91	1.78	1.46
6-8	0.25	0.38	0.50	0.66	1.32	1.29	1.10	0.98
8-10	0.09	0.25	0.41	0.62	0.99	1.03	0.87	0.88
10-12	0.02	0.13	0.36	0.59	0.44	0.59	0.58	0.69
12-16		0.07	0.43	0.90	0.24	0.54	0.70	1.02
16-20		0.01	0.25	0.72	0.03	0.31	0.65	0.92
20-24			0.12	0.56		0.14	0.51	0.90
24-28			0.04	0.30		0.01	0.22	0.64
28-32			0.03	0.13			0.08	0.43
32-36			0.02	0.07			0.02	0.34
36+				0.01				0.29

Results show a slightly higher bulk density of herbage DM in the 4-6 cm horizon compared to the 2-4 cm or 6-8 cm horizons, for treatments cut to a residual sward height of 12 cm. This could be an effect of the distribution of stem and dead material through layers of the sward.

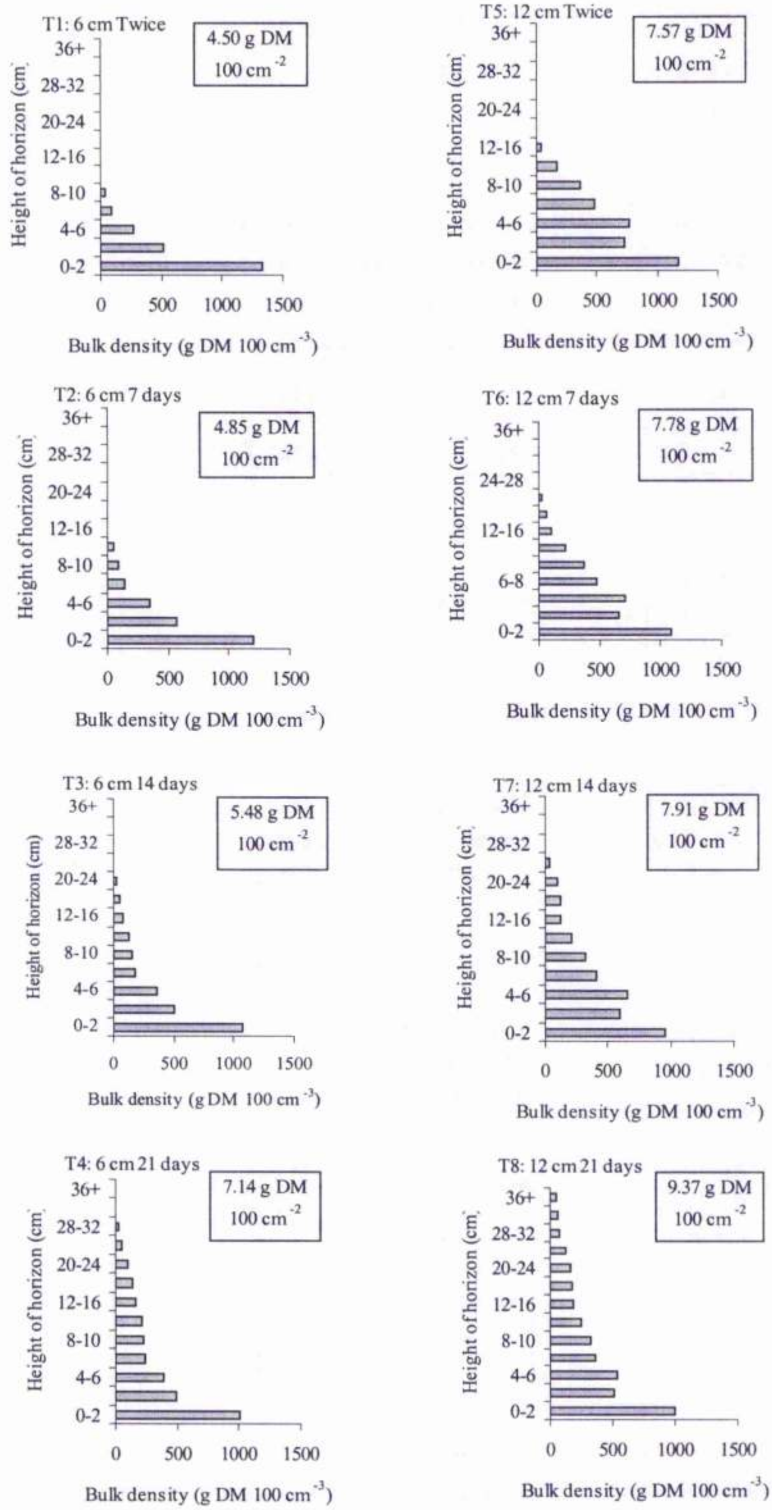


Figure 5.3 Mean bulk density per horizon per treatment, and total herbage mass to ground level from gripper samples, when swards at maximum regrowth ages

Mean cumulative herbage mass to residual heights of horizons cut from the sward gripper samples in the weeks when treatments reached their maximum regrowth ages are presented in Figure 5.4 and Figure 5.5. Exponential relationships fitted through the results, with the y intercept fixed as total herbage mass, are also shown for each treatment.

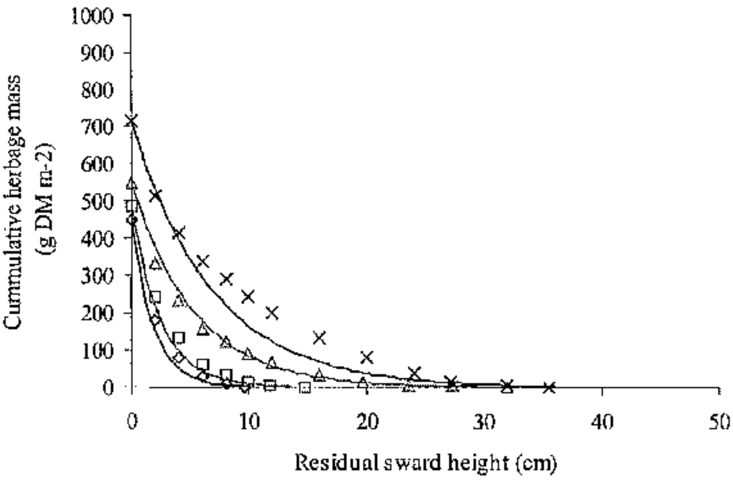


Figure 5.4 Mean cumulative herbage mass according at residual sward heights of horizons, and exponential relationships fitted to results T1 (◊), T2 (□), T3 (Δ), T4 (x)

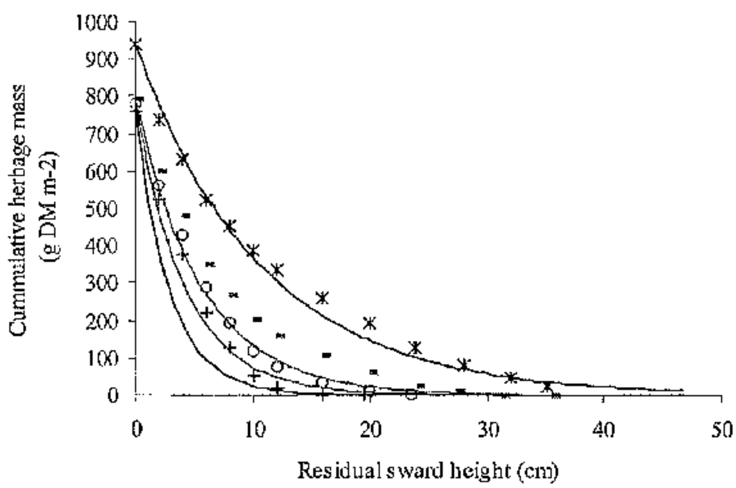


Figure 5.5 Mean cumulative herbage mass at residual sward heights of horizons, and exponential relationships fitted to results T5 (+), T6 (○), T7 (–), T8 (*)

Equations fitted to mean results of the cumulative vertical distribution of herbage mass through the sward are presented in Table 5.10. Results per treatment per week are presented in Appendix 10.

Table 5.10 Equations of exponential relationships ($Y = Me^{-b(h)}$) fitted to results of mean cumulative herbage mass (Y) (g DM m^{-2}) at residual sward heights (h) (cm), total mass (M) (g DM m^{-2}), and r^2 values, per Treatment

	Equation of trend line†	r^2
T1	y = 449.7 e^-0.5369 h	0.961
T2	y = 485.3 e^-0.3933 h	0.953
T3	y = 548.3 e^-0.1866 h	0.997
T4	y = 714.4 e^-0.1463 h	0.911
T5	y = 757.5 e^-0.3428 h	0.920
T6	y = 777.9 e^-0.2335 h	0.907
T7	y = 791.4 e^-0.1778 h	0.917
T8	y = 937.0 e^-0.0929 h	0.971

† ^, e raised to the power of $^{-b(h)}$

The empirically derived b values from the exponential relationships fitted to the distribution of mass for all treatments in weeks 1 to 9, plotted against sward surface height are presented in Figure 5.6. A strong relationship between b and sward height is observed when along with a power function relationship is fitted to the results (r^2 = 0.92).

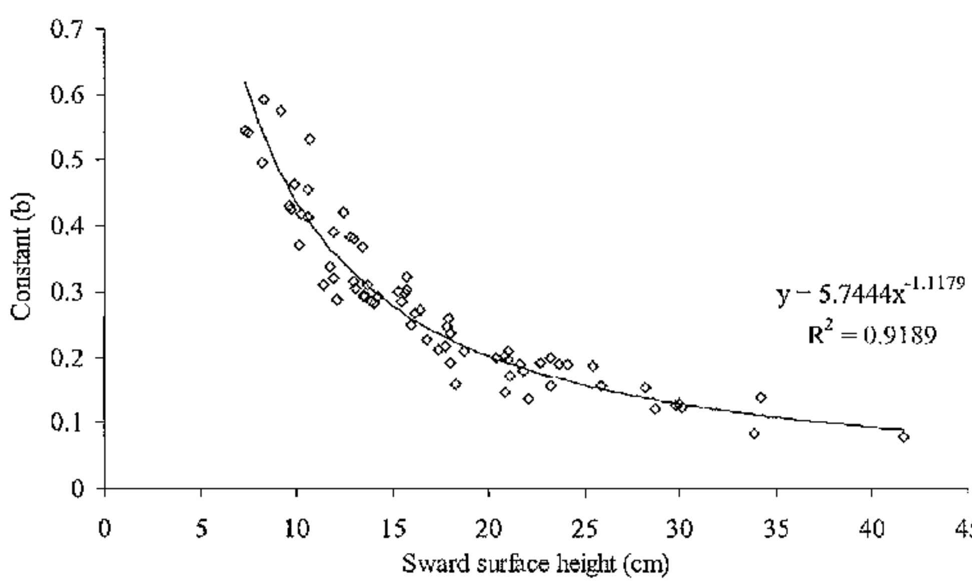


Figure 5.6 Power function relationship between constant (b) (from relationship $Y = Me^{-b(h)}$) and HFRO sward surface height (results all treatments weeks 1-9)

Proportions of total herbage DM in the top third of sward height per treatment for weeks when swards reached their maximum regrowth ages are shown in Table 5.11.

Table 5.11 Herbage mass (DM) in top third of HFRO sward height as a proportion of total herbage mass

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Mean	0.041	0.040	0.055	0.050	0.045	0.054	0.049	0.074
s.e.m.	0.0064	0.0037	0.0203	0.0061	0.0011	0.0104	0.0084	0.0096

5.3.3 Estimated bite mass

Estimates of bite mass from the swards created by the different cutting treatments, and assuming bite depths of a constant third or half of sward height, are presented in Table 5.12 and Table 5.13 respectively. Results are presented for weeks when swards were at their maximum regrowth ages, and as a mean of these weeks per treatment.

Table 5.12 Bite mass (g DM) estimated from bite depth 0.33 of sward surface height, bite area 100 cm^2

Residual height	6 cm				12 cm				s.e.m.	*P* value
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d		
Week 1	0.21	0.27			0.25	0.88				
Week 2	0.24	0.22	0.59		0.33	0.66	0.49			
Week 3	0.14	0.15		0.37	0.26	0.43		0.93		
Week 4	0.29	0.15	0.32		0.30	0.37	0.34			
Week 5	0.09	0.15			0.32	0.29				
Week 6	0.12	0.18	0.12	0.27	0.40	0.21	0.31	0.47		
Week 7	0.14	0.21			0.44	0.19				
Week 8	0.18	0.21	0.17		0.41	0.27	0.37			
Week 9	0.13	0.16		0.44	0.35	0.40		0.70		
Mean†	0.17^{a}	0.19^{a}	0.30^{ab}	0.36^{b}	0.34^{b}	0.41^{b}	0.38^{b}	0.70^{c}	0.045	<0.001
n	9	9	4	3	9	9	4	3		
s.e.m.	0.021	0.014	0.106	0.049	0.022	0.075	0.041	0.132		

†Means with different superscripts differ significantly $P < 0.05$, in this and subsequent tables

Table 5.13 Bite mass (g DM) estimated from bite depth of 0.50 sward surface height, bite area 100 cm^2

Residual height	6 cm				12 cm				s.e.m.	*P* value
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d		
Week 1	0.42	0.55			0.54	1.49				
Week 2	0.48	0.47	0.59		0.72	1.23	0.95			
Week 3	0.33	0.35		0.80	0.58	0.86		1.70		
Week 4	0.56	0.36	0.65		0.67	0.81	0.76			
Week 5	0.25	0.36			0.71	0.66				
Week 6	0.30	0.40	0.30	0.59	0.87	0.52	0.71	0.97		
Week 7	0.36	0.47			0.93	0.47				
Week 8	0.41	0.44	0.42		0.88	0.63	0.79			
Week 9	0.32	0.39		0.87	0.75	0.85		1.34		
Mean	0.38^a	0.42^a	0.49^a	0.75^b	0.74^b	0.84^b	0.80^b	1.34^c	0.064	<0.001
n	9	9	4	3	9	9	4	3		
s.e.m.	0.032	0.022	0.081	0.084	0.044	0.111	0.052	0.210		

From weekly results, estimates of bite mass ranged from 0.09 to 0.93 g DM, and 0.25 to 1.70 g DM, for bite depths of a third and half of sward height respectively. Estimated bite mass increased with increasing regrowth interval and mean bite mass was greater for swards cut to residual heights of 12 cm compared to 6 cm. For swards cut to 12 cm, bite mass was significantly greater for swards cut every 21 days compared to other treatments. There was no significant difference in estimates of bite mass between swards cut twice per week, every 7 days or 14 days, for swards cut to 12 cm ($P > 0.05$). Estimates of bite mass from swards cut to 6 cm were on average significantly greater when cutting frequency was 21 days compared to twice per week or 7 days. There was no significant difference however between cutting frequencies of 14 and 21 days. Assuming a bite depth of a third of sward height, a regrowth interval of 14 days was required when swards were cut to 6 cm, to achieve estimates of bite mass similar to the minimum estimated from swards cut to 12 cm.

Relationships between sward height and bite mass estimated when bite depth is either 0.33 or 0.5 of sward height for all treatments in each week of the experiment are presented in Figure 5.7. Variation between weeks per treatment was high and was greater for estimates of bite mass made assuming a bite depth of a third compared to a half of sward height (Table 5.12, Table 5.13, Figure 5.7). Variation could be attributed to differences in herbage growth rate and sward structure over the course of the experiment, which was indicated from sward height results. These changes may have been due to a combination of seasonal effects, weather conditions, and the cutting treatments imposed.

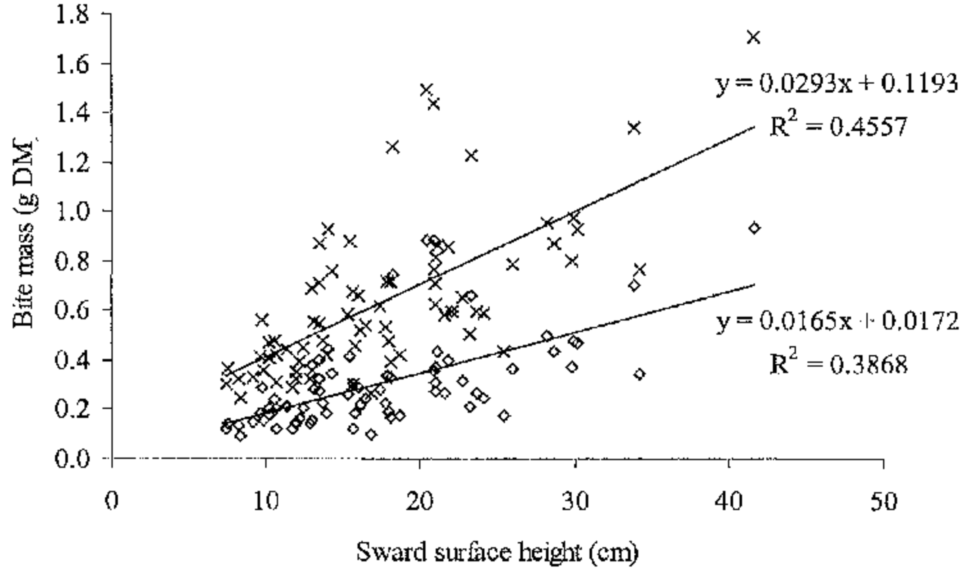


Figure 5.7 Relationship between HFRO sward surface height and bite mass estimated as 0.33 (◊) or 0.5 (x) sward height, bite area 100 cm^2

Variability in the relationship between bite mass, estimated when bite depth is 0.33 of sward height, and herbage mass in the top third of sward height demonstrates variability in the proportion of total herbage DM in the top third of sward height between swards (Figure 5.8).

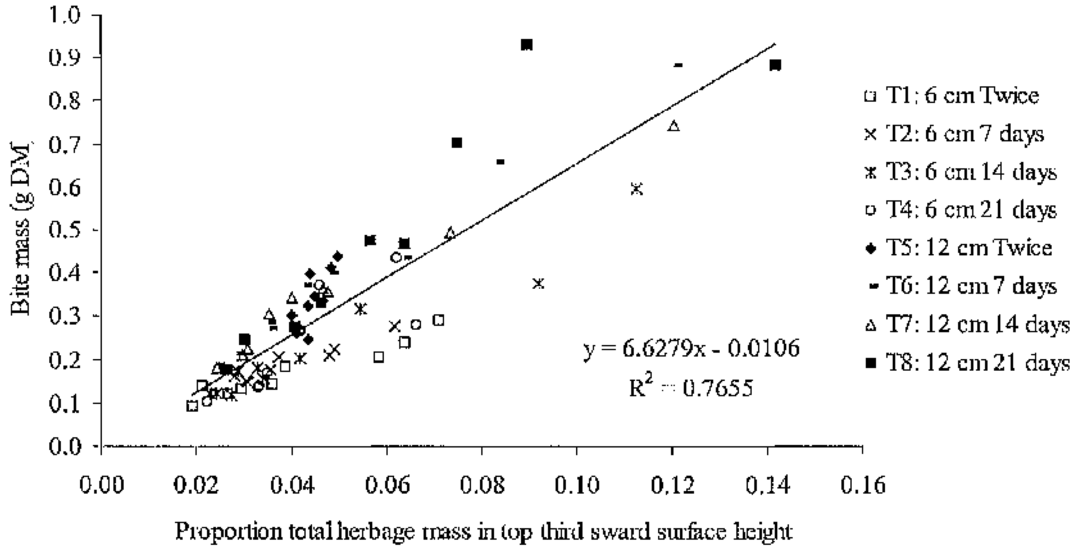


Figure 5.8 Relationship between proportion total herbage mass in top third of sward height (Barthram, 1986) and bite mass estimated from bite depth third sward height (results presented for weeks 1-9 for all treatments)

5.4 DISCUSSION

5.4.1 Measurement of vertical distribution of mass

The stratified clip technique developed by Barthram (1992) was considered to be the most appropriate method to provide the information required for the current study. The stratified clip technique has been used in a number of studies to measure vertical distribution of herbage in a sward, however various methods have been devised to collect samples from horizons. Some researchers have fitted vacuum attachments to powered hand shears (Forbes and Hodgson, 1985). Others have used methods to 'sandwich' a section of sward in a tall box with slats to separate horizons before cutting at ground level (Rhodes, 1971). Parga *et al.* (2000) simply took handfuls of grass at random from the swards which were cut at ground level and then into 5 cm layers; and in a similar type of procedure, Delagarde *et al.* (2000) cut grass to ground level from a 60 cm^2 quadrat. Samples were placed in a container with care to maintain the vertical structure of the sward, and then cut into layers. Another commonly applied technique has been to take turves of pasture (for example Swain, 2000). These turves can be cut to standard size, turned on edge, and then the material cut off at intervals down the sward profile. The stratified clip technique described by Barthram (1992) and utilised in the current study, also samples herbage from a known surface area of sward, and the gripping device ensures vertical structure of the herbage is maintained relatively well when removed from the sward.

Barthram *et al.* (2000) investigated three stratified clip methods to estimate herbage mass and its vertical distribution through the sward. The first method used the herbage gripping device (Barthram, 1992) which held a sample of 2 * 9 cm area while it was harvested and cut into layers in the field. The other methods involved cutting turves from the sward which were defined by either 10 * 10 cm or 2 * 9 cm quadrats. The methods were compared on three different swards; a sward before it was cut for silage, a sward grazed by cattle and a sward grazed by sheep. Total mass of herbage DM collected per area was higher with the gripping device on two of the three swards. The different methods however produced similar estimates of the vertical distribution of herbage mass in each of the sward types. The least variable results tended to be produced from the larger quadrat however the gripping device collected samples most quickly. The gripper method was most cost effective and was therefore suggested to be the most appropriate method to estimate vertical distribution of herbage, except where a high level of precision is required, in which case the turf method using a large quadrat would be preferred.

A limitation of the stratified technique is that it is destructive and leaves bare patches within the sward. A further problem has been the difficulty in removing cut herbage before it falls to a lower horizon, although this will largely be avoided with the sward gripper technique used in the current study when herbage samples are laid horizontally across a cutting grid. When measurements are being made on a tall canopy, and when leaves ascend then descend through horizons however, the technique may fail to collect herbage in the appropriate horizons, and leaves may be dragged upward increasing their height and increasing measurements of mass in higher horizons.

Vertical distribution of herbage in the sward has also been studied using point quadrat techniques (for example Hodgson, 1981). Graphs of the vertical distribution of point contacts within the sward are constructed from recordings allowing calculation of density of DM within any given horizon from knowledge of herbage mass per area and sward height. The advantage of point quadrat techniques over stratified clipping is that they are non-destructive. However they are particularly time consuming and do not allow the accurate measurement of DM in individual layers which was an essential requirement for the current study.

5.4.2 Effects of cutting treatments on sward structure

Distribution of herbage DM showed large variations from the top to the base of the swards. An increase in herbage DM and bulk density with increasing depth is compatible with results in the literature (for example, Clark *et al.*, 1974; Delagarde *et al.*, 2000). This can be related to an increasing proportion of sheaths, stem and dead material towards the base of the sward (Delagarde *et al.*, 2000b). Swards cut more frequently had lower herbage mass but increased mean bulk density. This may also be attributed to build up of stem, leaf sheaths and dead material in lower layers while cutting removed the lower density, leafy layers of regrowth.

Estimates of herbage mass ha^{-1} from sward gripper samples were significantly higher than measurements from cut strips of herbage. Barthram *et al.* (2000) similarly reports high estimates of total herbage mass from sward gripper samples. They suggest this could be due to the gripper unintentionally being placed into the sward to cover a larger area of sward than the actual area of the gripper.

An increase in bulk density in all layers of swards was observed as regrowth age increased. Delagarde *et al.* (2000) report a similar effect for strip-grazed sward and also a greater increase in bulk density with regrowth age earlier in the season. Very few results in the literature describe the shape of the vertical distribution of mass under different sward managements, or in relation to sward surface height or total mass. Barthram *et al.* (2000) compares measurements of vertical distribution between methods, but not between swards. Results from the present study demonstrate a good relationship ($r^2 = 0.92$) between b, from the general equation $Me^{-b(h)}$, and sward height; where M is total mass, b is an empirically derived value describing the distribution of herbage mass through the sward and h is the total sward height. This suggests that it might be possible to derive b based on sward height values and therefore link height with the vertical distribution of mass. This information could be used to generate a general relationship between sward height, total mass, and potential bite mass from a sward.

5.4.3 Estimates of bite mass

Measurements of bite mass in the literature from experiments with grazing cows range from approximately 0.23 g DM (Gibb *et al.*, 1997) to 1.28 g DM (McGilloway *et al.*, 1999). Bite masses predicted from the uppermost grazing horizon over the course of the current experiment range from 0.17 to 0.70 g DM, and 0.38 to 1.34 g DM, assuming constant bite depths of one third and one half of sward height respectively. These estimates of bite mass are therefore generally within the range of results reported from grazing cows. Results suggest gripper samples over-estimate herbage mass per unit area, and so it might be expected that estimates of bite mass based on these results will over-estimate of bite mass. This effect however should be consistent between estimates therefore allowing comparison between treatments and weeks.

Bite mass estimates did not consistently increase with increasing regrowth age of the sward. An increase in sward bulk density and bulk density of the grazed horizon compensated for lower sward height on swards that were cut more frequently. Bite mass was estimated to be significantly greater on the sward treatment cut to 12 cm and at the lowest cutting frequency, compared to any of the other treatments. This could be attributed to the higher sward height and also the higher density of material in the grazed horizon. At the high sward height of this treatment leaf material began to fold over, therefore increasing density of the grazed horizon.

Cattle have a strong tendency to graze by horizon (Ungar, 1996). From a simple description of bite dimensions, the profile of an initially uniform sward could therefore be divided into grazing horizons, each with a characteristic bite depth and bite area (Hodgson, 1981). There is evidence however that within a grazing horizon, bite mass declines with time during the depletion process (Laca *et al.*, 1994). Direct observation of cattle demonstrates that there is some overlap in bite areas with successive bites and Laca *et al.* (1994) has shown that bite area declines with the level of depletion of a sward. Studies with hand constructed swards demonstrate the sward surface grazed in the course of 6 bites comprises one contiguous area, rather than discrete areas separated with ungrazed herbage (Laca *et al.*, 1992a). Ungar and Ravid (1999) describe how grazing does not proceed across the surface of the sward in an entirely systematic way but instead leaves patches of herbage that yield bites of low bite area when subsequently grazed. They conclude that within-horizon bite area declines due to non-systematic bite placement, edge of area effects, and overlap of bite areas. Geometry of a bite may also be more complex than a simple cylindrical or rectangular model (Woodward, 1998).

Grazing therefore alters sward structure so that prediction of bite dimensions and bite mass from bite dimensions is more complicated at subsequent bites below the uppermost grazing horizon (Ungar and Ravid, 1999; Ungar *et al.*, 2001). Bites do not remove all herbage to a uniform depth but instead leave a range of residual heights. Ungar and Ravid (1999) describe how this unevenness of the surface of the sward could affect bite depth so that an identifiable horizon structure is not apparent at high levels of depletion. Variation in sward structure as a result of grazing along with possible differences in bite dimensions associated with sward structure make it difficult to predict bite mass from subsequent bites into the sward.

Results from grazing experiments support these theories. Bite mass has consistently been shown to decline as a sward is grazed down (Barrett *et al.*, 2001; McGilloway *et al.*, 1999). It appears therefore that higher bulk density with increasing depth in the sward is unable to compensate for reduced sward height, and along with effects of increased spatial heterogeneity (Swain, 2000) and a reduction in bite area (Laca *et al.*, 1992a), bite mass is reduced.

Bite mass is therefore expected to be highest in the uppermost grazing horizon, although mean bite mass as the sward is grazed down is very important in determining daily intake.

5.4.4 Relationship between cut and grazed swards

Grazing animals have a large effect on sward structure (Johnson and Parsons, 1985; Lemaire and Chapman, 1996). In particular, contamination with faeces and urine results in formation of frequently and less frequently grazed areas (McBride *et al.*, 2000), which differ in their structural and nutritional composition (Connell and

Baker, 2002; Garcia *et al.*, 2002). A grazed sward can therefore exhibit significant variations in the horizontal and vertical distribution of herbage between patches. This level of structural heterogeneity is not apparent in a cut sward. Creation of swards by cutting however does enable differences in structure to be investigated, and measurements to be made which can be used to study the implications and significance of different sward structures on herbage intake.

Variability in both vertical and horizontal structure across a grazed paddock has implications for use of the stratified clip technique to describe the vertical distribution of herbage mass. Calculating average values from samples taken from patches of different structure could provide misleading information regarding vertical structure of mass in the sward. This could in turn influence estimates of bite mass. It could be more appropriate to take samples from patches of sward of more similar structure, for example from frequently and infrequently grazed areas.

5.4.5 Estimation of bite mass from bite dimensions

While the evidence suggests cows bite to a depth of a constant proportion of sward height; and bite dimensions, bite mass and intake are dependent upon sward structural characteristics, there is variability in results between studies. Greater force required to sever a bite at lower depths in the sward as a result of greater sward density, could interact with sward height, and may determine the amount of tissue removed by affecting the depth to which the animal is prepared to graze (Illius *et al.*, 1995). The presence and height of stem and pseudo stem material within the sward could also form a barrier to grazing and affect bite mass (Barthram, 1980; Flores *et al.*, 1993).

A positive relationship has been demonstrated between bite area and sward height (McGilloway *et al.*, 2000). Although bite area is ultimately constrained by breadth of incisor arcade, cows grazing very tall swards can increase the effective bite area by sweeping herbage into mouth with their tongue (Laca *et al.*, 1992a). This has not been taken into consideration in estimates of bite mass in the current experiment. Bite depth must also reach a maximum above which anatomical constraints prevent further increases in bite depth. Laca *et al.* (1992a) observed mean bite depths from cattle of up to 10.2 cm, however bite depth declined as sward density increased.

There is a need therefore to quantify interactions between bite mass and sward structure using grazing cows, and also to consider interactions with other factors such as animal characteristics and supplementation.

5.5 CONCLUSION

Herbage DM in the volume of a bite is dependent upon the distribution of mass through horizons of the sward. Results from this study demonstrate large variations in sward height, sward density and vertical distribution of herbage mass, between swards that have been subjected to different cutting treatments. Results do suggest however that there could be a general relationship between sward height and vertical distribution of total herbage mass through the sward.

From the assumptions that bite depth is equal to a constant proportion of sward height, and that bite area remains constant irrespective of sward height or density, these sward cutting treatments were demonstrated to have significant effects on estimates of bite mass from the uppermost grazing horizon. Description of vertical distribution of herbage mass in a sward could therefore assist in prediction of bite mass and potential herbage intake from a sward. Whilst this experiment has demonstrated the potential for sward structure and the vertical distribution of mass to affect bite mass and intake, there is a need to quantify and examine interactions between sward characteristics and bite mass using grazing cows.

CHAPTER 6.0 EXPERIMENT 4

A technique to estimate bite mass of grazing cows from patches of a grazed sward using a transponder system, automatic behaviour recording equipment, and sward measurements

6.1 INTRODUCTION

A better understanding of the interactions between sward characteristics and grazing behaviour is required to improve prediction of herbage intake from a sward. Bite mass has a major effect on herbage intake and hence overall animal performance at pasture (McGilloway and Mayne, 1996). The importance of sward characteristics, and in particular sward height, density and leafiness, on bite mass is well recognised (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000). Results from Experiment 3 also demonstrate the potential for vertical distribution of herbage mass to have significant effects on bite mass and sward intake characteristics. Furthermore, sward structure across a grazed paddock is heterogeneous, and while this is expected to influence bite mass at the individual bite level, it also has an effect on overall herbage intake (Swain, 2000). In turn, active selection of specific sward components has important implications for understanding aspects of herbage intake (Schwinning and Parsons, 1999; Ungar and Noy-Meir, 1988). There is a requirement therefore for further detailed study of sward and animal interactions; and in particular to quantify effects of sward structure on bite mass using grazing animals. This would enable development of grassland management strategies and improve prediction of herbage intake potential from a sward. Additionally understanding of effects of supplementation on herbage intake could be advanced for development of appropriate supplementation strategies for grazing cows.

Quantifying interactions between sward structure and herbage intake has been hampered by the difficulty in making detailed measurements of herbage intake, and especially bite mass, under normal field grazing conditions. Calculation of bite mass requires measurement of herbage harvested from a specified area and a record of the number of bites taken. Existing techniques for measurement of bite mass include recording live weight before and after grazing (Barrett *et al.*, 2001; McGilloway *et al.*, 1999), or weighing material removed from oesophageally or ruminally fistulated animals (Jamieson and Hodgson, 1979), and counting the number of bites taken over the grazing period. Others have weighed hand-constructed swards before and after a recorded number of bites were taken (Laca *et al.*, 1992a) although these results might not be representative of normal grazing situations. A technique to measure bite mass under normal grazing conditions which has potential to consider heterogeneity of sward structure across the paddock has yet to be developed.

Measurement of bite mass within specific patches of a paddock to examine effects of sward structural heterogeneity requires a method to provide accurate spatial location of the animals, and to record grazing activity when they are within these patches. This information could be combined with measurements of herbage removed from the patches of the sward during grazing to estimate intake and bite mass. The potential for an active transponder system to record animal location and to derive patch level grazing efficiency values with dairy cows has been studied by Friend *et al.* (2002). Grazing efficiency was defined as length of time in a patch, and amount of material harvested from that patch during the given time interval estimated using measurements of sward height (Barthram, 1986). A similar active transponder system has been used successfully to study the activity of grazing animals at badger and rabbit latrine sites in relation to disease transmission (Daniels *et al.*, 2001; Hutchings and Harris, 1996). Information gathered from both an active transponder system and from automatic grazing behaviour recording equipment (for example, Rutter, 2000; Rutter *et al.*, 1997b), could potentially allow grazing time and number of bites in specific patches of the sward to be determined. If combined with measurements of herbage removed during grazing, this could give a better indication of grazing activity and also an estimate of mean bite mass from patches of the sward.

This experiment was designed to develop and evaluate methods to study grazing behaviour and measure bite mass, within patches of a grazed sward. Recordings of spatial location of animals using an active transponder system (Friend *et al.*, 2002) are combined with automatic recordings of their temporal pattern of grazing activity (Rutter, 2000; Rutter *et al.*, 1997) and sward measurements of herbage depletion.

Objectives of the study were;

- To investigate potential for development of a technique to measure bite mass within patches of a grazed sward using an active transponder system, automatic recordings of grazing behaviour and sward measurements.

- To conduct a preliminary experiment using these methods to make estimates of bite mass within patches of a grazed sward, and at different stages of herbage depletion over a 24-hour period.

6.2 MATERIALS AND METHODS

6.2.1 Experimental design

The experiment was conducted over a 4-day period from 24 to 27 April 2002, and involved four cows which grazed one-day paddocks with dimensions of 20 * 25 m (500 m^2). Cows were moved to a new paddock each day after the afternoon milking.

6.2.2 Animals and sward

Multiparous Holstein-Friesian cows which were on average 67 ± 7.1 days calved and had an average milk yield of 36.6 ± 4.77 kg d^{-1} at the start of the experiment were used. Cows were turned out to pasture for an increasing proportion of the day from 8 April, and turned out for 24 hours d^{-1} from 15 April. During the experimental period, animals were offered 6 kg fresh weight (FW) concentrate d^{-1}, split equally between morning and afternoon milkings. Concentrate was on average 877 g kg^{-1} dry matter (DM), and contained 191 g kg^{-1} DM crude protein, 90 g kg^{-1} DM acid detergent fibre, 205 g kg^{-1} DM neutral detergent fibre, 292 g kg^{-1} DM starch, and 12.2 MJ metabolisable energy (ME) kg^{-1} DM. The sward was predominantly perennial ryegrass (*Lolium perenne*), on free draining, sandy loam soils.

6.2.3 Animal measurements

The Bewator Cotag Granta Compact access control system (Bewator Cotag Ltd., Mercers Row, Cambridge, CB5 8EX, UK) was adapted to study activity of grazing cattle (Friend *et al.*, 2002; Swain *et al.*, 2002) (Figure 6.1). It was used to identify time periods cows spent within specific patches of the sward in each paddock.

This system involves surrounding a patch of sward to be monitored with a loop aerial. The aerial detects and reads active transponder tags (911, Bewator Cotag Ltd.) using a low frequency radio signal. The aerial is connected to a controller through a loop coupler. The controller is a transmitter and receiver that transmits at 137 kHz. The loop coupler then allows an aerial to be tuned into the system. When a tag enters the transmitting range of the system, it picks up the 137 kHz signal and responds by emitting a 66 kHz signal reply containing the tag identification code. This signal is received by the aerial and relayed to the controller. A serial port is provided for down loading, and a serial printer can be attached to the controller to output this information. When a tag makes a contact with the reading range of an aerial, and intermittently while the tag remains within this range; the gate number, time, date and tag identification number is logged and printed.

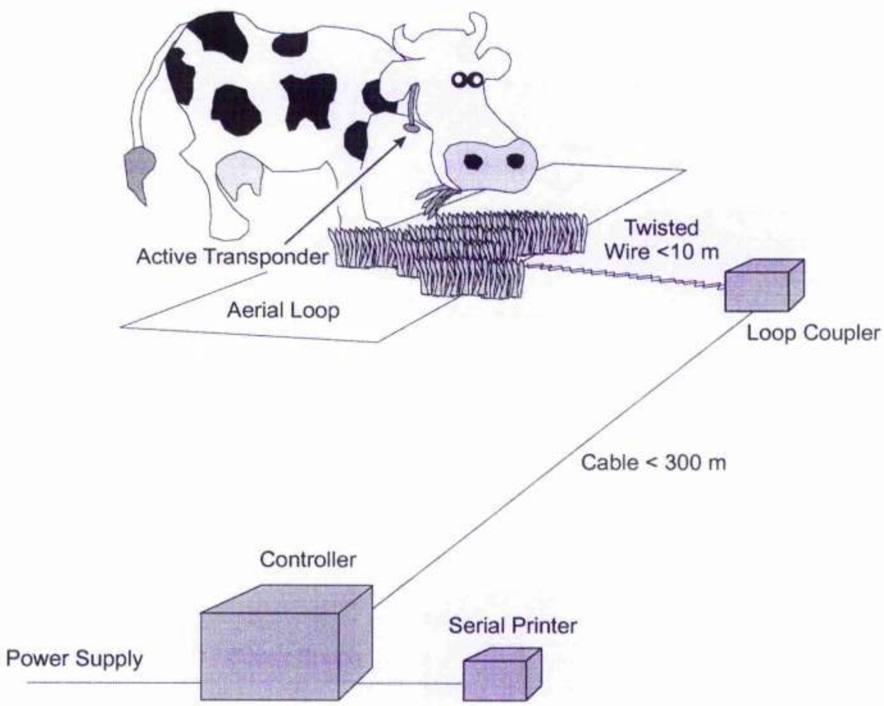


Figure 6.1 Field layout of active transponder equipment (Swain *et al.*, 2003)

For the purposes of this study, 8 areas of 3 * 2 m were marked within each paddock (Figure 6.2). Aerial loops were pegged down on top of the sward around the perimeter of each marked site. Loop couplers were adjusted to maximise the transmitting range of aerials, and detection distance of transponder tags outside the loop was estimated to be on average 25 cm. This gave an effective coverage area for each loop of 8.75 m^2. A transponder tag with a unique number code was attached to each cow's neck collar. Controllers received data from 4 aerial loops. Each controller had 4 channels and so the identity of the patch was recorded whenever a cow entered it. Relay time was between 2 and 33 seconds (Swain *et al.*, 2003) and so this provided an almost continuous record of the time individual cows spent in each patch.

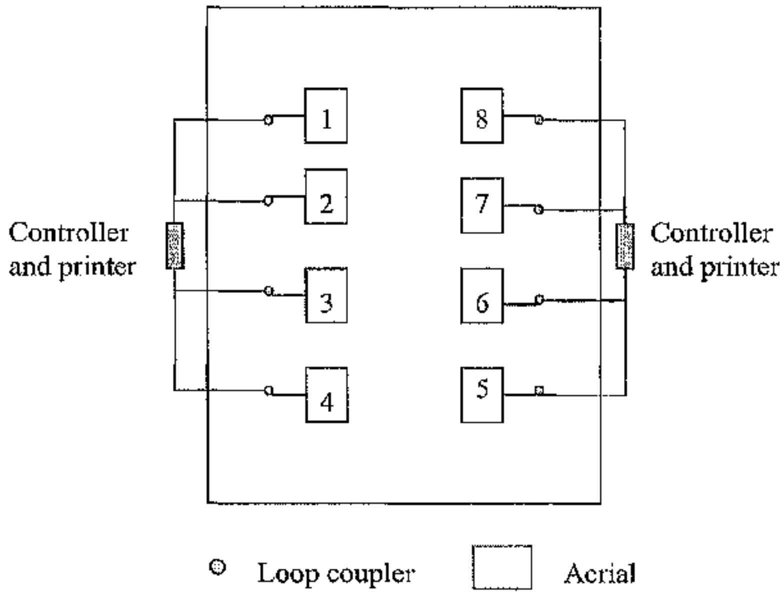


Figure 6.2 Arrangement of aerials and transponder system in paddock

Cows were fitted with solid-state behaviour recorders (Rutter *et al.*, 1997) to record their temporal patterns of grazing, ruminating and idling behaviour while in each of the paddocks. The automatic recordings of grazing behaviour were processed to identify periods of grazing, ruminating, idling and other activities, and to identify bites and chews during grazing (Rutter, 2000).

Cows were fitted with recorders immediately after afternoon milking on Day 1, prior to entry into the first paddock. Recorders were removed from cows and data downloaded daily at the end of the grazing period in each Paddock. Total grazing time was calculated as the sum of the periods of grazing jaw movement, including any periods of jaw inactivity less than 5 minutes. Periods of jaw inactivity greater than 5 minutes were interpreted as being inter-meal intervals (Rook and Huckle, 1997).

Milk yield was measured twice daily by flow meters. Live weight and condition score (Lowman *et al.*, 1973) were recorded on 26 May.

6.2.4 Sward measurements

6.2.4.1 Sward surface height

Sward surface height was measured using the HFRO sward stick (Barthram, 1986), and 10 heights were taken at random from each aerial area. Sward surface height was recorded in each aerial loop at 5 times over the day. Recordings were made at 15:00 h before cows entered the paddock; at 20:00 h, 08:00 h, and 11:00 h when cows were grazing, and at 14:00 h after cows were removed from the paddock.

6.2.4.2 Herbage mass

Herbage mass was estimated by cutting 1 * 0.076 m strips of herbage to ground level using battery operated hand shears. To estimate pre-grazing herbage mass, 1 strip of herbage was cut from each aerial area and the DM of each individual sample recorded. Post-grazing herbage mass was estimated by cutting 3 strips from each aerial area and bulking to one sample per aerial for DM calculation.

6.2.4.3 Vertical distribution of herbage mass

Vertical distribution of herbage mass was estimated for aerials 1, 3, 5, and 7 in each paddock using the sward gripper technique (Barthram, 1992). Six samples of 2.5 * 9.0 cm were taken per aerial and bulked into horizons through the sward. Herbage samples were cut into 2 cm horizons from ground level to 12 cm, and into 4 cm horizons above 12 cm.

6.2.5 Estimation of herbage intake

Herbage intake (*HI*) (kg DM cow^{-1} day^{-1}) was estimated from the difference in pre-grazing and post-grazing herbage mass (*HM*) (kg DM ha^{-1}) measured by cutting strips of herbage to ground level (Equation 6.1).

$$HI = pre\text{-}grazing\ HM - post\text{-}grazing\ HM \qquad (6.1)$$

6.2.6 Estimation of bite mass

Initial calculations of mean bite mass (*BM*) (g DM) over the whole grazing period in the aerial areas were made by combining information gathered from the behaviour recorders and active transponders with sward measurements (Method 1). Time periods when individual cows were within each aerial area were identified from active transponder recordings. This information was then combined with the grazing behaviour results to calculate number of bites in each aerial area per cow. Estimates of bite mass in individual aerial areas were made according to Method 2.

- Method 1: Number of bites in aerials estimated as a proportion of total grazing time (GT) (seconds (s) d^{-1}) in aerial areas, multiplied by total bites d^{-1} (Equation 6.3).

$$\textit{Bites in aerials} = (GT / GT \textit{ in aerials}) * \textit{total bites } d^{-1} \qquad (6.2)$$

Bite mass was then estimated from the difference in herbage mass at the beginning and end of the grazing period in the aerials divided by the total number of bites taken in the aerials by all cows (Equation 6.4).

$$BM = (\textit{Pre-grazing HM - post-grazing HM}) / \textit{estimated bites in aerials} \quad (6.3)$$

This method would be expected to enable more accurate representation of mean bite mass within the specified patches of the sward compared to estimates made from total bites taken in the whole paddock and estimated herbage intake of cows.

- Method 2: Two individual aerials were chosen from Paddocks 3 and 4 for more detailed analysis. Actual number of bites in the specified aerials for each cow was counted by aligning the information gathered from the transponders with behaviour recordings. Bite mass was then calculated using herbage mass measurements from cut strips within the aerial and number of bites specific to the chosen aerial (Equation 6.4).

$$BM = (\textit{Pre-grazing HM - post-grazing HM in aerial}) / \textit{total bites in aerial} \quad (6.4)$$

6.2.7 Estimation of herbage intake and bite mass from description of vertical distribution of herbage mass

Vertical distribution of herbage mass was described by fitting an exponential relationship to measurements of cumulative herbage mass to residual sward heights through the sward (Equation 6.5)

$$Y = M\, e^{-b\,(h)} \qquad (6.5)$$

where Y equals herbage mass (g DM) above residual sward height (h) (cm), M is total herbage mass and b is a constant. The y intercept was fixed as total herbage DM of the sample. Herbage intake could then be estimated from this description of herbage mass by fitting post grazing herbage sward height as residual sward height in Equation 6.5.

The relationship between sward height and herbage mass (Equation 6.5) was also used to estimate bite mass from calculations based on predicted bite area and bite depth, as in Experiment 3.

6.2.8 Estimation of bite mass during the depletion process

Bite mass as the sward was grazed down was estimated using a combination of sward and behavioural measurements. These included measurements of herbage mass calculated from cut strips at the beginning and end of the whole grazing period, sward height measurements over time, description of vertical distribution of herbage mass, and number of bites within time intervals.

Mean bite mass was estimated for 4 time intervals over the day by dividing herbage mass removed by total number of bites in each period. Herbage mass removed was estimated from sward surface height measurements at the beginning and end of each period, and a description of vertical distribution of total herbage mass calculated from stratified clip results using sward grippers (Barthram, 1992). The proportion of total herbage mass removed in each period was calculated from sward heights and the description of distribution of herbage mass (Equation 6.5). These proportions of herbage mass removed in the specified time intervals were applied to the measurement of total herbage mass removed per day calculated from strips of herbage cut to ground level at the beginning and end of the whole grazing period. Information from automatic behaviour recordings (Rutter *et al.*, 1997) was used to identify number of bites taken within the aerial areas during each time interval (Rutter, 2000).

6.3 RESULTS

6.3.1 Animal characteristics

Over the 4-day experimental period, cows had a mean milk yield of 36.9 ± 1.29 kg d^{-1}. They were on average in lactation 5 ± 0.48, and at the start of the experiment cows were 67 ± 3.6 days calved, had a mean live weight of 599 ± 18.2 kg, and condition score of 1.8 ± 0.12 (Table 6.1).

Table 6.1 Animal characteristics

Cow	Lactation number	† Days calved	‡ Milk yield (kg d^{-1})	Live weight	Condition score
1	5	76	40.3	624	1.75
2	4	69	35.4	556	1.50
3	4	65	37.4	634	2.00
4	6	59	34.6	582	2.00

† days calved at start, ‡ mean milk yield over experimental period

6.3.2 Sward measurements

6.3.2.1 Sward surface height

Mean sward surface heights, variability in mean sward heights between paddocks and variability between individual sward height measurements at each time point, are presented in Table 6.2. Mean sward height at each time point for each paddock is shown in Figure 6.3.

Table 6.2 Mean sward surface height (cm) of all paddocks, and variability between individual height measurements and paddocks

	Time (h)				
	15:00	19:00	08:00	11:00	14:00
Mean sward surface height	20.0	14.2	12.2	11.4	10.2
Variability between individual heights (s.e.m.)	0.20	0.17	0.16	0.15	0.14
Variability between means per paddock (s.e.m.)	0.31	0.37	0.22	0.11	0.25

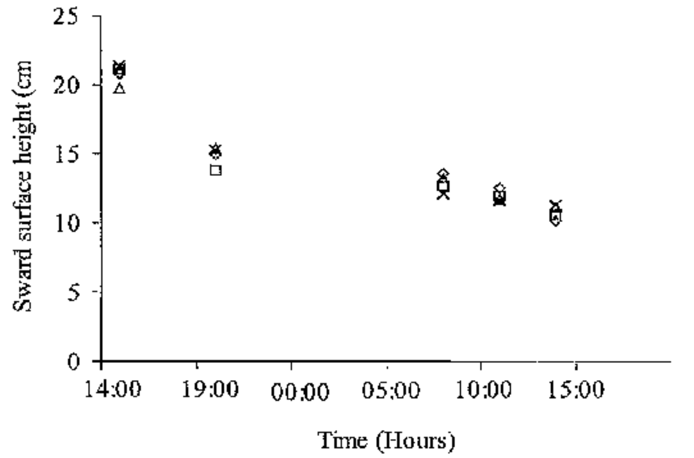


Figure 6.3 Mean sward surface height over time; Paddocks 1 (◊), 2 (□), 3 (Δ), 4 (x)

The greatest decline in sward height was observed in the period between 15:00 and 19:00 h. The coefficient of variation in individual sward height measurements was generally lowest before grazing. Variability in mean sward heights per paddock at each time point was low. Mean sward surface height results per paddock for each measurement period over the day, with variability between mean sward heights in each aerial and between individual height measurements, are presented in Appendix 11. Variability in sward height measurements before grazing was low and the frequency distribution of pre-grazing sward height measurements for all Paddock is presented in Appendix 12.

6.3.3 Herbage DM concentration

Herbage DM concentrations pre and post grazing, as calculated from samples cut to ground level for calculation of herbage mass, are presented in Table 6.3. Herbage DM was generally higher in the samples taken after the paddocks were grazed. Rainfall during days 2 and 3 reduced pre-grazing DM content of samples from Paddocks 2 and 3.

Table 6.3 Herbage DM (g kg^{-1} FW) pre and post-grazing, variability between aerials

	Pre-grazing		Post-grazing	
	Mean	s.e.m.	Mean	s.e.m.
Paddock 1	175	51.2	199	76.2
Paddock 2	155	55.3	206	87.4
Paddock 3	146	39.2	223	65.5
Paddock 4	173	60.6	170	55.1

6.3.4 Herbage mass calculated from cut strips

Mean pre and post-grazing herbage mass from samples cut to ground level for each paddock is presented in Table 6.4. Pre grazing herbage mass declined slightly from Paddock 1 to 4. Variability in herbage mass between aerials was greater in the post grazing samples.

Table 6.4 Mean herbage mass to ground level per Paddock pre and post-grazing, and variation between aerials (kg DM ha^{-1})

	Pre-grazing		Post-grazing	
	Mean	s.e.m.	Mean	s.e.m.
Paddock 1	3618	243.8	2266	199.8
Paddock 2	3320	130.9	2317	144.1
Paddock 3	3000	182.1	2188	160.5
Paddock 4	2910	143.5	2143	141.1

6.3.5 Sward density

Sward bulk density was highest in Paddock 1 (Table 6.5). Sward density was greater in the grazed sward compared to the ungrazed sward, which would be expected considering the negative relationship between sward height and density.

Table 6.5 Mean sward bulk density per Paddock pre and post-grazing, and variation between aerials (kg DM m^{-3})

	Pre-grazing		Post-grazing	
	Mean	s.e.m.	Mean	s.e.m.
Paddock 1	1.77	0.109	2.33	0.200
Paddock 2	1.48	0.075	2.44	0.176
Paddock 3	1.60	0.098	2.13	0.099
Paddock 4	1.57	0.113	2.06	0.108

6.3.6 Vertical distribution of herbage mass

Mean herbage mass per horizon per paddock, and variation between results from the 4 aerials sampled, is presented in Table 6.6.

Table 6.6 Herbage mass per horizon per paddock, mean and s.e.m. of samples from 4 aerials (g DM 135 cm^{-2})

	Paddock 1		Paddock 2		Paddock 3		Paddock 4	
Horizon (cm)	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.
0-2	3.10	0.207	3.18	0.026	3.49	0.383	2.99	0.148
2-4	1.27	0.126	1.15	0.104	0.97	0.041	1.19	0.064
4-6	0.96	0.083	0.89	0.018	0.74	0.050	0.92	0.042
6-8	1.06	0.060	0.85	0.178	0.86	0.042	0.92	0.054
8-10	0.84	0.077	0.65	0.125	0.71	0.044	0.81	0.069
10-12	0.60	0.061	0.59	0.049	0.55	0.038	0.65	0.101
12-16	0.83	0.089	0.82	0.087	0.76	0.065	0.61	0.018
16-20	0.34	0.058	0.34	0.047	0.34	0.068	0.34	0.065
20+	0.18	0.046	0.17	0.028	0.15	0.045	0.17	0.058

Cumulative herbage mass from the top to bottom of the sward was calculated for each paddock and an exponential relationship fitted through the results, as in Experiment 3 (Table 6.7). The Y intercept was set as total herbage mass in the sample. The r^2 value for each paddock was high indicating a good fit of the exponential relationship.

Table 6.7 Equations of exponential relationship ($Y = M\ e^{b\ (h)}$), fitted to results of mean cumulative herbage mass (Y) (g DM 135 m^{-2}) at residual sward heights (h) (cm), total mass (M) (g DM 135 cm^2), and r^2 values

	M	b	r^2
Paddock 1	9.17	0.1776	0.973
Paddock 2	8.63	0.1763	0.971
Paddock 3	8.56	0.1812	0.968
Paddock 4	8.60	0.1785	0.979

6.3.7 Herbage mass calculated from stratified clip measurements

Total herbage mass to ground level was calculated from samples taken with sward grippers for stratified clip measurements, and results are presented in Table 6.8. Estimates of herbage mass from the sward gripper samples are considerably greater per m^2 than pre-grazing herbage mass calculated from cut strips (Table 6.4).

Table 6.8 Total DM per 6 stratified clip samples (135 cm^2) and estimated herbage mass g DM m^{-2} (s.e.m. of DM aerial^{-1})

	g DM 135 cm^{-2}	s.e.m.	g DM m^{-2}
Paddock 1	9.17	0.554	679
Paddock 2	8.63	0.490	639
Paddock 3	8.56	0.375	634
Paddock 4	8.60	0.449	637

6.3.8 Grazing behaviour

Average results from the grazing behaviour recorders per paddock, and variation between cows, are presented in Table 6.9. Results for individual cows per day are presented in Appendix 13. Data recordings were incomplete for Cow 2 when in Paddock 1, and for Cows 2, 3, and 4 when in Paddock 2. Results presented in Table 6.9 therefore do not include Cow 2 in Paddock 1, there are no mean results for Paddock 2, and there are some missing values for subsequent calculations that are based on behaviour information.

Table 6.9 Mean grazing behaviour of cows in Paddocks 1, 3, and 4

	Paddock 1‡		Paddock 3		Paddock 4	
	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.
Grazing time (min d^{-1})	598	75	543	41	588	32
Bites	33126	2579	29241	2435	31488	2532
Chews	5229	2545	5765	2188	6283	2350
Total GJM†	38355	5105	35006	3162	37771	2015
Proportion GJM bites	0.88	0.045	0.84	0.06	0.84	0.06
Bites min^{-1} grazing time	56.1	2.77	53.8	3.24	53.6	3.26
Ruminating time (min d^{-1})	199	98	198	46	243	54
Mastications	13167	6196	13314	3070	13433	5347
Boli	242	113	237	57	9270	8977
Idling (min d^{-1})	458	26	517	27	407	103
Mastications	1122	35	1370	167	1272	74
Other (min d^{-1})	108	30	92	35	81	19
Mastications	7315	2230	8634	2394	9249	1246
Total eating time (min d^{-1})	551	69	511	44	552	26
Bites	32665	2541	28846	2415	31078	2413
Chews	5317	2582	5873	2176	6372	2335
Total GJM	37983	5105	34719	3213	37451	1991
Proportion GJM bites	0.87	0.05	0.84	0.058	0.83	0.060

† GJM, grazing jaw movements; ‡ Cow 2 not included in Paddock 1 results

Mean grazing time cow^{-1} $paddock^{-1}$ ranged from 543 to 598 minutes d^{-1}, with the highest mean grazing time recorded in Paddock 1. Grazing time per cow was highest for Cow 1 when in Paddock 1 at 746 minutes d^{-1}, and lowest for Cow 4 at 448 minutes d^{-1} when grazing in Paddock 3 (Appendix 13). Cow 1 grazed for the longest in each of the Paddocks. Mean bite rate calculated from total grazing time and number of bites was relatively constant between paddocks, and variability between individual animals was low. Mean bite rate for results from Paddocks 1, 3, and 4 was 54.3 (s.e.m. 1.68) bites min^{-1}. Ruminating times are low compared to results from Experiments 1 and 2 and compared to those reported in the literature (for example, Pulido and Leaver, 2001; Sayers *et al.*, 2000). Total time recorded as idling or other was high for all days of the experiment. It is possible that some of this time was actually ruminating time but not recognised as such by the Graze programme. Time recorded as other or idling will also include time removed from the Paddock for milking, and mastications will include those from eating supplements offered in the milking parlour.

6.3.9 Estimated herbage intake

Mean daily herbage intake calculated from the difference in herbage mass before and after grazing measured by cutting strips of herbage (Equation 6.1), was estimated to decline from 16.9 kg DM cow^{-1} in Paddock 1 to 9.6 kg DM cow^{-1} in Paddock 4 (Table 6.10).

Table 6.10 Herbage intake per paddock estimated from pre and post-grazing herbage mass calculated from cut strips

	Herbage intake		
	$g\ m^{-2}$	kg $paddock^{-1}$	kg DM cow^{-1}
Paddock 1	135	67.6	16.9
Paddock 2	100	50.1	12.5
Paddock 3	81	40.6	10.2
Paddock 4	77	38.3	9.6

6.3.10 Bite mass

Initial estimates of bite mass were calculated by estimating number of bites in aerials from grazing time in all aerial areas as a proportion of total grazing time (Equation 6.1), and total number of bites d^{-1}. Data used in the calculations of bite mass for each cow d^{-1} are presented in Appendix 14.

Mean bite mass per paddock as estimated from herbage removed calculated from cut strips (Table 6.10), and total number of bites in the aerial coverage areas (Appendix 14), is presented in Table 6.11. Bite mass was highest in Paddock 1 at 0.496 g DM, and very similar between Paddocks 3 and 4 at 0.279 and 0.289 g DM respectively.

Variation between paddocks in total bites in the aerial areas was small ranging from a total of 18560 in Paddock 4, to 20369 in Paddock 3 (Appendix 14). A significantly greater reduction in herbage mass over the grazing period in Paddock 1 however meant that mean bite mass was higher than when cows grazed subsequent paddocks.

Table 6.11 Estimated bite mass in all aerial areas calculated from herbage mass removed over grazing period and estimated bites in aerials

	Total bites in aerials	Herbage removed (g DM)		Mean bite mass (g DM)
		m^2	Total aerial area	
Paddock 1	19092	135	9465	0.496
Paddock 2	-	100	7016	-
Paddock 3	20369	81	5685	0.279
Paddock 4	18560	77	5366	0.289

6.3.11 Calculation of mean bite mass in individual aerials

Mean bite mass calculated for 2 individual aerial areas in Paddocks 3 and 4 (Equation 6.4) is presented in Table 6.12. These estimates show some variation from mean bite mass results estimated for all aerials in the paddock (Table 6.11).

Table 6.12 Mean bite mass in individual aerials

	Aerial	Total bites in aerial	s.e.m. (bites cow^{-1})	Pre-grazing herbage mass (g m^{-2})	Post-grazing herbage mass (g m^{-2})	Herbage removed (g m^{-2})	Total herbage removed (g DM $aerial^{-1}$)	Mean bite mass (g DM)
Paddock 3	1	3142	127.0	258	165	93	810	0.258
Paddock 3	7	2160	134.0	293	181	112	982	0.455
Paddock 4	6	2618	206.3	321	204	117	1025	0.391
Paddock 4	8	1992	127.1	267	208	59	514	0.258

6.3.12 Estimated bite mass over four time periods per day

Bite mass was estimated over the day by combining measurements of vertical distribution of herbage mass, sward height, herbage mass from cut strips, and number of bites within time periods. Data to calculate bite mass per period from number of bites in aerials per period, and herbage mass removed per period, are detailed in Appendices 15 and 16, for each paddock. Estimated mean bite mass and rate of intake over the four time periods is presented in Table 6.13 and Figure 6.4.

Table 6.13 Mean number bites in aerial areas, estimated herbage mass removed, bite mass and intake rate between time periods

Time periods (h) per Paddock	Estimated bites in aerials per period	Herbage mass removed all aerials (g DM)	Bite mass (g DM)	Rate of intake (g DM min^{-1} grazing)
Paddock 1				
15:00-19:00	3756	4862	1.29	67.4
19:00-08:00	10342	1254	0.12	6.5
08:00-11:00	4649	1254	0.27	13.6
11:00-14:00	2786	2080	0.75	41.8
Mean			*0.44*	*23.2*
Paddock 3				
15:00-19:00	3416	2611	0.76	40.3
19:00-08:00	8821	1445	0.16	8.7
08:00-11:00	2051	921	0.45	21.7
11:00-14:00	6286	693	0.11	6.0
Mean			*0.28*	*14.6*
Paddock 4				
15:00-19:00	4379	2590	0.59	32.0
19:00-08:00	9227	1750	0.19	10.0
08:00-11:00	1627	384	0.24	12.4
11:00-14:00	2729	665	0.24	13.0
Mean			*0.30*	*16.0*

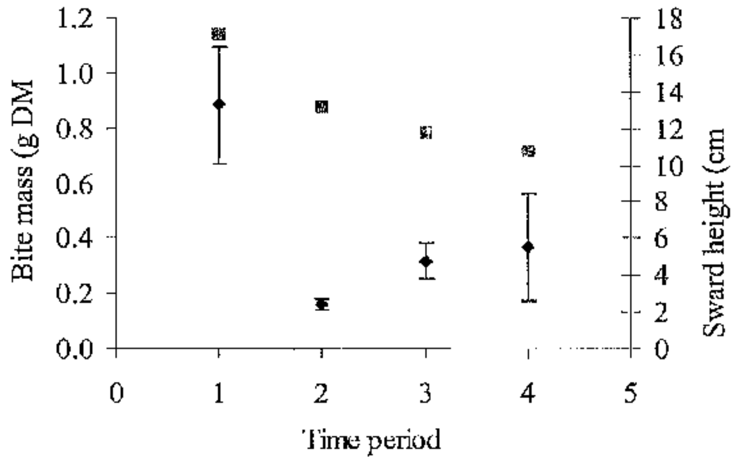


Figure 6.4 Mean bite mass (♦) and sward height (■) per period (error bars represent s.e.m. of bite mass between paddocks) (Period 1, 15:00-19:00 h; Period 2, 19:00-08:00 h; Period 3, 08:00-11:00 h; Period 4, 11:00-14:00 h)

Mean bite mass was estimated to be highest in the period from PM milking to dusk (Period 1) at 0.88 g DM (± 0.21); and lowest in the overnight period (Period 2) at

0.16 g DM (± 0.02). Bite mass increased to 0.32 g DM (± 0.07) in Period 3; and 0.37 g DM (± 0.19) in Period 4. Rate of herbage intake was also consistently highest in Period 1, and on average was lowest in Period 2. These results suggest therefore that there was not a consistent decline in bite mass or rate of intake with a reduction in mean sward surface height over time.

6.3.13 Calculation of bite mass from sward measurements and estimated bite dimensions

A further estimate of bite mass was made from the description of vertical distribution of herbage mass (Table 6.7) using the same technique as in Experiment 3, assuming that cows will bite to a depth of one third of sward height, and bite an area of 100 cm^2. These estimations of bite mass from each Paddock are presented in Table 6.14. Bite mass is estimated to be on average 0.60 g DM ± 0.023 which is higher than calculations of bite mass presented in Table 6.11 and Table 6.12. These estimates of bite mass from descriptions of the vertical structure of the sward however are made for the uppermost grazing horizon, and so are expected to be higher than mean bite mass over the whole grazing period as the sward is grazed down (Barrett *et al.*, 2001; McGilloway *et al.*, 1999). Furthermore, estimates of bite mass from the upper grazing horizon from the vertical distribution of mass results are closer to estimates of bite mass in Period 1 calculated from sward and behaviour measurements which averaged 0.88 g DM $bite^{-1}$ (Table 6.13).

Table 6.14 Estimated bite mass from vertical distribution of mass, $Y = Me^{-b(h)}$ where Y is herbage mass (g DM 135 m^{-2}) at residual sward height (h) (cm), M is total mass (g DM 135 cm^2); bite depth one third pre-grazing sward height, bite area 100 cm^2

	M	b	Mean sward height pre-grazing (cm)	Bite depth (cm)	Residual sward height (x) (cm)	Bite mass (g DM)
Paddock 1	9.17	0.1776	20.1	6.70	13.39	0.63
Paddock 2	8.63	0.1828	19.7	6.55	13.10	0.63
Paddock 3	8.56	0.1812	19.4	6.48	12.96	0.61
Paddock 4	8.60	0.1785	20.8	6.94	13.88	0.53

6.4 DISCUSSION

6.4.1 Daily herbage intake

Estimated daily herbage intake declined from 16.9 kg DM in Paddock 1 to 9.6 kg DM in Paddock 4. These values are within the range reported by others. For example Sayers *et al.* (2000) report average herbage intakes of 12.9 and 10.0 kg DM d^{-1} between May and September, for cows yielding above 30 kg milk d^{-1} and offered 5 or 10 kg FW concentrate d^{-1} respectively. Christie *et al.* (2000) reports higher herbage intakes of 15.8 kg DM d^{-1}, although daily herbage intakes of up to 20.7 kg DM d^{-1} have been recorded (Buckley and Dillon, 1998).

Overall, cows were presented with swards that would be expected to allow high levels of herbage intake. Sward were grazed down from a mean surface height (Barthram, 1986) of 20.0 cm to 10.2 cm, which is within or above the range of recommended pre and post-grazing sward heights for rotationally grazed paddocks (Hodgson *et al.*, 1986; Peyraud and Gonzalez-Rodrigez, 2000). The experiment was also conducted early in the season when nutritional quality of herbage is high (Beever *et al.*, 2000). In particular, highly digestible, leafy herbage associated with spring pasture is positively related to herbage intake (McGilloway and Mayne, 1996; Parga *et al.*, 2000). Differences in results between paddocks could be a consequence of variability in sward characteristics. Despite similar pre-grazing sward heights, estimates of pre-grazing herbage mass and bulk density declined from Paddock 1 to 4 (Table 6.4). Herbage mass to ground level recorded from cut strips of sward for example, was 3618 kg DM ha^{-1} in Paddock 1, and 2910 kg DM ha^{-1} in Paddock 4. Reduced levels of herbage intake are associated with lower levels of herbage mass (Stakelum, 1986a; Stakelum, 1986b). Herbage intake is also reduced when herbage allowance (kg cow^{-1} d^{-1}) declines (Delaby *et al.*, 2001; Peyraud *et al.*, 1996), or when mean sward bulk density (kg m^{-2}) is lower (Mayne *et al.*, 1997; McGilloway and Mayne, 1996); both of which would occur as a consequence of reduced herbage mass, but similar sward surface heights in the current study. Pre-grazing herbage DM content was also highest in Paddock 1, which has been associated with increased herbage DM intakes (Peyraud and Gonzalez-Rodrigez, 2000). Animal factors however could similarly have an affect. In particular, as a consequence of less favourable grazing conditions offered to the cows before the experiment, cows could have had greater hunger drive at the beginning of the experiment resulting in increased levels of herbage intake when they were given access to improved grazing conditions.

6.4.2 Grazing time and bite rate

Evidence suggests grazing time reaches a plateau at between 540 and 600 minutes d^{-1} (Rook and Huckle, 1996). In the current experiment, mean grazing time was high ranging from a maximum of 598 minutes d^{-1} in Paddock 1, to 543 minutes d^{-1} in Paddock 3, and so is would appear that herbage intake could have been restricted by the time cows had available for grazing. There was relatively little variation between grazing time or bite rate between Paddocks. A mean bite rate of 54.3 bites $minute^{-1}$ however is relatively high compared to results reported in the literature, for example (Barrett *et al.*, 2001). Therefore while estimated herbage intake per paddock is variable, measurements of grazing time, number of bites, and bite rate are similar between paddocks, and a reduction in herbage intake would be expected to have arisen as a consequence of lower mean bite mass.

6.4.3 Bite mass estimates

Mean bite mass was estimated to be highest in Paddock 1 at 0.5 g DM. This compares to estimates of 0.28 and 0.29 g DM $bite^{-1}$ for Paddocks 3 and 4 respectively. Higher bite mass in Paddock 1 could have been related to a higher pre-grazing herbage mass and bulk density (McGilloway *et al.*, 1999; McGilloway and Mayne, 1996). Cows can also adjust their bite dimensions to alter bite mass, and the evidence suggests that animals with greater hunger drive can increase bite mass by increasing their bite depth (McGilloway *et al.*, 1999; Patterson *et al.*, 1998). The reduction in mean sward height however was similar between paddocks, which suggests increased intake arose as a consequence of higher herbage mass in the grazed horizon.

Estimates of mean bite mass are within the range reported from experiments in the literature (Gibb *et al.*, 2002b; McGilloway and Mayne, 1996), although they appear to be low when compared to studies which have used animals with similar levels of milk production. Despite relatively similar levels of herbage intake to the present study Christie *et al.* (2000) for example, reports a mean bite mass of 0.73 g DM d^{-1};

and Sayers *et al.* (2000) recorded a mean bite mass of 0.60 g DM d^{-1}. The current study reported a higher total number of bites d^{-1} and longer grazing time compared to the studies by Christie *et al.* (2000) and Sayers *et al.* (2000). Differences in bite mass between experiments could be an effect of differences in sward structure. If potential bite mass from the sward is lower, then cows may have been forced to graze for longer and take more bites in an attempt to meet their energy requirements. Bite mass declines with a reduction in sward surface height and density (Mayne *et al.*, 1997; McGilloway *et al.*, 1999; McGilloway and Mayne, 1996). Swards grazed in the experiment by Christie *et al.* (2000) for example, had average pre-grazing surface heights of 25 to 40 cm which is higher than in the present experiment and so could explain higher estimates of bite mass.

On ungrazed swards with a mean sward height of 21.2 cm, which is similar to the current study, McGilloway *et al.* (1999) report mean bite mass of 1.28 g DM. After grazing to a height of 8.9 cm, mean bite mass was estimated to be 0.85 g DM. These estimates are considerably greater than those estimated in the current study. McGilloway *et al.* (1999) however calculated bite mass over 1 hour periods, using the live weight change method. Animals were fasted before grazing to ensure they had similar levels of hunger drive and would graze swards at an advanced stage of depletion however fasting has been shown to increase bite rate, intake rate, and bite mass (Patterson *et al.*, 1998). In practice, hunger drive normally declines as the animal grazes down through the sward canopy but this effect is not tested in this type of short-term study. Experiments were also conducted during the day and so there is no consideration of the temporal pattern of grazing activity (Orr *et al.*, 2001). Bite mass results reported by McGilloway *et al.* (1999) are therefore likely to be higher than when animals have not been fasted and graze a sward under normal pasture conditions. Differences in bite mass reported between studies therefore could also occur due to differences in methodologies to estimates bite mass. In particular, many estimates of bite mass have been made from short-term experiments.

Barrett *et al.* (2001) also carried out short term studies to estimate mean bite mass using the liveweight change method. Animals however were not fasted prior to recording periods. In their first experiment, cows were given access to a paddock with mean sward surface height of 23.8 cm at 07:00 h. Herbage intake measurements were made at four time points over the day as the sward was grazed down. Mean bite mass at 07:00 h was estimated to be 0.74 g DM, and declined as the sward was grazed down to 0.62 g DM bite^{-1} at 18:00 h when sward height was 13.0 cm. Mean bite mass over the 4 time periods studied over the day was 0.65 g DM. Estimates were therefore less than those reported by McGilloway *et al.* (1999), which could partly be attributed to use of non-fasted cows, but estimates are still higher than those calculated in the present study. Barrett *et al.* (2001) however made intake measurements at times chosen to coincide with early stages of a grazing meal. These chosen times were at 07:00 h and 18:00 h which were the periods immediately after morning and afternoon milkings, and at 11:00 h and 14:00 h when the majority of cows showed grazing activity. It could be speculated that bite mass will be greater at the beginning of a grazing meal when cows have greater hunger drive. In the experiment by Barrett *et al.* (2001), removing animals from pasture for milking, and to weigh animals and fit equipment before intake measurement periods, could also result in a period of fasting and its corresponding effects on intake, even if this was for a shorter time period than in other studies. Results reported by Barrett *et al.* (2001), McGilloway *et al.* (1999), and others who have used similar short-term methods to describe bite mass, are therefore likely to over-estimate bite mass, and may not be representative of herbage intake and mean bite mass over the day under normal grazing conditions.

6.4.4 Effects of time of day on estimates of bite mass

Estimation of bite mass during different time periods over the experiment, by calibration of sward height measurements with a description of the vertical distribution of herbage DM, indicated significant variation in bite mass over the day. The effects of the time of day on bite mass are confounded by changes in sward structure as the grazing period progressed. Estimations of bite mass however did not consistently decline as sward height was reduced. Bite mass was highest in the period between milking and 19:00 h, and reached a maximum of 1.29 g DM over this period in Paddock 1. Herbage availability was highest during this time, and the period after the afternoon milking and in the early evening before dusk also coincides with a well recognised period of grazing activity (Orr *et al.*, 2001). Others have also shown highest intake rate and bite mass during this time, with cows taking their largest meal in evening before dusk (Gibb *et al.*, 1998; Orr *et al.*, 2001; Rook *et al.*, 1994).

Bite mass was estimated to be lowest over night in the period between 19:00 and 08:00 h, when it averaged 0.16 g DM. This period would include some of the grazing meal before dusk but the majority would be the period of darkness when grazing activity is limited (Leaver, 1986). Bite mass was higher in the following day and although there was variation between paddocks, bite mass was on average greater in the final period from 11:00 to 14:00 h (0.37 g DM) compared to the period from 08:00 to 11:00 h (0.32 g DM). This was despite a decline in sward height with time. These results suggest that cows can alter bite dimensions and bite volume, and so adjust bite mass according to the time of day. Results therefore challenge the theory that cows will bite to a depth of a constant proportion of sward height, irrespective of initial sward surface height (Wade *et al.*, 1989). It is also possible that FW intake bite^{-1} was more constant than DM intake bite^{-1} between time periods. In particular, herbage DM concentration increases over the day and is generally highest in the evening (Orr *et al.*, 2001; Wilkinson *et al.*, 1994). Calculation of FW intake bite^{-1} could therefore have shown less variation between time periods than DM intake bite^{-1}.

6.4.5 Estimating bite mass from vertical distribution of herbage mass

Mean bite mass estimates from the description of vertical distribution of herbage mass were on average 0.28 g DM higher than those estimated from recordings of animal location, grazing behaviour, and herbage removed from specified areas of the sward. The highest estimate of 0.63 g DM bite^{-1} for Paddocks 1 and 2, was correlated with a higher measurement of total herbage mass in Paddock 1, and slightly greater sward height of Paddock 2. The estimates are for upper grazing horizon and therefore expected to indicate maximum potential bite mass from the sward (McGilloway *et al.*, 1999; Ungar, 1996). They are therefore closer to estimates of bite mass in Period 1 from afternoon milking to 19:00 which were on average 0.88 g DM and most likely to include a high proportion of bites from the upper grazing horizon of each Paddock. There is little variability in bite mass estimates between paddocks calculated from measurements of vertical distribution of mass since the same estimates of bite dimensions are used to estimate bite mass.

Bite mass results from combining grazing behaviour and location information with sward measurements and others for example, Orr *et al.* (2001) and Patterson *et al.* (1998), suggest bite dimensions might vary according to the time of day and hunger drive.

6.4.6 Variability in estimates of bite mass between patches of the sward

From the limited number of individual aerials for which mean bite mass was calculated, some variation in bite mass was observed between aerials in the same paddock. Mean bite mass from aerials 1 and 7 in Paddock 3, for example was estimated to be 0.26 and 0.47 g DM respectively, compared to 0.28 g DM for all aerials in the paddock. From the above discussion, it would appear that variability in mean bite mass between aerials could be a consequence of variability in sward structure, differences in the level of depletion, and also the time of day when bites were taken. There could also be variability in bite mass between individual cows and a limitation of this method is that differences between animals can not be detected easily. Furthermore, the reliability of the method to estimate bite mass must be evaluated and possible sources of error are discussed in the following sections.

6.4.7 Methodology

6.4.7.1 Calculation of herbage intake and bite mass

The proposed experimental technique to estimate bite mass offers advantages over some established methods. Use of oesophageally fistulated animals (for example, Jamieson and Hodgson, 1979a; Jamieson and Hodgson, 1979b) offers the only real method of directly measuring bite mass. Mean bite mass is calculated by dividing the number of bites taken during the grazing period by weight of material collected from the fistula. Sampling is usually conducted over relatively limited periods of time and at discrete times of the day, and so the technique provides only short-term measurements (Gibb and Penning, 2002). It is difficult therefore to consider temporal variation in selection and intake by the animal, especially where sward conditions are variable or changing rapidly. There are also ethical considerations for the surgical preparation of animals, the technique is expensive and labour intensive, and can result in abnormal grazing behaviour.

Artificial, hand constructed swards have been used to measure bite mass by weighing swards before and after grazing (Laca *et al.*, 1992a; Laca *et al.*, 1992b). They can allow effects of aspects of sward morphology and in particular sward height, density and mass; on mechanics of the grazing process such as bite mass, depth area and bite rate, to be investigated. Application of results to represent normal field grazing conditions however is questionable. Preparation of sward boards is also time consuming, the size of the area is very limited, variability in sward structure can not be adequately represented and temporal aspects of grazing activities can not be measured accurately (Gibb and Penning, 2002).

Further methods have combined an estimate of herbage intake with recordings of grazing behaviour to estimate bite mass. These include measurement of liveweight change to estimate herbage intake over the grazing period (Huckle *et al.*, 1994), and automatic recordings of grazing behaviour to calculate mean intake per bite (for example, McGilloway *et al.*, 1999). The major limitation of this method is the short-term nature of the measurements, and the need to account for insensible weight loss and weight loss as faeces and urine. There can also be some weight gain from non-forage intake of, for example, supplementary minerals, water and soil. The method is labour intensive and relies on a high degree of accuracy in the balance used. It also tends to have been used after animals have been fasted to ensure they all have a similar hunger drive and will graze during the recording period, for example McGilloway *et al.* (1999), and so intake results may not be representative of normal grazing behaviour (Patterson *et al.*, 1998).

Estimates of daily herbage intake using markers such as *n*-alkanes (Mayes *et al.*, 1986), can be combined with grazing behaviour recordings to calculate mean bite mass (Sayers *et al.*, 2000). Friend *et al.* (2002) examined the potential for a marker technique to examine selection behaviour from patches of a sward by spraying different *n*-alkanes on different patches of the sward. Markers which provide daily estimates of herbage intake however, may not provide sufficiently detailed information for bite level studies or to examine temporal patterns of bite mass and intake. They do however give information on intake of individual animals, which is not possible from sward measurements of intake.

The proposed method attempts to overcome some of the limitations of existing methods and has potential to measure bite mass under relatively normal field grazing conditions. It can provide estimates over the longer-term compared with most existing methods. A major potential advantage of the technique is the ability to estimate bite mass within different patches of a grazed area, and also in different time periods. Ability of the method to provide precise estimates of bite mass however is dependant upon reliability of methods used to record grazing location and behaviour, and herbage mass removed from the sward.

6.4.7.2 Recording spatial location to obtain patch level behavioural information

A recording of spatial location of grazing cows is required to calculate intake within patches of a sward over the grazing period. The active transponder system used in this study (Friend *et al.*, 2002; Swain *et al.*, 2002) provides a continuous recording of times animals were within defined patches of the sward. It offers a number of advantages over existing methods of recording location of grazing animals. In particular, direct observations of animal location and behaviour are labour intensive, not possible during hours of darkness, and require the animal and grazing areas to be marked, which could potentially affect grazing behaviour (Fehmi and Laca, 2001). A global positioning system using satellite technology (GPS) was used by Rutter *et al.* (1997a) to track movements of grazing sheep. GPS can provide a continuous record of animal location but does not give the accuracy required for detailed patch level monitoring (Friend *et al.*, 2002). Laser based equipment has been used by Fehmi and Laca (2001) to remotely record animal location and behaviour at a distances of 1 to 200 m and for periods of seconds to hours, and was shown to be potentially more accurate than GPS systems. Laser-based recording however relies on the operator being able to physically observe the animal and so is not suitable for recording in darkness. These methods can therefore be labour intensive and none are able to provide spatially accurate, continuous and reliable data over 24 hours. A transponder system, used in this study and similar to that used by others (Daniels *et al.*, 2001; Friend *et al.*, 2002; Hutchings and Harris, 1996), could therefore have advantages over other techniques since it can provide a continuous, 24 hour record of animal location which could be accurate enough for detailed patch level studies.

Continuous recordings of both animal location and grazing behaviour have been used by Cook *et al.* (2002) to monitor grazing times of animals within different areas. They used the 'Texas Radio Information System' to record animal movement between paddocks. Animals were dosed with a transponder bolus that was read and logged automatically when the animal passed an antenna on a race between paddocks. However, animals were taught to use specific entrances and exits between paddocks which could affect or constrain their normal pattern of grazing activity. There could be potential for development of their technique to provide patch level information and the authors suggest the possibility for antenna to range in size from 0.15 m^2 to 4 m^2. An active transponder system as used in the present experiment however is currently better developed for recording animal location within patches of the same paddock on the smaller spatial scale. Subsequent studies have also demonstrated presence of aerial loops pegged down on the sward surface does not affect grazing behaviour (Swain *et al.*, 2002).

In this experiment, active transponders were attached to cows neck collars, which should provide information when the animals' head is within aerial areas, and so enable identification of bites taken within patches when results are combined with grazing behaviour recordings. Variability in the reading range of aerial loops however must be considered and knowledge of the coverage area is required to calculate herbage mass removed through grazing, and so provide an accurate estimation of mean bite mass. Subsequent experimental work conducted with the active transponder system (Swain *et al.*, 2002) has demonstrated that there is some variability in the coverage area of aerial loops according to the direction of approach of the transponder tag to the aerial and its height above ground level. There is also some variability according to the size of the aerial loop. This work has suggested that to enable easier measurement of the coverage area and to quantify variability in the reading range, the aerial loop should be circular and the detection distance of transponders from the loop should be tested prior to the start of an experiment.

6.4.7.3 Measurements of grazing behaviour and integration with location information

The IGER automatic behaviour recording equipment (Rutter *et al.*, 1997) and Graze software (Rutter, 2000) is a well developed system for the automatic recording and analysis of grazing behaviour in cattle. The system can identify the main behavioural states of eating, ruminating and resting. During bouts of grazing, it can also distinguish between chewing and biting jaw movements (Champion *et al.*, 1997). This behaviour recording system can therefore provide continuous, detailed information on the temporal pattern of grazing activity required for calculation of grazing and intake from patches of the sward in the present experiment.

Combining continuous recordings of grazing behaviour and animal location allowed the number of bites taken within patches of the sward by individual cows to be estimated. Counting bites taken in each period when cows were in separate aerial areas was particularly time consuming. Development of automatic behaviour recorders so that they also automatically detect and record times when cows are within aerial coverage areas, so that bites between time points can be counted more easily and quickly would assist in analysis of results and improve application of the method. It would also remove possible errors occurring by miss matching grazing behaviour and location information.

6.4.7.4 Estimating herbage removed from the sward by grazing

The proposed method to estimate bite mass relies heavily upon estimation of herbage intake from sward measurements. Sward techniques to estimate herbage intake are based on differences in herbage mass estimated at the beginning and end of grazing periods. Under field conditions, the need to maintain sward structure and variability in its structure prevent it is destruction for direct measurement. The aim must therefore be to obtain a sufficiently accurate estimation of herbage mass before and after grazing. Estimates of herbage mass can be obtained by cutting strips of herbage from the sward before and after grazing to represent herbage mass in the grazed area (Meijs, 1986; Meijs and Hoekstra, 1984). In the present experiment it is similarly assumed that herbage mass calculated from cut strips of sward is representative of the grazed area.

This method can be susceptible to bias due to herbage growth and senescence and selection by the animal. Herbage intake can be over-estimated if trampling removes forage from the sward cut to calculate post-grazing herbage mass, especially if a cutting height is not low enough to include the trampled herbage. Cutting herbage to ground level as in the current experiment should avoid this problem. Effects of faecal and urine contamination in the aerial areas however can present problems when estimating herbage removed from the areas. Additionally, sward measurements can not be used to obtain individual intakes for animals in groups since this would require animals to be kept on individual plots which could affect their normal grazing behaviour (Rook and Huckle, 1995).

Correction for contribution of herbage growth to post-grazing measurements of herbage mass is required when the grazing period is considered to be of sufficient duration for herbage growth to have a significant effect on herbage mass. A formula for estimation of herbage accumulation was originally determined by Linehan *et al.* (1947). Use of exclusion cages could enable an estimation of herbage growth although herbage growth in an ungrazed area may not provide a good representation of herbage accumulation in the grazed area (Frame, 1993). In this experiment, no account was taken of herbage accumulation over the grazing period as this was not be expected to be significant over 24 hours (Stakelum, 1986a). Sward based techniques are therefore generally most applicable when grazing periods are relatively short and grazing pressure is high (Gibb and Penning, 2002).

To improve precision and avoid destruction of large areas of sward for estimation of herbage mass, a double sampling technique has frequently been used (Frame, 1993). Local regressions can be established to relate herbage mass determined by a destructive technique, with a non-destructive measurement such as sward height. Regressions can be established for swards before and after grazing to estimate intake. Establishing a relationship between sward height measurements and herbage mass is complicated by variation in mean bulk density of swards and vertical distribution of mass through layers of the sward, as demonstrated in Experiment 3 and by others, for example Delagarde *et al.* (2000). A description of vertical distribution of mass could therefore provide a better description of the sward to calculate herbage mass removed from non-destructive sward height measurements taken at various stages of the grazing down process, as in the current study. While total herbage mass estimates from stratified clip results were high, descriptions of vertical distribution of mass from the swards could be applied to herbage mass measurements from cut strips of herbage to estimate herbage removed between time points. Calibration of herbage mass with sward height avoids the need to make further cuts of herbage to estimate herbage intake within different time periods.

Substantially greater measurements of herbage mass from gripper samples compared to estimates from cut strips of sward have also been observed in Experiment 3 and by Barthram *et al.* (2000). It would seem that this is a result of gripper samples covering a larger surface area of sward than the area of the gripper which is used to calculate herbage mass (Barthram *et al.*, 2000). Development of the gripper technique to make reliable estimates of total herbage mass from gripper samples, and calibration of results with sward surface height could then potentially avoid the requirement to cut strips of herbage to measure herbage mass pre and post-grazing.

A system based on sward measurements to estimate herbage mass before and after grazing therefore can be complicated if herbage mass accumulates significantly during the grazing period. It can also be inappropriate where herbage utilisation is low due to low pre grazing herbage mass or low grazing pressure (Gibb and Penning, 2002). This could be the case when continuous variable stocking management is used to maintain sward height and herbage mass.

6.5 CONCLUSION

This study demonstrates that there is potential to make detailed measurements of grazing behaviour and estimate bite mass from patches of a grazed sward by combining information gathered from automatic grazing behaviour recorders, an active transponder system, and sward measurements of herbage removed over the grazing period.

The proposed technique offers some potential advantages over existing methodologies to study grazing activity and estimate bite mass. In particular, recordings can be made under relatively normal field grazing conditions, and there is potential to investigate effects of sward structural heterogeneity by measuring herbage intake characteristics at the patch level within the sward. The system could therefore be used to investigate selection behaviour and intake between patches of different sward structures within a grazed area, or to study effects of herbage species or plant varieties.

An initial experiment using the method detected differences in mean bite mass between paddocks, and between patches of the sward within a paddock. Results indicate bite mass could vary according to the time of day, and bite mass did not consistently decline with a reduction in sward height. On average, the highest estimates of bite mass were made in the Period between the afternoon milking and 19:00 h; while lowest estimates were made in the period overnight from 19:00 h to 08:00 h.

The method requires development and evaluation however to determine and improve the reliability of results. Combining recordings of grazing behaviour and spatial location can enable grazing activity of individual cows within patches of the sward to be investigated. Reliability of this information is dependent upon accurately matching times of the continuous recordings of grazing behaviour and location to enable grazing activity within the aerial coverage areas to be measured. The technique and the ease of analysing and interpreting results could therefore be improved if automatic behaviour recording equipment also detected and recorded times when cows were within the aerial coverage areas.

Estimation of herbage removed from sward measurements could be used to estimate bite mass and rate of herbage intake. This method however relies upon obtaining accurate measurements of herbage removed by grazing from the specified patches of sward. In relation to the active transponder system, sward coverage area of the aerial and its variability must be quantified. Development of the stratified clip technique to describe sward structure could improve prediction of herbage intake from patches of the sward over specified time periods. Estimation of herbage removed from sward measurements however does not allow variability in intake between cows to be examined, and this method may not be applicable when the grazing period is very short or where the level of herbage depletion is low.

A reliable method which allows detailed investigation of interactions between sward characteristics and grazing behaviour and intake under normal field grazing conditions, could ultimately improve prediction of potential animal performance from pasture and enable appropriate supplementation of grazing cows.

CHAPTER 7.0 GENERAL DISCUSSION

7.1 MILK PRODUCTION FROM GRAZED PASTURE

7.1.1 The importance of herbage intake and bite mass

Milk production from grazed pasture is dependant upon genetic potential of the cow, herbage intake and herbage quality (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000). Herbage intake is a major factor limiting milk production from potentially high yielding cows (Peyraud and Delaby, 2001). Mayne and Laidlaw (1999) as cited in Mayne (2001), report a mean herbage intake of 18.7 kg DM d^{-1} from studies with high yielding cows, which they calculate has potential to support up to 33 kg milk d^{-1}, assuming a herbage metabolisable energy (ME) content of 12 MJ kg dry matter $(DM)^{-1}$. Results from the literature indicate maximum levels of herbage intake of 20.7 kg DM d^{-1} (Buckley and Dillon, 1998). Assuming a potential ME content of herbage of between 10 and 12 MJ kg DM^{-1}, this is theoretically capable of sustaining milk yields of between 29.7 and 38.2 kg d^{-1} (AFRC, 1993). These high levels of herbage intake and milk production from pasture however are rarely achieved in practice.

Grazing time and bite rate place behavioural constraints on herbage intake (Rook and Huckle, 1996). Potentially high yielding cows are more likely to reach these constraints as they attempt to achieve high levels of intake to meet their nutritional requirements for high levels of milk production. Bite mass then becomes the most critical variable that determines the rate of herbage intake (McGilloway and Mayne, 1996). Assuming maximum grazing time of 10 h d^{-1} and 60 bites $minute^{-1}$ (Phillips and Leaver, 1986; Rook and Huckle, 1996) theoretical levels of herbage intake to support between 25 and 35 kg milk d^{-1} increase from 15.3 to 19.4 kg DM d^{-1}, and mean bite mass increases from 0.43 to 0.54 g DM (Table 7.1). Higher levels of herbage intake and bite mass are required to achieve equivalent ME intakes when herbage ME content is lower. If cows are restricted by time they have available to graze, and grazing time is less than 10 h d^{-1}, mean bite mass required to support a given level of milk production also increases. Similarly, if bite rate is below the maximum achievable, higher levels of bite mass are required to maintain intake rate.

For example, a reduction in bite rate from 60 to 55 bites minute^{-1} when cows are grazing for 10 h d^{-1} would reduce daily herbage intake by 9.1 percent.

Table 7.1 Theoretical herbage DM intake and mean bite mass required to support milk yields 25 to 35 kg d^{-1}

	Milk yield (kg d^{-1})		
	25	30	35
Herbage intake (kg DM d^{-1})†	15.3	17.4	19.4
Mean bite mass (g DM)‡	0.43	0.48	0.54

† Calculated according to (AFRC, 1993), assuming live weight 630 kg, milk 39.4 g kg^{-1} fat, 31.9 g kg^{-1} protein, 44.2 g kg^{-1} lactose, no liveweight change, $q_m = 0.59$; ‡ grazing time 600 min d^{-1}, 60 bites minute^{-1}

There is a negative relationship between bite mass and bite rate (Ungar, 1996). Bite rate however is a characteristic of the individual animal and it is not possible to influence rate of biting on a given sward structure through management. Bite mass on the other hand, is highly dependant upon sward characteristics (McGilloway *et al.*, 1999; Parga *et al.*, 2000). Providing a sward that allow cows to achieve high levels of bite mass therefore provides the best management opportunity to encourage high levels of herbage intake to support the requirements of potentially high yielding cows.

7.1.2 Herbage intake and grazing behaviour results, Experiments 1, 2, and 4

Herbage intake and animal performance from pasture is dependant upon interactions between sward, animal, environmental and management factors (McGilloway *et al.*, 1996; Peyraud *et al.*, 2000). A summary of results from the grazing experiments conducted in this study, along with measurements of some of the major factors affecting herbage intake and grazing behaviour are presented in Table 7.2. An estimate of mean bite mass from the concentrate feeding experiments (Experiments 1 and 2) is made from measurements of herbage intake and grazing time, and estimates of mean bite rate (Table 7.2). In these calculations, bite rate was assumed to be 55 bites minute^{-1}. Actual bite mass would depend upon rate of biting, and for example, would be greater if mean bite rate over the day was lower. Within experiments, there was variability in results over time, and between animals and treatment groups. Highest estimates of herbage intake were measured in Experiment 2, and *n*-alkane estimates of intake per treatment reached a maximum of 20.0 kg DM d^{-1}, which is close to maximum values reported in the literature (Buckley and Dillon, 1998).

Table 7.2 Herbage intake, grazing behaviour, sward and animal characteristics; Experiments 1, 2 and 4

	Experiment 1	Experiment 2				Experiment 4
	13 Aug-16 Sept	22-26 May	19-23 Jun	17-21 Jul	14-18 Aug	24-27 Apr
Herbage intake (kg DM d^{-1})[†]	11.1	15.0	15.2	13.5	13.0	12.3
Herbage intake (kg FW d^{-1})[†]	49.8	71.8	88.4	49.5	69.9	75.9
ME intake (MJ d^{-1})	113.2	171.0	164.2	145.8	131.3	141.5[‡]
Rate of intake (kg DM h^{-1})	1.20	2.82	2.92	2.45	2.40	1.37
Mean bite mass (g DM)	0.36	0.51	0.53	0.45	0.44	0.35
Grazing time (min d^{-1})	572	542	527	553	566	538
Sward surface height (cm)	9.6	10.7	12.3	11.5	10.1	20.8[§]
c.v (%)	32.8	29.2	34.0	37.9	38.1	17.1
Herbage DM (g kg^{-1} FW)	223	209	172	273	186	162
Herbage ME (MJ kg^{-1} DM)	10.2	11.4	10.8	10.8	10.1	-
Concentrate intake (kg DM d^{-1})	7.66	5.60	5.24	5.83	5.83	5.12
Milk yield (kg d^{-1})	31.3	37.6	34.5	31.5	27.7	36.4

[†] Experiments 1 and 2 (AFRC, 1993), Experiment 4 calculated from cut strips of herbage to ground level pre and post grazing; [‡] Estimated ME 11.5 MJ kg DM; [§] Pre-grazing height

7.2 Effects of sward characteristics on herbage intake

7.2.1 Sward height

The major sward variables affecting herbage intake and performance of grazing cows are sward height, herbage mass, bulk density, leafiness and herbage quality (McGilloway and Mayne, 1996; Peyraud and Gonzalez-Rodrigez, 2000).

Sward surface height is considered to be the most important sward factor influencing herbage intake (Hodgson, 1981; Mayne *et al.*, 1997; McGilloway *et al.*, 1999). Bite mass, rate of intake, and daily herbage intake is expected to increase with increasing sward surface height on continuously grazed swards (Pulido and Leaver, 1997; Gibb *et al.*, 1999). On rotationally grazed swards, bite mass and intake rate declines as the sward is grazed down (McGilloway *et al.*, 1999; Barrett *et al.*, 2001).

Mean sward height was lower in Experiment 1 compared to Experiment 2, which could explain a slightly lower bite mass and herbage intake in the first experiment. Estimated bite mass and herbage intake was also lowest towards the end of

Experiment 2 which correlates with the lowest mean sward height compared to earlier periods of this Experiment. Although methodologies to estimate daily herbage intake and bite mass are different, bite mass is estimated to be similar in Experiments 1 and 4, despite large differences in sward height. Estimated mean bite mass in Experiment 4 is low considering a mean pre-grazing sward height of 20.0 cm and post grazing height of 10.2 cm.

The relationship between sward height, herbage intake and grazing behaviour therefore is variable between experiments in the current study, and this is also true for studies reported in the literature (for example, Gibb et al., 1997b; McGilloway *et al.*, 1999; Pullido and Leaver, 2001). Mean sward height has limitations as a descriptor of herbage available. It does not adequately describe other sward characteristics known to have an effect on components of herbage intake, for example herbage mass, bulk density, leafiness and herbage quality, and variability in sward structure across the grazed area (Peyraud and Gonzalez-Rodrigez, 2000; Swain, 2000).

7.2.2 Sward height, density and the vertical distribution of herbage mass

At similar sward heights, bite mass and herbage intake are expected to be greater on a sward with higher herbage mass and bulk density (Mayne *et al.*, 1997), although this can be affected by the distribution of bulk density through the sward (McGilloway *et al.*, 1999). Experiment 3 demonstrates potential for the vertical structure of the sward to affect bite mass. There could therefore be an effect of differences in sward bulk density, herbage mass and the vertical distribution of mass between experiments in this study, on intake and grazing behaviour, however these sward variables were not measured in Experiments 1 and 2.

Experiment 3 shows variability in the vertical distribution of mass according to sward cutting treatments that were designed to simulate different grazing managements. There is a strong exponential relationship between cumulative herbage mass through layers of the swards ($Y = M\,e^{-b(h)}$) ($r^2 = 0.907$-0.997). Results then demonstrate a good relationship between the constant b and sward height ($b = 5.7444 * \text{sward height}^{-1.1179}$, $r^2 = 0.919$). It could therefore be possible to predict potential bite mass from a sward from measurements of sward height and total mass along with estimates of bite dimensions.

Assuming a bite depth of a constant proportion of one third tiller height, and bite area of 100 cm^2, bite mass can be estimated for different sward heights and at different levels of total herbage mass, using the relationships generated in Experiment 3 (Table 7.3). When herbage mass is 3500 kg DM ha^{-1}, for example, this relationship predicts sward surface height must be at least 14 cm to achieve a bite mass of 0.48 g DM, which was calculated to be required to support 30 kg milk d^{-1} (Table 7.1). When herbage mass is lower, for example, 3000 kg DM ha^{-1}, a sward height of at least 16 cm is estimated to be required to support 25 kg milk d^{-1}. To achieve high levels of bite mass, increased sward height or total herbage mass is required. Current sward surface height recommendations for high yielding, continuously grazed cows range from 7 to 12 cm (Mayne *et al.*, 2000; Peyraud and Gonzalez-Rodrigez, 2000). To achieve a bite mass of 0.54 g DM to support 35 kg milk d^{-1} (Table 7.1), relationships obtained from Experiment 3 demonstrate a total herbage mass of 3950 kg DM ha^{-1} is required at a sward height of 12 cm. Actual bite mass on different sward structures however will depend upon interactions between animal behaviour, in particular bite dimensions, and sward characteristics.

Table 7.3 Estimated bite mass for different levels of herbage mass and sward surface height, from the relationship $Y = Me^{-b(h)}$, where Y is bite mass (g DM) above residual sward height (h) (cm), M is total mass (g DM m^{-2}), and b = (5.7444 * sward surface height $^{-1.1179}$)

Herbage mass (kg DM ha-1)	Sward surface height (cm)	Constant b	Residual sward height (cm)	Bite mass † (g DM)
3000	10.0	0.438	6.7	0.37
3000	12.0	0.357	8.0	0.39
3000	14.0	0.301	9.3	0.41
3000	16.0	0.259	10.7	0.43
3500	10.0	0.438	6.7	0.43
3500	12.0	0.357	8.0	0.45
3500	14.0	0.301	9.3	0.48
3500	16.0	0.259	10.7	0.50

† Assuming bite depth one third tiller height, bite area 100 cm^2

7.2.3 Herbage quality

Herbage quality affects intake, and in particular herbage digestibility is positively associated with herbage intake (McGilloway and Mayne, 1996). Increased levels of herbage intake and bite mass have been reported when green leaf mass is higher, and green leaf mass in the lower layers of the sward is also particularly important (Parga *et al.*, 2000). Sward leafiness is positively correlated with herbage quality (Beever *et al.*, 2000). Leafiness generally declines as the season progresses, especially if plants are allowed to enter their reproductive stages of development (Parsons and Chapman, 2000). Bite mass and herbage intake are reduced on very tall swards if this is associated with reduced sward quality and reduced green leaf mass (Gibb *et al.*, 1997; Christie *et al.*, 2000). Leafiness and herbage quality also decline on rotationally grazed swards as they are grazed down (McGilloway *et al.*, 1999). Lower herbage quality in Experiment 2, which is evident from an increase in NDF and decline in digestibility and ME content, was associated with reduced daily herbage intake and rate of intake, as well as lower estimates of bite mass when calculated on a DM basis (Table 7.2). Lower levels of herbage intake observed in Experiment 1 could also be linked to a fall in herbage quality late in the season. Despite the high quality of early season herbage on offer to cows in Experiment 4, a low DM content of the herbage compared to the other experiments, could have had a negative effect on DM intake per bite (Laca *et al.*, 1992; McGilloway and Mayne, 1996).

As herbage quality, and in particular ME content declines, herbage DM intake must increase in order to maintain the same level of animal performance. If cows are restricted by grazing time and have reached their maximum bite rate, sward conditions must permit an increase in mean bite mass to avoid a reduction in animal performance. An increase in herbage availability to counter the effects of lower herbage quality is therefore expected to be particularly important for cows with high milk yield potential.

7.2.4 Sward structural heterogeneity

Variability in sward structure will determine intake characteristics of the sward at the individual bite level. An important aspect of sward structure not reflected in mean sward measurements is the variation in structure that exists across the grazed area

(Garcia *et al.*, 2002). The effect of these characteristics on bite dimensions and bite mass, and then selection between patches of different structures determines intake from the sward. Some of the variability in sward height can be described by classifying areas of the sward as either frequently or infrequently grazed patches (McBride *et al.*, 2000; Ginane and Petit, 2002). The lower sward height of the more frequently grazed patches will restrict bite mass, however higher herbage quality and leafiness can encourage cows to graze these areas in preference to the taller, but poorer quality, less frequently grazed patches. Animals will tend to increase grazing of infrequently grazed patches as the height of frequently grazed patches declines (Dumont *et al.*, 1995).

Heterogeneity in sward structure is expected to increase over the grazing season, especially when grazing pressure is low (Connell and Baker, 2002). Sward structural heterogeneity could become increasingly important as the season progresses when cows become less prepared to graze infrequently grazed patches as herbage becomes more mature (Gibb *et al.*, 1997; Ginane and Petit, 2002). The coefficient of variation between individual sward height measurements was considerably lower in the ungrazed, early season sward of Experiment 4, compared to the grazed swards of Experiments 1 and 2. Variability between sward height measurements generally increased as Experiment 2 progressed, and was also high in the late season sward of Experiment 1 (Figure 7.1). An increase in spatial heterogeneity of the sward could contribute to lower bite mass and reduced daily herbage intake as the season progressed in Experiment 2, and to the low level of herbage intake and bite mass estimated in Experiment 1. Low grazing pressure to maintain high target sward heights and high herbage availability results in increased spatial heterogeneity and greater qualitative and quantitative variability in the sward (Connell and Baker, 2002; Stakelum and Dillon, 1990).

Representation of sward height by a single mean is potentially misleading, especially when sward structure becomes more heterogeneous and the sward consists of patches of frequently and infrequently grazed areas, and when height measurement frequencies show a skewed distribution. Behavioural responses of cows in longer term grazing studies may therefore not be simply a consequence of different sward heights but to differences in sward structure and spatial pattern of frequently and infrequently grazed patches.

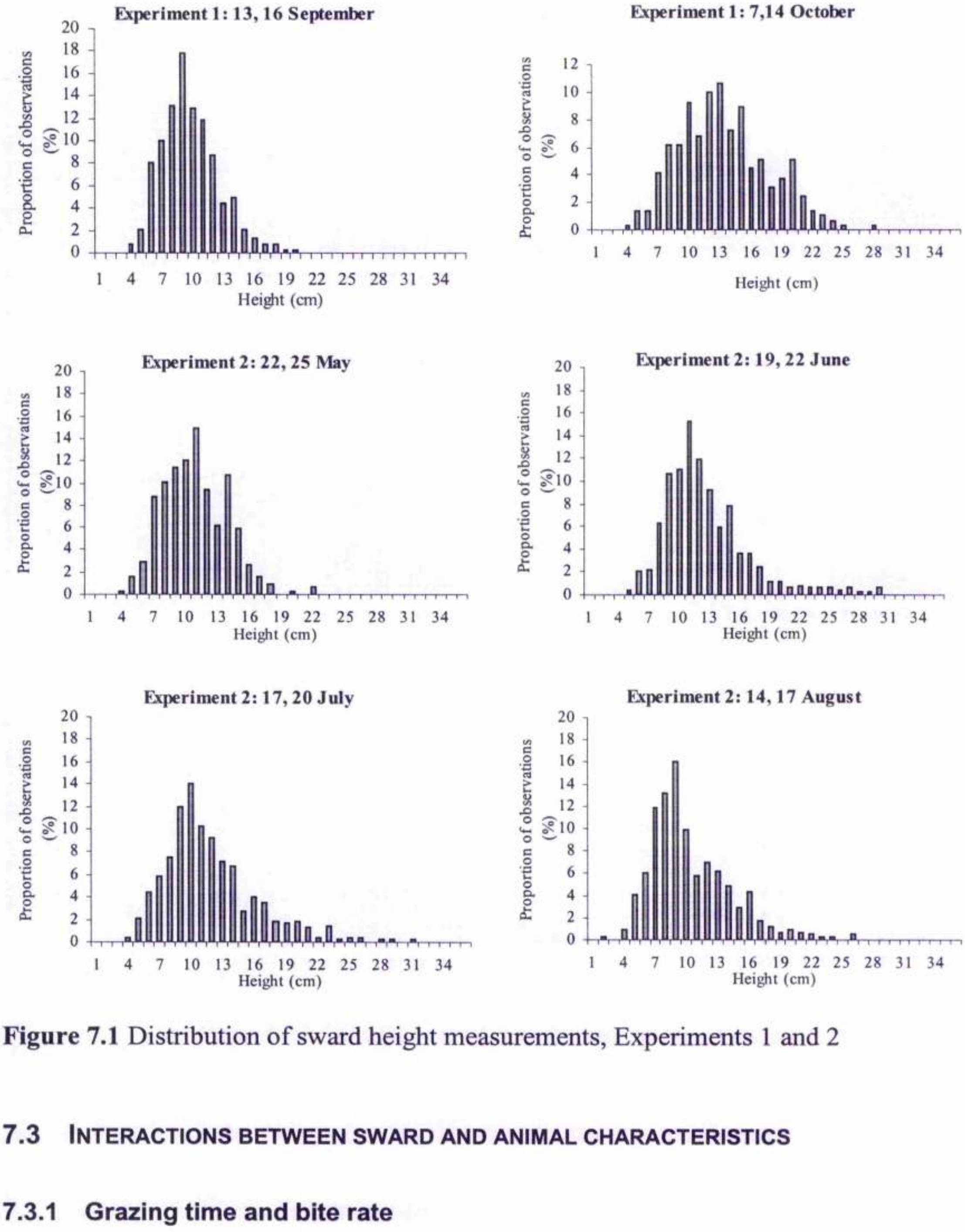


Figure 7.1 Distribution of sward height measurements, Experiments 1 and 2

7.3 INTERACTIONS BETWEEN SWARD AND ANIMAL CHARACTERISTICS

7.3.1 Grazing time and bite rate

Cows can adjust aspects of their grazing behaviour in response to changes in sward, animal, and management factors, in an attempt to maintain herbage intake rates (McGilloway *et al*., 1999; Ungar, 1996). Lengthening grazing time by increasing the duration of individual meals is one way that cows can increase daily intake (Gibb *et* *al.*, 1999). In Experiment 2, grazing time was highest latest in the season, yet herbage intake was lowest. Grazing time may therefore have been increased to achieve desired levels of DM and energy intake when potential bite mass was reduced as a consequence of lower mean sward height, increased spatial heterogeneity, and reduced herbage quality. Grazing time was also high in Experiment 1, which was similarly conducted on a late season sward.

Grazing time is restricted by the time required to perform other activities and in particular rumination. As herbage intake increases, time required for rumination also increases (Gibb *et al.*, 1999). In the absence of supplements offered in the parlour at milking, cows frequently ruminate during milking, however they are reluctant to ruminate during the time spent walking to and from the parlour (Gibb *et al.*, 1997). Rumination is precluded by social interaction and drinking, and idling behaviour when the animal is not grazing or ruminating, is also required for the digestive process. Mean grazing time in Experiments 1, 2, and 4 was high considering grazing time is expected to reach a plateau at between 9 and 10 hours d^{-1} (Rook *et al.*, 1994). This suggests cows were grazing for close to their maximum possible time and herbage intake could have been restricted by sward conditions that define maximum DM intake $bite^{-1}$. It also suggests cows were grazing to obtain the maximum possible bite mass from the herbage available. In Experiment 1 some cows were removed from pasture to receive an additional concentrate feed. This could therefore have had a negative effect on herbage intake by reducing time available for grazing. As sward quality and digestibility declines, time required for rumination also increases (Beever *et al.*, 2000). Time available for grazing could therefore be further reduced later in the grazing season if herbage quality is lower.

Evidence suggests cows adjust grazing time before bite rate or bite dimensions, to maintain herbage intake to match their energy requirements (Gibb *et al.*, 1999). Increasing rate of biting however does provide a further mechanism for grazing cows to increase their intake rate. Gibb *et al.* (1997) argued that lactating cows are unlikely to be able to increase grazing jaw movement rate to any appreciable extent over the long term in response to low bite mass due to the adoption of a preferred grazing jaw movement frequency. Increased bite rate after periods of fasting, demonstrated for example by Patterson *et al.* (1998), are not sustained over the long term, and animals revert to lower rates than what they are capable. Cows however can alter their grazing strategy to increase the ratio of biting to non-biting jaw movements in the evening (Gibb *et al.*, 1998). Results from Experiment 4 also suggest an increased bite mass and rate of intake in the evening.

Bite rate has been demonstrated to be more variable than bite mass (Barrett *et al.*, 2001). It may be that bite rate is more easily adjusted by the cow than bite mass. Bite rate may therefore be used as a means of regulating intake in preference to bite mass in response to small physiological changes.

7.3.2 Bite mass

Cows can potentially increase bite mass to increase their intake rate by altering bite dimensions. The opportunity for cows to adjust dimensions of a bite, and for example bite deeper in to the sward, could be dependent upon sward structure. The impact of increasing bite depth on bite mass for example, will depend upon the vertical distribution of herbage mass in the sward. Presence of an ungrazeable, vegetative fraction at the base of the sward also restricts maximum bite depth, and this is likely to be especially relevant on shorter swards (Gibb *et al.*, 1999). Possibility for cows to alter their bite area is greater on taller swards by sweep of the tongue beyond the area encompassed by the incisor arcade (Laca *et al.*, 1992). Rigid pseudo-stem material at the base of the sward limits this possibility to increase bite area and hence bite mass.

A temporal pattern of grazing activity observed in Experiment 4, and by others, for example Orr *et al.*, (2001), can affect short-term measurements of bite mass and grazing activity. It is therefore difficult to compare results between short-term studies undertaken at different time periods over the day (for example, Barrett *et al.*, 2001; McGilloway *et al.*, 1999). Measurements made during peak periods of grazing activity however may give an indication of maximum potential bite mass and rate of intake from a sward.

7.3.3 Physiological state of the animal

The animals physiological state is a consequence of factors such as body weight, parity, stage of lactation and milk yield, and can have a significant effect on instantaneous and daily intake (Penning *et al.*, 1995; Gibb *et al.*, 1999; Christie *et al.*, 2000). Greater nutritional requirements may promote an increase in total grazing time, bite rate and bite mass (Penning *et al.*, 1995). The extent to which cows are prepared to modify their grazing behaviour could therefore be dependent on their physiological state and the difference between their energy demands and potential energy supply from pasture.

From the above discussion, it could be predicted that in response to increasing nutritional demands and reduced energy balance, cows would adjust their grazing behaviour in the order of grazing time, bite rate and bite mass. Gibb *et al.* (1999) for example found lactating cows achieved higher daily herbage intakes than dry cows with lower energy requirements by grazing for longer. While Patterson *et al.* (1998) found that after a limited period of fasting (3h), cows increased their bite rate but not bite mass; however as the period of fasting was extended (6 h), they also increased bite mass. Potential for cows to adjust bite dimensions can interact with, and possibly be restricted by, sward characteristics (Gibb *et al.*, 1999). On tall rotationally grazed swards Christie *et al.* (2000) however, found a positive effect of milk yield potential on daily herbage intake was principally mediated through increased intake per bite.

From a number of studies in the literature, it has been demonstrated that cows bite to a depth of a constant proportion of sward height (Wade *et al.*, 1989; Laca *et al.*, 1992). Ability of cows to alter bite mass according to their physiological state, an effect of fasting, and also a temporal effect on bite mass, suggests bite depth may be modified disproportionately of sward height and other sward structural characteristics.

Differences in estimated bite mass between Experiments 1 and 2 could therefore result from differences in animal requirements and potential, as well as differences in sward characteristics and overall energy balance. The reduced energy requirement to support lower levels of milk production from later lactation cows in Experiment 2 could also contribute to the lower levels of herbage intake later in the season.

7.4 RESPONSES TO CONCENTRATE SUPPLEMENTATION

A major challenge when managing high genetic merit cows at pasture is to achieve high enough levels of DM intake to support their nutritional requirements for high levels of milk production, and so avoid excessive loss of live weight which can result in health, fertility and welfare problems (Pryce *et al.*, 2001; Rauw *et al.*, 1998).

Concentrate supplementation can enable grazing cows to perform closer to their production potential and avoid excessive liveweight loss when there is a shortfall between potential herbage intake from the sward, and the cow's intake requirements (Mayne *et al.*, 2000; Peyraud and Delaby, 2001).

Milk production response is highly dependant upon the effect of concentrates on herbage intake, and in particular the rate of substitution of herbage for concentrate (McGilloway and Mayne, 1996; Pulido and Leaver, 2001). A lower substitution rate and greater milk yield response to supplementation is expected from cows that are unable to meet their intake requirements from herbage alone (Delaby *et al.*, 2001). Efficiency of concentrate supplementation for milk production is greater from cows with a high milk production potential (Dillon *et al.*, 1999; Hoden *et al.*, 1991; Peyraud *et al.*, 1998), and when sward characteristics do not enable them to meet their intake requirements (Gibb *et al.*, 2002b; Meijs and Hoekstra, 1984).

High responses to supplementation of above 1 kg milk kg^{-1} concentrate dry matter (DM) have been achieved when cows have been offered up to 5.4 kg concentrate DM d^{-1} (for example, Delaby *et al.*, 2001; Gibb *et al.*, 2002b; Wales *et al.*, 1999; Wilkins *et al.*, 1994). High efficiencies of up to 0.86 kg milk kg^{-1} concentrate DM, have also been reported when grazing cows are fed up to 10 kg concentrate DM d^{-1} (Sayers *et al.*, 2000; Reis and Combs, 2000). In the current study, a similarly high milk yield response of 1.01 kg and 0.83 kg milk kg^{-1} DM concentrate intake was observed when concentrate supplementation was increased from 5.1 to 7.7 kg DM d^{-1}, and from 7.7 to 10.2 kg DM d^{-1} respectively. In this experiment, low potential herbage DM intake as a consequence of deterioration in sward and herbage quality associated with late season swards, which was unable to meet the cows intake requirements contributed to high milk yield responses to supplementation.

Results from Experiment 1 and others, for example Delaby *et al.* (2001) and Reis and Combs (2000), demonstrate a decline in marginal efficiency of supplementation for milk production with increasing concentrate level. The shape of the response to increasing concentrate level however is dependant upon interactions between potential herbage intake from the sward, quality of herbage selected, the animals nutritional demands and milk production potential, as well as concentrate allowance (Delaby *et al.*, 2001; Mayne *et al.*, 2000; Pullido and Leaver 2001). Results from Experiment 1 suggest herbage intake, and hence substitution rate and milk production response to supplementation, are dependant upon the proportion of the cows ME requirements for maintenance plus milk production that are met from concentrate intake. The response to concentrate supplementation of grazing cows could therefore be summarised in terms of energy balance, and this has also been suggested by others (for example, Peyraud and Delaby, 2001).

Substitution rate and milk production responses to increasing levels of supplementation are therefore affected by interactions between the animal's nutritional requirements, and hence production potential, as well as its potential energy and nutrient intake from the sward, and the level of supplementation (Peyraud and Delaby, 2001). Concentrate composition can also interact with concentrate allowance to affect animal performance at pasture. Levels and types of energy and protein in concentrates can affect energy and nitrogen (N) supply to the rumen and so influence rumen microbial activity and microbial protein supply to the animal. High inputs of rapidly fermentable energy, such as starch, can increase concentrations of volatile fatty acids and lactate in the rumen and so lower rumen pH (Sutton *et al.*, 1987). This can reduce activity of rumen microbes, and so decrease rate of passage of material through the rumen which can restrict further herbage intake (Arriaga-Jordan and Holmes, 1986). The present study however demonstrates that concentrate energy source has a limited effect on milk production and this is in agreement with others, for example, Fisher *et al.* (1996), Gibb *et al.* (2002a), and Sayers *et al.* (2000). Results from Experiment 2 actually demonstrate a slight positive effect of a higher starch concentrate on milk production and herbage intake, and this difference between treatments increased as the season progressed. It is possible that a higher starch concentrate actually increased supply of fermentable energy to the rumen and improved the balance between rapidly available rumen N from herbage and fermentable energy (Beever *et al.*, 2000; Kolver *et al.*, 1998).

Greater effects of concentrate energy source could be expected when the ratio of concentrate to herbage in the diet increases (Sayers *et al.*, 2000; Schwarz *et al.*, 1995). Effects of concentrate energy source might therefore be particularly important for high genetic merit cows when it is necessary to offer high levels of concentrates for them to achieve their potential level of milk production. Type of starch in the supplement can also have an effect on intake or milk production. Negative effects of a high starch concentrate on animal performance have most often been reported from rapidly degradable types of starch such as barley grain (Fisher *et al.*, 1996; Khalili and Sairanen, 2000). Less rapidly degradable starch such as maize (Schwarz *et al.*, 1995; Valk *et al.*, 1990), or a mixture of ingredients (van Vuuren *et al.*, 1986) as fed in the current study, have less of a disruptive effect on intake and animal performance. Concentrate composition may also interact with herbage quality, which affects the total level and availability of fermentable energy and N in the rumen (Schwarz *et al.*, 1995).

While energy tends to be the major factor limiting animal performance from pasture, grazing cows can also respond to protein supplementation (Hongerholt and Muller, 1998). Responses to improved protein supply can in particular be expected from potentially high yielding cows which have increased metabolisable protein requirements (Hongerholt and Muller, 1998; Neilsen *et al.*, 2002).

While fresh herbage is high in crude protein (Beever *et al.*, 2000), the majority of this protein is rapidly degradable in the rumen (Beever *et al.*, 1986). Inclusion of an additive formulated to reduce the degradability of dietary protein in the current experiment increased herbage intake and herbage intake rate; and had significant beneficial effects on animal performance. Reduced degradability of dietary protein would increase RUP supply to the animal, which along with higher microbial protein flow to the small intestine, could improve animal performance (Hongerholt and Muller, 1998). Increased microbial activity could also improve digestion of fibre and passage of material through the rumen and so promote increased herbage intake

(Arriaga-Jordan and Holmes, 1986), further supporting higher levels of milk production.

Effects of concentrate composition on herbage intake and animal performance are therefore dependant upon interactions between characteristics of the supplement, animal requirements and milk production potential, the level and proportion concentrate in the total diet, potential intake from the sward and quality of herbage selected.

7.5 GRAZING MANAGEMENT AND SUPPLEMENTATION OF HIGH GENETIC MERIT COWS

Achieving high levels of herbage intake from grazed pasture requires a high herbage allowance, and in particular provision of continuously grazed cows with a high herbage mass and sward height (Pulido and Leaver, 2001; Stakelum, 1986b), and leaving a high post grazing herbage mass and sward height in rotational systems (McGilloway *et al.*, 1999). Sward characteristics to allow high mean bite mass and herbage intake per cow however can result in poor herbage utilisation, and reduced grazing pressure can result in deterioration of sward quality and structure, particularly during the spring and early summer period (Mayne *et al.*, 2000; Stakelum and Dillon, 1991). Improving efficiency of production and optimising utilisation of grazed pasture may therefore not necessarily mean maximising herbage intake. The challenge when managing high genetic merit cows at pasture is to achieve a balance between herbage intake per cow, herbage utilisation and maintenance of sward quality over the season.

Rotational grazing facilitates management practices, and in particular leader-follower grazing or an alternating grazing and cutting system, to utilise high residual herbage masses (Mayne *et al.*, 1988, 2000; Leaver, 1985). In other systems, and in particular under continuous grazing, it could be more appropriate to offer a lower target sward height to maintain sward quality, and provide cows with supplements to maintain high levels of total DM intake. Concentrate supplements should then be offered according to the cows milk production potential, or target milk yield, and potential intake from the sward. The economic value and viability of concentrate supplementation should consider direct and immediate effects of supplementation on herbage intake and milk production. Effects of supplementation on live weight and body condition (Delaby *et al.*, 2001); which can affect health, welfare, and fertility (Pryce *et al.*, 2001), as well as residual milk yield responses to concentrate supplementation (Ferris *et al.*, 1999a), must be taken into account. The value of herbage that is spared as a result of substitution for concentrate should be considered, and reduced intake from a sward could also potentially affect herbage growth and production (Lemaire and Chapman, 1996). Overall, the net benefit or cost of supplementation must consider the economic value of these responses less direct costs of supplementation.

7.6 OPPORTUNITIES FOR FUTURE RESEARCH IDENTIFIED BY THE STUDY

Information from grazing cows yielding more than between 25 and 30 kg milk d^{-1} is limited. This is despite the continuing rise in genetic potential for milk production of the UK dairy herd and the aim to reduce costs of production (Lindberg *et al.*, 1998; McGilloway and Mayne, 1996). Future research efforts should therefore focus on obtaining information from higher genetic merit cows yielding above approximately 30 kg milk d^{-1}.

Concentrate allowance and composition can affect herbage intake and the efficiency of supplementation for milk production. Experiment 2 demonstrates potential for additives formulated to reduce dietary protein degradability to improve animal performance from pasture. Variability in responses to the additive over the season however indicates the requirement for greater understanding of its mode of action, and its interaction with sward quality, herbage availability and animal requirements. The evidence from this study and others, for example Hongerholt and Muller (1998) and Neilsen *et al.* (2002), suggests high yielding cows can respond to improved protein supply. Further study is therefore required to determine the optimum level and type of protein supplementation, and the benefits of including an additive to reduce dietary protein degradability, for milk production from higher yielding grazing cows.

The major effects of concentrate allowance and concentrate formulation on animal performance occur as a consequence of effects on grazing behaviour and herbage intake. When higher yielding cows attempt to meet their intake requirements from pasture, they are more likely to reach constraints on time available to graze and rate of biting (Rook and Huckle, 1996). The greatest opportunity to these animals have to increase their intake rate is by increasing bite mass. Bite mass is highly dependant upon sward characteristics, which is demonstrated in Experiment 3 and by others, for example, Barrett *et al.* (2001) and McGilloway *et al.* (1999). Factors affecting bite mass require further investigation to improve knowledge of effects of sward characteristics on herbage intake, and understand interactions between the sward, the grazing animal and responses to supplementation.

Experiment 3 demonstrates sward height and the vertical distribution of herbage mass in a sward can potentially have significant effects on estimates of bite mass. These results from cut swards suggest a general relationship between sward height and the vertical distribution of mass, as described by the constant b from the relationship $Y = M\,e^{-b\,(h)}$, where Y is herbage mass above sward height (h), and M is total herbage mass. Whether such a relationship between sward height and the constant b exists in grazed swards must be examined. Effect of factors such as frequency of defoliation, time after defoliation, and time of year, on vertical distribution of mass also requires investigation. Results could potentially be used for modelling purposes to generate a general description of bite mass from measurements of sward height and total mass, when combined with knowledge of bite dimensions and grazing behaviour.

There is a need however to quantify interactions between sward structure, supplementation, animal characteristics, and grazing behaviour using grazing cows. Heterogeneity of sward structure and quality across a grazed area can have significant effects on bite mass and hence total herbage intake (Swain, 2000). Methods must therefore be developed to obtain reliable measurements of grazing behaviour, herbage intake and bite mass which take into consideration variability in sward structure across the paddock. This requires continuous accurate recording of animal location and grazing activity within patches of a sward. The active transponder system (Swain *et al.*, 2003) facilitates automatic recording of location within specified patches of a sward. The method would be enhanced, and analysis simplified, if automatic behaviour recorders (for example, Rutter *et al*, 1997b) could detect and record times animals are within specific areas which detect the transponders. Development of a laser positioning system (for example, Fehmi *et al.* 2001) could provide an alternative method of monitoring animal location without physically marking out areas of the sward or fixing transponders to cows. Creation of patches of sward with different structural characteristics would enable examination of effects on selection and grazing behaviour. Similarly, differences between individual animals and interactions between sward conditions and supplementation could be examined. Combining a marker technique to estimate herbage intake with recordings of grazing behaviour could provide estimates of herbage intake from individual animals. Spraying different *n*-alkanes onto patches of grazed sward (Friend *et al.*, 2002) for example, would enable measurement of intake from patches of the sward by individual cows which is not possible from sward measurements. However this method requires development to enable measurement of temporal patterns of intake from patches of the sward.

Future grazing research should therefore aim to quantify interactions between sward structure, supplementation and grazing activity, and focus on factors affecting bite mass. This will enable development of grazing management strategies to exploit the potential of grazed grass, and provide recommendations for the most appropriate levels and types of supplementation for higher genetic merit cows.

CHAPTER 8.0 CONCLUSION

Concentrate supplementation can allow grazing dairy cows to perform closer to their production potential. Milk production responses to supplementation however are variable and are particularly dependent upon effects of the supplement on herbage intake. Effects of concentrate allowance and the composition of concentrate on animal performance depend upon interactions with sward structure, herbage quality, and animal characteristics.

From Experiment 1 it can be concluded:

1. High milk yield responses to high levels of concentrate supplementation can be achieved late in the grazing season. Milk yield responses of 1.01 kg milk kg concentrate DM for example, can be achieved from cows yielding on average 28.8 kg milk d^{-1} when concentrate is increased from 5.1 to 7.7 kg DM d^{-1}, and cows are continuously grazed at an average sward height of 9.6 cm in late summer.

2. Marginal efficiency of concentrate supplementation for milk production declines with increasing concentrate allowance. In this study for example, milk yield response to increasing concentrate allowance from 7.7 to 10.2 kg DM d^{-1} was 0.83 kg milk d^{-1} kg^{-1} concentrate DM intake.

3. With increasing concentrate intake there is a tendency for improved milk protein concentration and increased milk protein yield. Milk fat content can be reduced slightly although greater milk volume with higher concentrate intake can increase total milk fat yield.

4. Concentrate supplementation can increase total ME intake and improve the energy balance of grazing cows. Under the conditions of Experiment 1, liveweight gain increased with increasing concentrate intake.

5. Increasing concentrate allowance reduces herbage intake. In Experiment 1, a high substitution rate of herbage for concentrate of 1.12 kg DM d^{-1} and 0.28 kg DM d^{-1} kg^{-1} concentrate DM was estimated, when concentrate allowance increased from 5.1 to 7.7, and from 7.7 to 10.2 kg DM d^{-1}, respectively. Total ME intake increases with increasing concentrate intake however due to a higher ME content of concentrate compared to herbage.

6. Substitution of herbage for concentrate can be mediated through a reduction in grazing time. For example, in this study grazing time was reduced from 666 minutes cow^{-1} d^{-1}, by 36 and 39 minutes kg^{-1} concentrate DM intake d^{-1}, when concentrate allowance increased from 5.2 to 7.7 and 7.7 to 10.2 kg DM respectively.

7. Grazing time declines as the proportion of a cows energy requirements for maintenance and milk production which are met from concentrate ME intake increases (Experiment 1, r^2 = 0.57). Grazing time is positively related to estimates of herbage intake and so herbage intake is higher and substitution rate is reduced when cows are in lower energy balance, and lower proportions of their energy requirements are met from concentrate intake.

8. Increasing the level of concentrate supplementation to grazing cows over the housing period has limited effects on animal performance when cows are already obtaining a high proportion of their intake requirements to support their production potential from herbage and concentrate.

9. Herbage intake can be restricted by behavioural constraints on maximum grazing time and bite rate. Cows are more likely to reach these constraints on herbage intake if they have high intake requirements to support high potential levels of milk production, or when sward conditions restrict bite mass. In this study, removal of animals from pasture for an additional concentrate feed for approximately 30 minutes d^{-1} could have contributed to high substitution rates observed by reducing time available for grazing.

Overall, the actual shape of the milk yield response to increasing levels of supplementation will interact with herbage intake potential from the sward, herbage quality, and the milk production potential and nutritional requirements of the cow. Greater responses to higher levels of supplementation are therefore expected from higher yielding cows, and when sward and herbage quality declines to reduce potential intake from the sward, which is generally observed as the season progresses. As concentrate allowance increases, the marginal milk yield response to supplementation declines as the cow approaches its nutritional requirements, and substitution rate increases.

Disruption of the rumen environment by high inputs of a high starch, cereal-based concentrate could contribute to high substitution rates observed in Experiment 1 (Reis and Combs, 2000; Schwartz *et al.*, 1985). Previous studies demonstrate variability in effects in concentrate energy source on performance of grazing cows. There is limited information on effects of concentrate composition on performance of cows yielding above 30 kg milk d^{-1}. Under conditions of the study in Experiment 2, it can be concluded:

1. Concentrate energy source has minimal effects on animal performance over the grazing season, when cows with an initial milk yield of 38.9 kg d^{-1} are offered 5.3 kg concentrate DM d^{-1}, and continuously grazed at a sward height of 10 to 12 cm.

2. Milk yield and herbage intake however, can increase slightly when animals are offered a higher starch compared to higher fibre supplement as the season progresses. This correlates with changes in sward characteristics and herbage quality. Increased energy supply to the rumen from the starchy concentrate may be a better complement for the higher NDF, and lower ME and WSC content of herbage later in the season. There could therefore be some benefits of supplementing grazing cows with specific energy sources according to sward characteristics and the composition of herbage selected.

3. Cows with higher milk production potential have increased metabolisable protein requirements and can demonstrate greater production responses to improved protein supply (Hongerholt and Muller, 1998). Supplementation with an additive

formulated to reduce the rate of dietary protein degradation can increase milk yield, and yields of protein and lactose. Mean milk yields of additive and control treatments in this study for example, were 34.4 and 32.9 kg d^{-1} respectively over the grazing season, and cows supplemented with the additive also gained more liveweight.

4. Higher levels of production with the additive treatment are supported by increased estimates of total daily herbage intake and the rate of herbage DM intake.

5. Positive effects of inclusion of the additive on herbage intake and milk production under the conditions of the study decline as the season progresses. This effect correlates with changes in sward characteristics, and in particular increased heterogeneity and reduced herbage quality; reduced milk production potential of later lactation cows; and concentrates forming an increasing proportion of the total diet. The additive's mode of action requires further investigation to quantify sward and animal factors affecting milk production responses to its inclusion in the diet of grazing cows.

Effects of concentrate allowance, concentrate energy source, and protein supplementation on animal performance are influenced by sward characteristics, herbage quality, animal production potential, and the level and degradability of supplementary energy and protein. To improve grazing management and concentrate supplementation strategies it is important to quantify interactions between sward characteristics, animal factors, grazing behaviour, herbage intake, and supplementation.

Bite mass has a significant effect on herbage intake, especially for higher yielding cows which can be restricted by grazing time and maximum bite rate. Sward characteristics have a major effect on bite mass. Herbage DM in the volume of a bite is dependent upon the distribution of mass through horizons of the sward. From swards cut to represent different grazing management practices in Experiment 3, it can be concluded that:

1. Sward surface height and herbage mass increase with increasing regrowth interval, and are higher for swards cut to a target height of 6 cm compared to 12 cm at equivalent regrowth ages.

2. Sward height (cm) and herbage mass (kg DM ha^{-1}) are positively correlated (r^2 = 0.47). Mean bulk density of herbage to ground level declines with increasing age of regrowth, and mean bulk density is similar for swards cut to either 6 cm or 12 cm at equivalent regrowth ages.

3. Herbage mass and bulk density increase through horizons of the sward from the top to the base of the sward canopy. There is a strong exponential relationship, $Y = Me^{-b(h)}$, between mean cumulative herbage mass (Y), total herbage mass (M), and residual sward height (h) through horizons of the sward (r^2 values 0.907 to 0.997 for different cutting treatments).

4. Assuming a constant bite area of 100 cm^2, estimates of bite mass from the uppermost grazing horizon range from 0.09 to 0.93 g DM and 0.25 to 1.70 g DM when bite depth is estimated as a third or half of sward height respectively.

5. Under the assumptions made in the study, bite mass is positively associated with sward surface height and r^2 values for the linear relationship between the two variables were 0.39 and 0.46 when bite depth was assumed to be a third and a half of sward height respectively.

6. Empirically derived b values for the exponential relationships fitted to the distribution of herbage mass in cut swards demonstrate a strong power function relationship with sward surface height; $b = 5.7444\ \textit{sward surface height}^{-1.1179}$ (r^2 = 0.92).

A general relationship between sward height, total herbage mass and the constant b could be used to estimate bite mass from measurements of sward height, total mass, and estimates of bite dimensions. However there is a need to quantify and interactions between sward characteristics and bite mass using grazing cows. From Experiment 4 it can be concluded:

1. Detailed measurements of grazing behaviour and estimates of bite mass from patches of a grazed sward, can be made by combining information gathered from automatic grazing behaviour recorders, an active transponder system, and sward measurements of herbage removed over the grazing period.

2. An initial experiment using this method estimates a range in mean bite mass of between 0.26 and 0.50 g DM over 24 h between paddocks, and between patches of the sward within a paddock.

3. There can be a temporal effect on bite mass and bite mass does not decline consistently with a reduction in sward height. Over 4 measurement periods in 24 h, bite mass ranged from 0.16 to 0.88 when mean sward surface height declined from 20.0 to 10.0 cm. Bite mass is highest in the period between afternoon milking and dusk; and lowest overnight. Variability in estimated bite mass between patches of sward in the same paddock with similar sward structures could be a consequence of time of day when the patches were grazed.

4. The method requires development and evaluation to determine and improve the reliability of results. Accuracy of intake and grazing behaviour information obtained is dependent upon matching times of the continuous recordings of grazing behaviour and location. The technique could be improved, and the ease of analysing and interpreting results would be simplified, if automatic behaviour recording equipment also detected and recorded times when cows were within aerial coverage areas. Sward coverage area of the aerial and its variability must also be quantified.

5. Development of the stratified clip technique to describe sward structure could improve prediction of herbage intake from patches of the sward over specified time periods. Estimation of herbage removed from sward measurements however does not allow variability in intake between cows to be examined. The method may not be applicable when the grazing period is very short or where the level of herbage depletion is low.

6. A reliable method which allows detailed investigation of interactions between sward characteristics and grazing behaviour and intake under normal field grazing conditions, could ultimately improve prediction of potential animal performance from pasture and enable appropriate supplementation of grazing cows.

Overall, despite the continuing rise in genetic potential for milk production of the UK dairy herd and the aim to reduce costs of production, information from grazing cows yielding more than between 25 and 30 kg milk d^{-1} is limited. Future research efforts should therefore focus on obtaining information from higher genetic merit cows yielding above approximately 30 kg milk d^{-1}. Research should aim to quantify interactions between sward structure, supplementation and grazing activity, and focus on factors affecting bite mass. This will enable development of grazing management strategies to exploit the potential of grazed grass, and provide recommendations for the most appropriate levels and types of supplementation for higher genetic merit cows.

BIBLIOGRAPHY

AFRC (1993) *Energy and protein requirements of ruminants*. CAB International, Wallingford.

Agnew K.W., Yan T. and Gordon F.J. (1998) Nutrition of the high genetic merit dairy cow - energy metabolism studies. In: Garnsworthy P.C. and Wiseman J. (eds) *Recent Advances in Animal Nutrition 1998, Nottingham University Press, Nottingham.* pp. 181-208.

Alberda T. and Sibma L. (1968) Dry matter production and light interception of crop surfaces. 3. Actual herbage production in different years compared with potential values. *Journal of the British Grassland Society*, **23**, 206-215.

Allden W.G. and Whittaker I.A.M. (1970) The determinants of herbage intake by grazing sheep: The inter-relationships of factors influencing herbage intake and availability. *Australian Journal of Agricultural Research*, **21**, 755-766.

Allen M.S. (1996) Physical constraints on voluntary intake of forages by ruminants. *Journal of Animal Science*, **74**, 3063-3075.

Allen M.S. (2000) Effects of diet on short-term regulation of feed intake by lactating dairy cattle. *Journal of Dairy Science*, **83**, 1598-1624.

Arriaga-Jordan C.M. and Holmes W. (1986a) The effect of cereal concentrate supplementation on the digestibility of herbage-based diets for lactating dairy cows. *Journal of Agricultural Science*, **106**, 581-592.

Arriaga-Jordan C.M. and Holmes W. (1986b) The effect of concentrate supplementation on high-yielding dairy-cows under 2 systems of grazing. *Journal of Agricultural Science*, **107**, 453-461.

Baker L., Alvareze F. and Le Du Y.L.P. (1981) The effect of herbage allowance upon the herbage intake and performance of suckler cows. *Grass and Forage Science*, **36**, 189-199.

Baker R.D. (1986a) Advances in cow grazing systems. In: Frame J. (ed) *Grazing. British Grassland Society Occasional Symposium No. 19, Malvern, Worcestershire.* pp. 155-166.

Baker R.D. (1986b) Efficient use of nitrogen fertilizers. In: Cooper, J.P. and Raymond W.F. (eds) *Grassland Manuring. British Grassland Society Occasional Symposium No. 20*, pp. 15-27.

Bao J., Giller P.S. and Kett J.J. (1992) The effect of milk production level on grazing behaviour of Friesian cows under variable pasture conditions. *Irish Journal of Agricultural and Food Research*, **31**, 23-33.

Barrett P.D., Laidlaw A.S., Christie H. and Mayne C.S. (2000) Herbage intake potential and bite dimensions of dairy cows when grazing a one day paddock. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 97-98.

Barrett P.D., Laidlaw A.S., Mayne C.S. and Christie H. (2001) Pattern of herbage intake rate and bite dimensions of rotationally grazed dairy cows as sward height declines. *Grass and Forage Science*, **56**, 362-373.

Barthram G.T. (1980) Sward structure and depth of the grazed horizon. *Grass and Forage Science*, **36**, 130-131.

Barthram G.T. (1986) Experimental techniques: the HFRO sward stick. In: *Hill Farming Research Organisation. Biennial Report, 1984-85.* pp 29-30.

Barthram G.T. (1992) New equipment for determining vertical distribution of herbage mass in swards. In: *Proceedings of the 3rd Research Conference of the British Grassland Society.* pp 17-18.

Barthram G.T., Elston D.A. and Bolton G.R. (2000) A comparison of three methods for measuring the vertical distribution of herbage mass in grassland. *Grass and Forage Science*, **55**, 193-200.

Beever D.E., Losada H.R., Cammell S.B., Evans R.T. and Haines M.J. (1986) Effect of forage species and season on nutrient digestion and supply in grazing cattle. *British Journal of Nutrition*, **56**, 209-225.

Beever D.E., Offer N. and Gill M. (2000) The feeding value of grass and grass products. In: Hopkins A. (ed) *Grass - Its Production and Utilization Blackwell Science Ltd., Oxford.* pp. 140-195.

Beever D.E. and Siddons R.C. (1986) Digestion and metabolism in grazing ruminants. In: Milligan L.P., Grovum W.L. and Dobson A. (eds) *Control of*

Digestion and Metabolism in Ruminants, Prentice-Hall, Banff, Canada. pp. 479-497.

Black J.L. and Kenney P.A. (1984) Factors affecting diet selection by sheep. 2. Height and density of pasture. *Australian Journal of Agricultural Research*, **35**, 565-578.

Buckley F. and Dillon P. (1998) The effect of genotype and feeding system on the performance of Holstein Friesian cows at pasture. *Irish Grassland and Animal Production Association Journal*, **32**, 3-12.

Buckley F., Dillon P., Crosse S., Flynn S. and Rath M. (2000a) The performance of Holstein Friesian dairy cows of high and medium genetic merit for milk production on grass-based feeding systems. *Livestock Production Science*, **64**, 107-119.

Buckley F., Dillon P., Rath M. and Veerkamp R.F. (2000b) The relationship between genetic merit for yield and live weight, condition score and energy balance of spring calving Holstein Friesian dairy cows on grass based systems of milk production. *Journal of Dairy Science*, **83**, 1878-1886.

Burtis G.Y. and Phillips C.J.C. (1987) The effect of herbage surface water and the provision of supplementary forage on the intake and feeding behaviour of cattle. *Grass and Forage Science*, **42**, 259-264.

Caird L. and Holmes W. (1986) The prediction of voluntary intake of grazing cows. *Journal of Agricultural Science*, **107**, 43-54.

Camlin M.S. (1997) Grasses. In: Weddell J.R. (ed) *Seeds of Progress. British Grassland Society Occasional Symposium No. 31.*

Carrere P., Louault F., De Faccio Carvalho P.C., Lafarge M. and Soussana J.F. (2001) How does the vertical and horizontal structure of a perennial ryegrass and white clover sward influence grazing? *Grass and Forage Science*, **56**, 118-130.

Champion R.A., Rutter S.M. and Orr R.J. (1997) Distinguishing bites and chews in recordings of the grazing jaw movements of cattle. In: *5th British Grassland Society Research Conference, Seale Hayne Faculty of Agriculture, University of Plymouth.* pp. 171-172.

Chilibroste P., Tamminga S., Boer H., Gibb M.J. and den Dikken G. (2000) Duration of regrowth of ryegrass (*Lolium perenne*) effects on grazing behaviour, intake, rumen fill, and fermentation of lactating dairy cows. *Journal of Dairy Science*, **83**, 984-995.

Christie H., Mayne C.S., Laidlaw A.S., Patterson D.C. and McGilloway D.A. (2000) Effect of sward manipulation and milk yield potential on herbage intake of grazing dairy cows. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 79-84.

Clark H., Newton P.C.D. and Barker D.J. (1999) Physiological and morphological responses to elevated CO_2 and a soil moisture deficit of temperate pasture species growing in an established plant community. *Journal of Experimental Botany*, **50**, 233-242.

Clark J., Kat C. and Santhirasegaram K. (1974) The dry-matter production, botanical composition, *in vitro* digestibility and protein percentage of pasture layers. *Journal of the British Grassland Society*, **29**, 179-184.

Coffey M. (1992) Genetic trends. Has progress been made in the past six years? *Holstein Friesian Journal*, 62-65.

Combellas J. and Hodgson J. (1979) Herbage intake and milk production by grazing dairy cows. 1. The effects of variations in herbage mass and daily herbage allowance in a short-term trial. *Grass and Forage Science*, **34**, 209-214.

Connell J. and Baker L. (2002) The effect of the frequently grazed patch height on the utilisation of the infrequently grazed patch within a sward. In: Durand J-L., Emile J-C, Huyghe C. and Lemaire G. (eds) *Multi-function Grasslands. Quality Forages, Animal Products and Landscapes. Proceedings of the 19th General Meeting of the European Grassland Federation, La Rochelle, France.* pp. 240-241.

Cook J.E., Champion R.A. and Rook A.J. (2002) Use of electronic animal identification in an operant conditioning system for grazing sheep. In: *Proceedings of the Xth European Intake Workshop, Reykjavik, Iceland.*

Cooper J.P. (1951) Studies on growth and development in Lolium. II Pattern of bud development of the shoot apex and its ecological significance. *Journal of Ecology*, **39**, 228-270.

Cooper J.P. (1970) Potential production and energy conversion in temperate and tropical grasses. *Herbage Abstracts*, **40**, 1-15.

Cooper J.P. and Tainton (1968) Light and temperature requirements for the growth of temperate and tropical grasses. *Herbage Abstracts*, **38**, 167-176.

Corrall A.J. and Fenlon J.S. (1978) A comparative method for describing the season distribution of production from grasses. *Journal of Agricultural Science*, **91**, 61-67.

Curll M.L. and Wilkins R.J. (1982) Frequency and severity of defoliation of grass and clover by sheep at different stocking rates. *Grass and Forage Science*, **37**, 291-297.

Daniels M.J., Ball N., Hutchings M.R. and Greig A. (2001) The grazing response of cattle to pasture contaminated with rabbit faeces and the implications for the transmission of paratuberculosis. *Veterinary Journal*, **161**, 306-313.

Davies D.A. and Hopkins A. (1996) *Production benefits of legumes in grassland.* In: Younie D. (ed) *British Grassland Society Occasional Symposium No. 30.* pp. 234-236.

Delaby L., Peyraud J.L. and Delagarde R. (1999) Milk production at grazing without concentrate supplementation. *Rencontres Recherches Ruminants*, **6**, 123-126.

Delaby L., Peyraud J.L. and Delagarde R. (2001) Effect of the level of concentrate supplementation, herbage allowance and milk yield at turn-out on the performance of dairy cows in mid lactation at grazing. *Animal Science*, **73**, 171-181.

Delaby L., Peyraud J.L., Verite R. and Marquis B. (1996) Effect of protein content in the concentrate and level of nitrogen fertilisation on the performance of dairy cows on pasture. *Annales de Zootechnie*, **45**, 327-341.

Delagarde R., Peyraud J.L. and Delaby L. (1997) The effect of nitrogen fertilization level and protein supplementation on herbage intake, feeding behaviour and digestion in grazing dairy cows. *Animal Feed Science and Technology*, **66**, 165-180.

Delagarde R., Peyraud J.L. and Delaby L. (1999) Influence of carbohydrate or protein supplementation on intake, behaviour and digestion in dairy cows strip-grazing low-nitrogen fertilised perennial ryegrass. *Annales de Zootechnie*, **48**, 81-96.

Delagarde R., Peyraud J.L. and Delaby L. (2000a) Herbage intake of strip-grazing dairy cows: effects of herbage allowance, concentrate supplementation level and initial milk yield. In: Soegaard K., Ohlsson C., Sehested J., Hutchings N.J., and Kristensen T. (eds) *Grassland Farming – Balancing environmental and economic demands. Proceedings of the 18th General Meeting of the European Grassland Federation, Aalborg, Denmark.* pp. 309-311.

Delagarde R., Peyraud J.L. and Delaby L. (2000b) Influence of herbage allowance on intake and behaviour of dairy cows grazing perennial ryegrass swards in autumn. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 101-102.

Delagarde R., Peyraud J.L., Delaby L. and Faverdin P. (2000c) Vertical distribution of biomass, chemical composition and pepsin-cellulase digestibility in a perennial ryegrass sward: interaction with month of year, regrowth age and time of day. *Animal Feed Science and Technology*, **84**, 49-68.

Dennis W.D. and Woledge J. (1985) The effect of nitrogenous fertilizer on the photosynthesis and growth of white clover/perennial ryegrass swards. *Annals of Botany*, **55**, 171-178.

Dillon P., Buckley F., Snijders S. and Crosse S. (1999) The effect of cow genetic index and grass-based feeding system on the performance of spring-calving Holstein-Friesian cows in second lactation. In: Oldham J.D., Simm G., Groen A.F., Pryce J.E. and Lawrence T.L.J. (eds) *Metabolic Stress in Dairy Cows. British Society of Animal Science. Occasional Publication No. 24.* pp. 141-146.

Dillon P., Crosse S. and O'Brien B. (1997) Effect of concentrate supplementation of grazing dairy cows in early lactation on milk production and milk processing quality. *Irish Journal of Agricultural and Food Research*, **36**, 145-159.

Dillon P. and Stakelum G. (1988) Herbage and dosed alkanes as grass measurement technique for dairy cows (abstract). *Irish Journal of Agricultural and Food Research*, **28**, 104.

Dove H. and Mayes R.W. (1996) Plant wax components: A new approach to estimating intake and diet composition in herbivores. *Journal of Nutrition*, **126**, 13-26.

Dumont B., Petit M. and D'hour P. (1995) Choice of sheep and cattle between vegetative and reproductive cocksfoot patches. *Applied Animal Behaviour Science*, **43**, 1-15.

Ernst P., Le Du Y.L.P. and Carlier L. (1980) Animal and sward production under rotational and continuous grazing management - a critical review. In: Prins, W.J. and Arnold, G.H. (eds) *European Grassland Association International Symposium on the Role of Nitrogen in Intensive Grassland Production, Wageningen.* pp. 199-126.

Evans R.T. (1981) Production from swards grazed by dairy cows. *Grass and Forage Science*, **36**, 132-134.

Fehmi J.S. and Laca E.A. (2001) A note on using a laser-based technique for recording of behaviour and location of free-ranging animals. *Applied Animal Behaviour Science*, **71**, 335-339.

Ferris C.P., Gordon F.J., Patterson D.C., Mayne C.S. and Kilpatrick D.J. (1999a) The influence of dairy cow genetic merit on the direct and residual response to level of concentrate supplementation. *Journal of Agricultural Science*, **132**, 467-481.

Ferris C.P., Gordon F.J., Patterson D.C., Porter M.G. and Yan T. (1999b) The effect of genetic merit and concentrate proportion in the diet on nutrient utilization by lactating dairy cows. *Journal of Agricultural Science*, **132**, 483-490.

Fisher G.E.J. and Dowdeswell A.M. (1995) The performance of summer-calving cows grazing perennial ryegrass swards. *Grass and Forage Science*, **50**, 315-323.

Fisher G.E.J., Dowdeswell A.M. and Perrott G. (1996) The effects of sward characteristics and supplement type on the herbage intake and milk production of summer-calving cows. *Grass and Forage Science*, **51**, 121-130.

Fisher G.E.J., Roberts D.J. and Dowdeswell A.M. (1995) The manipulation of grass swards for summer-calving dairy cows. *Grass and Forage Science*, **50**, 424-438.

Flores E.R., Laca E.A., Griggs T.C. and Demment M.W. (1993) Sward height and vertical morphological-differentiation determine cattle bite dimensions. *Agronomy Journal*, **85**, 527-532.

Forbes J.M. (1996) Integration of regulatory signals controlling forage intake in ruminants. *Journal of Animal Science*, **74**, 3029-3035.

Forbes J.M. and Hodgson J. (1985) Comparitive studies of the influence of sward conditions on the ingestive behaviour of cows and sheep. *Grass and Forage Science*, **40**, 69-77.

Frame J. (1991) Herbage production and quality of a range of secondary grass species at five rates of fertilizer nitrogen application. *Grass and Forage Science*, **46**, 139-151.

Frame J. (1993) Herbage mass. In: Davies A., Baker R.D., Grant S.A., and Laidlaw A.S. (eds) *Sward Measurement Handbook, British Grassland Society, Reading. pp. 39-68.*

Friend M.A., Swain D.L., Mayes R.W. and Hutchings M.R. (2002) Combining an active transponder system with sprayed n-alkanes to monitor spatial and temporal grazing patterns of contaminated pastures. In: *Proceedings of the Xth European Intake Workshop, Reykjavik, Iceland.*

Garcia F., Carrere P., Soussana J.F. and Baumont R. (2002) Selective defoliation has a major influence on heterogeneity development in swards extensively grazed by sheep. In: Durand J-L., Emile J-C, Huyghe C. and Lemaire G. (eds) *Multi-function Grasslands. Quality Forages, Animal Products and Landscapes. Proceedings of the 19th General Meeting of the European Grassland Federation, La Rochelle, France.* pp. 248-249.

Gibb M.J., Huckle C.A. and Nuthall R. (1997a) The effect of level of concentrate offered in parlour on intake and grazing behaviour by lactating dairy cows. In: *Proceedings of the 5th British Grassland Society Research Conference, Devon.* pp. 173-174.

Gibb M.J., Huckle C.A. and Nuthall R. (1998) Effect of time of day on grazing behaviour by lactating dairy cows. *Grass and Forage Science,* **53**, 41-46.

Gibb M.J., Huckle C.A. and Nuthall R. (2000) Effect of temporal pattern of supplementation on grazing behaviour and herbage intake by dairy cows. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 91-96.

Gibb M.J., Huckle C.A. and Nuthall R. (2002a) Effect of type of supplement offered out of parlour on grazing behaviour and performance by lactating dairy cows grazing continuously stocked grass swards. *Animal Science,* **75**, 153-167.

Gibb M.J., Huckle C.A. and Nuthall R. (2002b) Effects of level of concentrate supplementation on grazing behaviour and performance by lactating dairy cows grazing continuously stocked grass swards. *Animal Science,* **74**, 319-335.

Gibb M.J., Huckle C.A., Nuthall R. and Rook A.J. (1997b) Effect of sward surface height on intake and grazing behaviour by lactating Holstein Friesian cows. *Grass and Forage Science,* **52**, 309-321.

Gibb M.J., Huckle C.A., Nuthall R. and Rook A.J. (1999) The effect of physiological state (lactating or dry) and sward surface height on grazing behaviour and intake by dairy cows. *Applied Animal Behaviour Science,* **63**, 269-287.

Gibb M.J. and Penning P.D. (2002) The development and use of techniques for investigating intake and ingestive behaviour during grazing. In: *Proceedings of the Xth European Intake Workshop, Reykjavik, Iceland.*

Ginane C. and Petit M. (2002) How can heifers diet choice be changed with the reduction of preferred sward prehensibility and time available to graze? In: Durand J-L., Emile J-C, Huyghe C. and Lemaire G. (eds) *Multi-function Grasslands. Quality Forages, Animal Products and Landscapes. Proceedings* *of the 19th General Meeting of the European Grassland Federation, La Rochelle, France.* pp. 250-251.

Givens D.I., Everington J.M. and Adamson A.H. (1989) The nutritive value of spring-grown herbage produced on farms throughout England and Wales over 4 years. 1. The effect of stage of maturity and other factors on chemical composition, apparent digestibility and energy values measured in vivo. *Animal Feed Science and Technology*, **27**, 157-172.

Givens D.I., Moss A.M. and Adamson A.H. (1993) Influence of growth stage and season on the energy value of fresh herbage. 1. Changes in metabolisable energy content. *Grass and Forage Science*, **48**, 166-174.

Gleeson P. (1981) Concentrate supplementation for spring calving cows. *Grass and Forage Science*, **36**, 138-149.

Gordon F.J., Patterson D.C., Yan T., Porter M.G., Mayne C.S. and Unsworth E.F. (1995) The influence of genetic index for milk-production on the response to complete diet feeding and the utilization of energy and nitrogen. *Animal Science*, **61**, 199-210.

Grainger C. and Mathews G.L. (1989) Positive relation between substitution rate and pasture allowance for cows receiving concentrates (abstract). *Australian Journal of Experimental Agriculture*, **29**, 355-360.

Grant S.A., Barthram G.T., Torvell L., King J. and Elston D.A. (1988) Comparison of herbage production under continuous stocking and intermittent grazing. *Grass and Forage Science*, **43**, 29-39.

Greenhalgh J.F.D., Reid G.W., Aitken J.N. and Florence E. (1966) The effects of grazing intensity on herbage consumption and animal production. *Journal of Agricultural Science*, **67**, 13-23.

Hoden A., Peyraud J.L., Muller A., Delaby L. and Faverdin P. (1991) Simplified rotational grazing management of dairy-cows. Effects of rates of stocking and concentrate. *Journal of Agricultural Science*, **116**, 417-428.

Hodgson J. (1981) Variations in the surface characteristics of the sward and the short-term rate of herbage intake by calves and lambs. *Grass and Forage Science*, **36**, 49-57.

Hodgson J., Mackie C.K. and Parker J.W.G. (1986) Sward surface heights for efficient grazing. *Grass Farmer*, **24**, 5-10.

Holden L.A., Muller L.D., Lykos T. and Cassidy T.W. (1995) Effect of corn silage supplementation on intake and milk production in cows grazing grass pasture. *Journal of Dairy Science*, **78**, 154-160.

Holmes C.W. (1974) The Massey grass meter. In: *Dairy Farming Annual, Massey University.* pp. 26-30.

Holmes C.W. (1988) Genetic merit and efficiency of milk production by the dairy cow. In: Garnsworthy P.C. (ed) *Nutrition and Lactation in the Dairy Cow, Butterworths, UK.*

Hongerholt D.D. and Muller L.D. (1998) Supplementation of rumen-undegradable protein to the diets of early lactation Holstein cows on grass pasture. *Journal of Dairy Science*, **81**, 2204-2214.

Hopkins A. (2000a) Herbage production. In: Hopkins A. (ed) *Grass - Its Production and Utilization, Blackwell Science Ltd., Oxford.* pp. 90-110.

Hopkins A. (2000b) Introduction. In: Hopkins A. (ed) *Grass - Its Production and Utilization, Blackwell Science Ltd., Oxford.* pp. 1-12.

Hopkins A., Gilbey J., Dibb C., Bowling P.J. and Murray P.J. (1990) Response of permanent and reseeded grassland to fertilizer nitrogen. 1. Herbage production and herbage quality. *Grass and Forage Science*, **45**, 43-55.

Huckle C.A., Nuthall R. and Gibb M.J. (1994) The use of short-term weight changes to measure intake rates in grazing dairy cattle. In: *Proceedings of the 4th British Grassland Society Research Conference, University of Reading.* pp. 157-158.

Hutchings M.R. and Harris S. (1996) An active transponder system for remotely monitoring animal activity at specific sites. *Journal of Zoology*, **240**, 798-804.

Illius A.W. and Gordon I.J. (1987) The allometry of food intake in grazing ruminants. *Journal of Animal Ecology*, **56**, 989-999.

Illius A.W. and Gordon I.J. (1991) Prediction of intake and digestion in ruminants by a model of rumen kinetics integrating animal size and plant characteristics. *Journal of Agricultural Science*, **116**, 145-157.

Illius A.W., Gordon I.J., Milne J.D. and Wright W. (1995) Costs and benefits of foraging on grasses varying in canopy structure and resistance to defoliation. *Functional Ecology*, **9**, 894-903.

Illius A.W. and Jessop N.S. (1996) Metabolic constraints on voluntary intake in ruminants. *Journal of Animal Science*, **74**, 3052-3062.

Jamieson W.S. and Hodgson J. (1979a) The effect of daily herbage allowance and sward characteristics upon the ingestive behaviour and herbage intake of calves under strip-grazing management. *Grass and Forage Science*, **34**, 261-272.

Jamieson W.S. and Hodgson J. (1979b) The effects of variation in sward characteristics upon the ingestive behaviour and herbage intake of calves and lambs under a continuous stocking management. *Grass and Forage Science*, **34**, 273-282.

Jewiss O.R. (1993) Shoot development and number. In: Davies A., Baker R.D., Grant S.A. and Laidlaw A.S. (eds) *Sward Measurement Handbook. British Grassland Society, Reading.* pp. 99-120.

Johnson I.R. and Parsons A.J. (1985) Use of a model to analyse the effects of continuous grazing managements on seasonal patterns of grass production. *Grass and Forage Science*, **40**, 449-458.

Journet M. and Demarquilly C. (1979) Grazing. In: Broster W.H. and Swan H. (eds) *Feeding Strategy for the High Yielding Dairy Cow, Canada Publishing Co., St. Albans.* pp. 295-321.

Keady T.W.J. and Anderson D. (2000) The cost of producing and feeding grazed grass and grass silage. In: *Proceedings of the 6th British Grassland Society Research Conference, Scottish Agricultural College, Aberdeen.* pp. 105-106.

Khalili H. and Sairanen A. (2000) Effect of concentrate type on rumen fermentation and milk production of cows at pasture. *Animal Feed Science and Technology*, **84**, 199-212.

Kibon A. and Holmes C.W. (1987) The effect of height of pasture and concentrate composition on dairy cows grazed on continuously stocked pasture. *Journal of Agricultural Science*, **109**, 293-301.

Knowlton K.F., Glenn B.P. and Erdman R.A. (1998) Performance, ruminal fermentation, and site of starch digestion in early lactation cows fed corn grain harvested and processed differently. *Journal of Dairy Science*, **81**, 1972-1984.

Kolver E., Muller L.D., Varga G.A. and Cassidy T.J. (1998) Synchronization of ruminal degradation of supplemental carbohydrate with pasture nitrogen in lactating dairy cows. *Journal of Dairy Science*, **81**, 2017-2028.

Laca E.A., Distel R.A., Griggs T.C. and Demment M.W. (1994) Effects of canopy structure on patch depression by grazers. *Ecology*, **75**, 706-716.

Laca E.A., Ungar E.D., Seligman N. and Demment M.W. (1992a) Effects of sward height and bulk density on bite dimensions of cattle grazing homogenous swards. *Grass and Forage Science*, **47**, 91-102.

Laca E.A., Ungar E.D., Seligman N.G. and Ramey M.R. (1992b) An integrated methodology for studying short-term grazing behaviour of cattle. *Grass and Forage Science*, **47**, 81-90.

Laca E.A., Ungar E.D., Seligman N.G., Ramey M.R. and Demment M.W. (1992c) An integrated methodology for studying short-term grazing behaviour of cattle. *Grass and Forage Science*, **47**, 81-90.

Laca E.A. and Wallis De Vries M.F. (2000) Acoustic measurement of intake and grazing behaviour of cattle. *Grass and Forage Science*, **55**, 97-104.

Laredo M.A., Simpson G.D., Minson D.J. and Orpin C.G. (1991) The potential for using *n*-alkanes in tropical forages as a marker for determination of dry matter intake by grazing ruminants. *Journal of Agricultural Science*, **72**, 1375-1380.

Lawes Agricultural Trust (1998) Genstat 5, Release 4.1. *Rothamstead Experimental Station.*

Lawes Agricultural Trust (2002) Genstat 6, Release 6.1. *Rothamstead Experimental Station.*

Lazenby A. (1981) British grasslands: past, present and future. *Grass and Forage Science*, **36**, 243-266.

Le Du Y.L.P., Baker R.D. and Newberry R.D. (1981) Herbage intake and milk production by grazing dairy cows. 3. The effect of grazing severity under continuous stocking. *Grass and Forage Science*, **36**, 307-318.

Le Du Y.L.P., Combellas J., Hodgson J. and Baker R.D. (1979) Herbage intake and milk production by grazing dairy cows. 2. The effects of level of winter feeding and daily herbage allowance. *Grass and Forage Science*, **34**, 249-260.

Leafe E.L. (1988) Introduction - The history of improved grasslands. In: Jones M.B. and Lazenby A. (eds) *The Grass Crop, Chapman and Hall, London.*

Leaver J.D. (1968) Use of supplementary feeds for grazing dairy cows. *Dairy Science Abstracts*, **30**, 355-361.

Leaver J.D. (1982) Grass height as an indicator for supplementary feeding of continuously stocked dairy cows. *Grass and Forage Science*, **37**, 285-290.

Leaver J.D. (1983) In: W. Haresign (ed) *Recent Advances in Animal Nutrition, Butterworths, London.* pp. 199-208.

Leaver J.D. (1985) Milk production from grazed temperate grassland. *Journal of Dairy Research*, **52**, 313-344.

Lee M.R.F., Jones E.L., Moorby J.M., Humphreys M.O., Theodorou M.K., MacRae J.C. and Scollan N.D. (2000) Production responses from lambs grazing on Lolium perenne selected for high water soluble carbohydrate. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 45-50.

Lemaire G. and Chapman D.E. (1996) Tissue flows in grazed plant communities. In: Hodgson J. and Illius A.W. (eds) *The Ecology and Management of Grazing Systems, CAB International, Oxon.* pp. 3-36.

Leng R.A. and Nolan J.V. (1984) Nitrogen metabolism in the rumen. *Journal of Dairy Science*, **67**, 1072-1091.

Lindberg C.M., Swanson G.J.T. and Mrode R.A. (1998) Genetic and phenotypic trends in production traits in the United Kingdom dairy herd. In: *Proceedings of the British Society of Animal Science Winter Meeting, Scarborough.* pp. 191.

Linehan P.A., Lowe J. and Stewart R.H. (1947) The output of pasture and its measurement. *Journal of the British Grassland Society*, **2**, 145-168.

Lowman B.G., Scott N. and Somerville S. (1973) Condition scoring of cattle. *Bulletin of the East of Scotland College of Agriculture, No. 6.*

MAFF (1985) The prediction of ME values of compound feed-stuffs for ruminant animals. Summary of the recommendations of a working party sponsored by MAFF. *HMSO.*

MAFF (1993) Prediction of the energy values of compound feeding stuffs for farm animals, PB 1285. *HMSO.*

Marshall S.A., Campbell C.P. and Buchanan-Smith J.G. (1998) Seasonal changes in quality and botanical composition of a rotationally grazed grass-legume pasture in southern Ontario. *Canadian Journal of Animal Science*, **78**, 205-210.

Mayes R.W. and Duncan A.J. (1999) New developments in the use of plant-wax markers to determine intake. In: *Proceedings of the V^{th} International Symposium on the Nutrition of Herbivores: Emerging techniques for studying the nutrition of free-ranging herbivores.*

Mayes R.W., Lamb C.S. and Colgrove P.M. (1986) The use of dosed and herbage n-alkanes as markers for the determination of herbage intake. *Journal of Agricultural Science*, **107**, 161-170.

Mayne C.S. (1991) Effects of supplementation on the performance of both growing and lactating cattle at pasture. In: Mayne C.S. (ed) *Management Issues for Grassland Farmers in the 1990s. British Grassland Society Occasional Symposium No. 25.* pp. 55-71.

Mayne C.S. (2001) Science to practice - optimising the use of grazed grass. In: *The right mix. British Grassland Society, November 2001, Great Malvern, Worcesershire.*

Mayne C.S., Clements A.J. and Woodcock S.C.F. (1990) An evaluation of the effects of grazing management systems involving preferential treatment of high-yielding dairy cows on animal performance and sward utilization. *Grass and Forage Science*, **45**, 167-178.

Mayne C.S., McGilloway D.A., Cushnahan A. and Laidlaw A.S. (1997) The effects of sward height and bulk density on herbage intake and grazing behaviour of dairy cows. In: *Proceedings of the XVIII International Grassland Congress, Canada.* pp.15-16.

Mayne C.S., Newberry R.D. and Woodcock S.C.F. (1988) The effects of a flexible grazing management strategy and leader/follower grazing on the milk production of grazing dairy cows and on sward characteristics. *Grass and Forage Science*, **43**, 137-150.

Mayne C.S., Newberry R.D., Woodcock S.C.F. and Wilkins R.J. (1987) Effect of grazing severity on grass utilization and milk production of rotationally grazed dairy cows. *Grass and Forage Science*, **42**, 59-72.

Mayne C.S., Steen R.W.J. and Vipond J.E. (2000) *Grazing management for profit.* In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 201-210

Mayne C.S., Wright I.A. and Fisher G.E.J. (2000) Grassland management under grazing and animal response. In: Hopkins A. (ed) *Grass - Its Production and Utilization Blackwell Science Ltd., Oxford.* pp. 247-291.

McBride J., Baker L.J. and G.E.J. F. (2000) The effect of manipulating the stocking density of dairy cows to increase the grazing pressure in the mid season on the morphology and utilisation of rejected patches in a sward. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 33-38.

McDonald P., Edwards R.A., Greenhalgh J.F.D. and Morgan C.A. (1995) *Animal Nutrition*. (5th Edition). Longman.

McGilloway D.A., Cushnahan A., Laidlaw A.S., Mayne C.S. and Kilpatrick D.J. (1999) The relationship between level of sward height reduction in a rotationally grazed sward and short-term intake rates of dairy cows. *Grass and Forage Science*, **54**, 116-126.

McGilloway D.A., Laidlaw A.S., Mayne C.S. and Kilpatrick D.J. (2000) Development of a model to predict bite mass and daily intake by grazing dairy cows. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 111-112.

McGilloway D.A. and Mayne C.S. (1996) *The importance of grass availability for the high genetic merit dairy cow.* In: Garnsworthy P.C. and Wiseman J. (eds) *Recent Advances in Animal Nutrition, Nottingham University Press, Nottingham.* pp. 135-168.

McMeekan C.P. and Walshe M.J. (1963) The inter-relationships of grazing method and stocking rate on the efficiency of pasture utilization by dairy cattle. *Journal of Agricultural Science*, **61**, 147-166.

Meijs J.A.C. (1986) Concentrate supplementation of grazing dairy cows. 2. Effect of concentrate composition on herbage intake and milk production. *Grass and Forage Science*, **41**, 229-235.

Meijs J.A.C. and Hoekstra J.A. (1984) Concentrate supplementation of grazing dairy cows. 1. Effect of concentrate intake and herbage allowance on herbage intake. *Grass and Forage Science*, **39**, 59-66.

Milne J.A., Hodgson J., Thompson R., Souter W.G. and Barthram G.T. (1982) The diet injested by sheep grazing swards differing in white clover and perennial ryegrass content. *Grass and Forage Science*, **37**, 209-218.

Minson D.J. (1963) The effect of pelleting and wafering on the feeding value of roughage - A review. *Journal of the British Grassland Society*, **18**, 39-49.

Monsi M. and Saeki T. (1953) Uber den Lichtfaktor in den Planengesellshaften und seiner Bedeutung fur die Stoffproduction. *Japanese Journal of Botany*, **14**, 22-52.

Moore L.A. (1964) Symposium on forage utilization: Nutritive value of forage as affected by physical form. Part 1. General principles involved with ruminants and effect of feeding pelleted or wafered forage to dairy cattle. *Journal of Animal Science*, **23**, 230-241.

Neaves P.J., Parker W.J. and Holmes C.W. (1996) A farm level model to aid decisions regarding the feeding of concentrates to dairy cattle. *The New Zealand Society of Animal Production*, **56**, 280-284.

Neilsen H.M., Friggens N.C., Lovendahl P., HJensen J. and Ingvartsen K.L. (2002) Influence of breed, parity, and stage of lactation on lactational performance and relationship between body fatness and live weight. *Livestock Production Science*, **In press**.

Newton J.E. and Blackman G.E. (1970) The penetration of solar radiaion through leaf canopies of different structure. *Annals of Botany*, **34**, 329-348.

O'Connell J.M., Buckley F., Rath M. and Dillon P. (2000) The effects of cow genetic merit and feeding treatment on milk production, herbage intake and grazing behaviour of dairy cows. *Irish Journal of Agricultural and Food Research*, **39**, 369-381.

O'Mara F.P., Murphy J.J. and Rath M. (2000) The effect of concentrate supplements differing in ruminal protein degradability on milk production and blood metabolite concentrations of dairy cows grazing perennial ryegrass pasture. *Livestock Production Science*, **64**, 183-191.

Orr R.J., Parsons A.J., Treacher T.T. and Penning P.D. (1988) Seasonal patterns of grass production under cutting or continuous stocking managements. *Grass and Forage Science*, **43**, 199-207.

Orr R.J., Rutter S.M., Penning P.D. and Rook A.J. (2001) Matching grass supply to grazing patterns for dairy cows. *Grass and Forage Science*, **56**, 352-361.

Orr R.J., Rutter S.M., Penning P.D., Yarrow N.H. and Champion R.A. (1996) Grazing behaviour and herbage intake rate by Friesian dairy heifers grazing ryegrass or white clover. In: *Proceedings of Legumes in Sustainable Farming Systems, British Grassland Society, Aberdeen.* pp. 1-4.

Orskov E.R. (1982) *Protein nutrition in ruminants*. Academic Press Limited, London.

Orskov E.R. (1986) Starch digestion and utilization in ruminants. *Journal of Animal Science*, **63**, 1634-1633.

Palmquist D.L. and Jenkins T.C. (1980) Fat in lactation rations: review. *Journal of Dairy Science*, **63**, 1-14.

Parga J., Peyraud J.L. and Delagarde R. (2000) Effect of sward structure and herbage allowance on herbage intake and digestion by strip grazing dairy cows. In: Rook A.J. and Penning P.J. (eds) *Grazing Management. British Grassland Society Occasional Symposium No. 34, Harrogate.* pp. 61-66.

Parsons A.J. and Chapman D.E. (2000) The principles of pasture growth and utilisation. In: Hopkins A. (ed) *Grass - Its Production and Utilization Blackwell Science Ltd., Oxford.* pp. 31-89.

Parsons A.J., Collett B. and Lewis J. (1984) Changes in structure and physiology of a perennial ryegrass sward when released from a continuous stocking management: implications for the use of exclusion cages in continuously stocked swards. *Grass and Forage Science*, **39**, 1-9.

Parsons A.J., Johnson I.R. and Harvey A. (1988) Use of a model to optimise the interaction between frequency and severity of intermittent defoliation and to provide a fundamental comparison of the continuous and intermittent defoliation of grass. *Grass and Forage Science*, **43**, 49-59.

Parsons A.J., Leafe E.L., Collett B., Penning P.D. and Lewis J. (1983a) The physiology of grass production under grazing. II. Photosynthesis, crop growth and animal intake of continuously-grazed swards. *Journal of Applied Ecology*, **20**, 127-139.

Parsons A.J., Leafe E.L., Collett B. and Stiles W. (1983b) The physiology of grass production under grazing. I. Characteristics of leaf and canopy photosynthesis of continuously-grazed swards. *Journal of Applied Ecology*, **20**, 117-126.

Parsons A.J., Thornley J.H.M., Newman J. and Penning P.D. (1994) A mechanistic model of some physical determinants of intake rate and diet selection in two-species temperate grassland sward. *Functional Ecology*, **8**, 187-204.

Patterson D.M., McGilloway D.A., Cushnahan A., Mayne C.S. and Laidlaw A.S. (1998) Effect of duration of fasting period on short-term intake rates of lactating dairy cows. *Animal Science*, **66**, 299-305.

Penning P.D., Parsons A.J. and Orr R.J. (1994) Intake and behaviour responses by sheep to changes in sward characteristics under rotational grazing. *Grass and Forage Science*, **49**.

Peyraud J.L. and Astigarraga L. (1998) Review of the effect of nitrogen fertilization on the chemical composition, intake, digestion and nutritive value of fresh herbage: consequences on animal nutrition and N balance. *Animal Feed Science and Technology*, **72**, 235-259.

Peyraud J.L., Comeron E.A., Wade M.H. and Lemaire G. (1996) The effect of daily herbage allowance, herbage mass and animal factors upon herbage intake by grazing cows. *Annales de Zootechnie*, **45**, 201-217.

Peyraud J.L. and Delaby L. (2001) Ideal concentrate feeds for grazing dairy cows - responses to supplementation in interaction with grazing management and grass quality. In: Garnsworthy P.C. and Wiseman J. (eds) *Recent Advances in Animal Nutrition 2001, Nottingham University Press, Nottingham*, pp. 203-220.

Peyraud J.L., Delaby L., Delagarde R. and Marquis B. (1998) Effect of energy supplementation and herbage allowance on herbage intake by grazing dairy cows. *Rencontres Recherches Ruminants*, 217-220.

Peyraud J.L. and Gonzalez-Rodrigez A. (2000) *Relations between grass production, supplementation and intake in grazing dairy cows*. In: Soegaard K., Ohlsson C., Sehested J., Hutchings N.J., and Kristensen T. (eds) *Grassland Farming – Balancing environmental and economic demands. Proceedings of the 18th General Meeting of the European Grassland Federation, Aalborg, Denmark.* pp. 269-282.

Phillips C.J.C. (1988) The use of conserved forage as a supplement for grazing dairy cows. *Grass and Forage Science*, **43**, 215-230.

Phillips C.J.C. and Leaver J.D. (1985a) Supplementary feeding of forage to grazing dairy cows. 1. Offering hay to dairy cows at high and low stocking rates. *Grass and Forage Science*, **40**, 183-192.

Phillips C.J.C. and Leaver J.D. (1985b) Supplementary feeding of forage to grazing dairy cows. 2. Offering grass silage in early and late season. *Grass and Forage Science*, **40**, 193-199.

Phillips C.J.C. and Leaver J.D. (1986) Seasonal and diurnal variation in the grazing behavior of dairy cows. In: Frame J. (ed) *Grazing. British Grassland Society Occasional Symposium No. 19, Malvern, Worcestershire.* pp. 98-104.

Pryce J.E., Coffey M. and Simm G. (2001) The relationship between body condition score and reproductive performance. *Journal of Dairy Science*, **84**, 1508-1515.

Pryce J.E., Coffey M.P., Brotherstone S.H. and Woolliams J.A. (2002) Genetic relationships between calving interval and body condition score conditional on milk yield. *Journal of Dairy Science*, **85**, 1590-1595.

Pryce J.E., Veerkamp R.F., Thompson R., W.G. H. and Simm G. (1997) Genetic aspects of common health disorders and measures of fertility in Holstein Friesian dairy cattle. *Animal Science*, **65**, 353-360.

Pulido R. and Leaver J.D. (1997) Effect of milk yield, sward height and concentrate supplementation level on herbage intake and grazing behaviour of set-stocked dairy cattle in spring. In: *Proceedings of the XVIII International Grassland Congress, Canada.* pp. 19-20.

Pulido R.G. and Leaver J.D. (2001) Quantifying the influence of sward height, concentrate level and initial milk yield on the milk production and grazing behaviour of continuously stocked dairy cows. *Grass and Forage Science*, **56**, 57-67.

Rauw W.M., Kanis E., Noordhuizen-Stassen E.N. and Grommers F.J. (1998) Undesirable side effects of selection for high production efficiency in farm animals: a review. *Livestock Production Science*, **56**, 15-33.

Reis R.B. and Combs D.K. (2000) Effects of increasing levels of grain supplementation on rumen environment and lactation performance of dairy cows grazing grass-legume pasture. *Journal of Dairy Science*, **83**, 2888-2898.

Rhodes I. (1971) Productivity and canopy structure of two contrasting varieties of perennial ryegrass (*Lolium perenne* L.) grown in a controlled environment. *Journal of the British Grassland Society*, **26**, 9-15.

Robaina A.C., Grainger C., Moate P., Taylor J. and Stewart J. (1998) Responses to grain feeding by grazing dairy cows. *Australian Journal of Experimental Agriculture*, **38**, 541-549.

Robson M.J. (1972) The effect of temperature on the growth of S170 tall fescue (Festuca arundinacea). 1. Constant temperature. *Journal of Applied Ecology*, **9**, 647-657.

Robson M.J., Ryle G.J.A. and Woledge J. (1988) The grass plant - it's form and function. In: Jones M.B. and Lazenby A. (eds) *The Grass Crop, Chapman and Hall, London.* pp. 25-83.

Rook A.J. (2000) Principles of foraging and grazing behaviour. In: Hopkins A. (ed) *Grass - Its Production and Utilization Blackwell Science Ltd., Oxford.* pp. 229-246.

Rook A.J. and Huckle C.A. (1995) Synchronization of ingestive behaviour by grazing dairy cows. *Animal Science*, **60**, 25-30.

Rook A.J. and Huckle C.A. (1996) Sources of variation in the grazing behaviour of dairy cows. *Journal of Agricultural Science*, **126**, 227-233.

Rook A.J. and Huckle C.A. (1997) Activity bout criteria for grazing dairy cows. *Applied Animal Behaviour Science*, **54**, 89-96.

Rook A.J., Huckle C.A. and Penning P.D. (1994a) Effects of sward height and concentrate supplementation on the ingestive behaviour of spring-calving dairy-cows grazing grass clover swards. *Applied Animal Behaviour Science*, **40**, 101-112.

Rook A.J., Huckle C.A. and Wilkins R.J. (1994b) The effects of sward height and concentrate supplementation on the performance of spring calving dairy-cows grazing perennial ryegrass white clover swards. *Animal Production*, **58**, 167-172.

Russell J.B. and Wilson D.B. (1996) Why are ruminal cellulolytic bacteria unable to digest cellulose at low pH? *Journal of Dairy Science*, **79**, 1503-1509.

Rutter S.M. (2000) Graze: a program to analyse recordings of jaw movements of ruminants. *Behaviour Research Methods, Instruments and Computers*, **32**, 86-92.

Rutter S.M., Beresford N.A. and Roberts G. (1997a) Use of GPS to identify the grazing areas of hill sheep. *Computers and Electronics in Agriculture*, **17**, 177-188.

Rutter S.M., Champion R.A. and Penning P.D. (1997b) An automatic system to record foraging behaviour in free-ranging ruminants. *Applied Animal Behaviour Science*, **54**, 185-195.

Rutter S.M., Orr R.J., Penning P.D., Yarrow N.H. and Champion R.A. (2002) Ingestive behaviour of heifers grazing monocultures of ryegrass or white clover. *Applied Animal Behaviour Science*, **76**, 1-9.

Rutter S.M., Orr R.J., Penning P.D., Yarrow N.H., Champion R.A. and Atkinson L.D. (1998) Dietary preference of dairy cows grazing grass and clover. In: *Proceedings of the Winter Meeting of the British Society of Animal Science, Scarborough*. pp. 51.

Ryle G.J.A. and Langer R.H.M. (1963) Studies on the physiology of flowering in timothy. I. Influence of daylength and temperature on initiation and differentiation of the inflorescence. *Annals of Botany*, **27**, 213-231.

Sarker A.B. and Holmes W. (1974) The influence of supplementary feeding on the herbage intake and grazing behaviour of dry cows. *Journal of the British Grassland Society*, **29**, 141-143.

Sayers H.J., Mayne C.S. and Bartram C.G. (2000) The effect of level and type of supplement and changes in the chemical composition of herbage as the season progresses on herbage intake and animal performance of high yielding dairy cows. In: Rook A.J. and Penning P.J. (eds) *Grazing Management.*

British Grassland Society Occasional Symposium No. 34, Harrogate. pp. 85-90.

Schwarz F.J., Haffner J. and Kirchgessner M. (1995) Supplementation of zero-grazed dairy cows with molassed sugar beet pulp, maize or a cereal-rich concentrate. *Animal Feed Science and Technology*, **54**, 237-248.

Schwinning S. and Parsons A.J. (1999) The stability of grazing systems revisited: spatial models and the role of heterogeneity. *Functional Ecology*, **13**, 737-747.

Sheldrick R.D. (2000) Sward estabilshment and renovation. In: Hopkins A. (ed) *Grass - Its Production and Utilization Blackwell Science Ltd., Oxford.* pp. 13-30.

Simon J.C. and Lemaire G. (1987) Tillering and leaf area index in grasses in the vegetative phase. *Grass and Forage Science*, **42**, 373-380.

Sorensen A., Alamer M. and Knight C.H. (1998) Physiological characteristics of high genetic merit and low genetic merit dairy cows: a comparison. In: *Proceedings of the British Society of Animal Science Winter Meeting, Scarborough, 1998.* pp. 4.

Spedding C.R.W., Large R.V. and Kydd D.D. (1966). The evaluation of herbage speciec by grazing animals. In: Hill A.G.G. (ed) *Procedings of the Xth International Grassland Congress, Helsinki, Finland.* pp. 479-483.

Stakelum G. (1986a) Herbage intake of grazing dairy-cows. 1. Effect of autumn supplementation with concentrates and herbage allowance on herbage intake. *Irish Journal of Agricultural Research*, **25**, 31-40.

Stakelum G. (1986b) Herbage intake of grazing dairy-cows. 2. Effect of herbage allowance, herbage mass and concentrate feeding on the intake of cows grazing primary spring grass. *Irish Journal of Agricultural Research*, **25**, 41-51.

Stakelum G. (1986c) Herbage intake of grazing dairy-cows. 3. Effects of herbage mass, herbage allowance and concentrate feeding on the herbage intake of dairy-cows grazing on midsummer pasture. *Irish Journal of Agricultural Research*, **25**, 179-189.

Stakelum G. (1996) Irish grassland and animal production association journal, **30**, 33-45.

Stakelum G. and Dillon P. (1991) Influence of sward structure and digestibility on the intake and performance of lactating and growing cattle. In: Mayne C.S. (ed) *Management Issues for the Grassland Farmer in the 1990's. British Grassland Society Occasional Symposium No. 25.* pp. 30-42.

Steg A., van Straalen W.M., Hindle V.A., Wensink W.A., Dooper F.M.H. and Schils R.L.M. (1994) Rumen degradation and intestinal digestion of grass and clover at two maturity levels during the season in dairy cows. *Grass and Forage Science,* **49**, 378-390.

Sutton J.D., Bines J.A., Morant S.V., Napper D.J. and Givens D.I. (1987) A comparison of starchy and fibrous concentrates for milk production, energy utilisation and hay intake by Friesian cows. *Journal of Agricultural Science,* **109**, 375-386.

Swain D.L. (2000) Sward structural variations and the implications in relation to optimising grazing intake. In: Soegaard K., Ohlsson C., Sehested J., Hutchings N.J., and Kristensen T. (eds) *Grassland Farming – Balancing environmental and economic demands. Proceedings of the 18th General Meeting of the European Grassland Federation, Aalborg, Denmark.* pp. 283-285.

Swain D.L., Wilson L.A. and Dickinson J. (2003) Evaluation of an active transponder system to monitor spatial and temporal location of cattle within patches of a grazed sward. *Submitted Applied Animal Behaviour Science.*

Tamminga S. and Sudekum K.H. (2000) *Optimize feeding value of forage protein.* In: Soegaard K., Ohlsson C., Sehested J., Hutchings N.J., and Kristensen T. (eds) *Grassland Farming – Balancing environmental and economic demands. Proceedings of the 18th General Meeting of the European Grassland Federation, Aalborg, Denmark.* pp. 143-156.

Tesfa A.T., Virkajarvi P., Tuori M. and Syrjalaqvist L. (1995) Effects of supplementary concentrate composition on milk-yield, milk-composition and pasture utilization of rotationally grazed dairy-cows. *Animal Feed Science and Technology,* **56**, 143-154.

Ungar E.D. (1996) Ingestive behaviour. In: Hodgson J. and Illius A.W. (eds) *The Ecology and Management of Grazing Systems, CAB International, Oxon.* pp. 185-218.

Ungar E.D. and Noy-Meir I. (1988) Herbage intake in relation to availability and sward structure: grazing processes and optimal foraging. *Journal of Applied Ecology*, **35**, 1045-1062.

Ungar E.D. and Ravid N. (1999) Bite horizons and dimensions for cattle grazing herbage to high levels of depletion. *Grass and Forage Science*, **54**, 357-364.

Ungar E.D., Ravid N. and Bruckental I. (2001) Bite dimensions for cattle grazing herbage at low levels of depletion. *Grass and Forage Science*, **56**, 35-45.

Valk H., Kappers I.E. and Tamminga S. (1996) *In sacco* degradation characteristics of organic matter, neutral detergent fibre and crude protein of fresh grass fertilized with different amounts of nitrogen. *Animal Feed Science and Technology*, **63**, 63-87.

Valk H., Leusink-Kappers I.E. and van Vuuren A.M. (2000) Effect of reducing nitrogen fertilizer on grassland on grass intake, digestibility and milk production of dairy cows. *Livestock Production Science*, **63**, 27-38.

Valk H., Poelhuis H.W.K. and Wentink H.J. (1990) Effect of fibrous and starchy carbohydrates in concentrates as supplements in a herbage-based diet for high-yielding dairy-cows. *Netherlands Journal of Agricultural Science*, **38**, 475-486.

van Vuuren A.M., van der Koelen C.J. and vroons de Bruin J. (1986) Influence of level and composition of concentrate supplements on rumen fermentation patterns of grazing dairy-cows. *Netherlands Journal of Agricultural Science*, **34**, 457-467.

van Vuuren A.M., van der Koelen C.J. and vroons de Bruin J. (1993a) Ryegrass versus corn starch or beet pulp fiber diet effects on digestion and intestinal amino acids in dairy cows. *Journal of Dairy Science*, **76**, 2692-2700.

van Vuuren A.M., van Der Koelen C.J. and Vroons-de Bruin J. (1993b) Ryegrass versus corn starch or beet pulp fiber diet effects on digestion and intestinal amino acids in dairy cows. *Journal of Dairy Science*, **76**, 2692-2700.

Veerkamp R.F., Simm G. and Oldham J.D. (1994) Effects of interaction between genotype and feeding system on milk-production, feed-intake, efficiency and body tissue mobilization in dairy-cows. *Livestock Production Science*, **39**, 229-241.

Virkajarvi P., Sairanen A., Nousiainen J.I. and Khalili H. (2002) Effect of herbage allowance on pasture utilization, regrowth and milk yield of dairy cows in early, mid and late season. *Animal Feed Science and Technology*, **97**, 23-40.

Vulich S.A., Hanrahan J.P. and O'Riordan E.G. (1993) Pasture sampling for the estimation of herbage intake using n-alkanes: evaluation of alternative sampling procedures. *Irish Journal of Agricultural Research*, **32**, 1-11.

Wade M.H., Peyraud J.L., Lemaire G. and Comeron E.A. (1989) *The dynamics of daily area and depth of grazing and herbage intake of cows in a five day paddock system*. In: *Proceedings of the 16th International Grassland Congress, Nice*. pp. 1111-1112.

Waldo D.R. (1986) Effect of forage quality on intake and forage-concentrate interactions. *Journal of Dairy Science*, **69**, 617-631.

Wales W.J., Doyle P.T., Stockdale C.R. and Dellow D. (1999) Effects of variations in herbage mass, allowance, and level of supplement on nutrient intake and milk production of dairy cows in spring and summer. *Australian Journal of Experimental Agriculture*, **39**, 119-130.

Weisbjerg M.R. and Soegaard K. (2000) *Protein degradability of grass and grass/clover during the grazing season*. In: Soegaard K., Ohlsson C., Sehested J., Hutchings N.J., and Kristensen T. (eds) *Grassland Farming – Balancing environmental and economic demands. Proceedings of the 18th General Meeting of the European Grassland Federation, Aalborg, Denmark*. pp. 216-218.

Wilkins R.J., Gibb M.J. and Huckle C.A. (1995) Lactation performance of spring-calving dairy cows grazing mixed perennial ryegrass white clover swards of differing composition and height. *Grass and Forage Science*, **50**, 199-208.

Wilkins R.J., Gibb M.J., Huckle C.A. and Clements A.J. (1994) Effect of supplementation on production by spring-calving dairy-cows grazing swards of differing clover content. *Grass and Forage Science*, **49**, 465-475.

Wilkinson J.M., Price W.R., Russell S.R. and Jones P. (1994) Diurnal variation in dry matter and sugar content of ryegrass. In: *Proceedings of the 4th British Grassland Society Research Conference, Reading*. pp. 61-62.

Williams T.E. (1980) Herbage production: grasses and leguminous forage crops. In: Hopkins A. (ed) *Grass - Its Production and Utilization Blackwell Science Ltd., Oxford*. pp. 6-69.

Woledge J. (1971) The effect of light intensity during growth on the subsequent rate of photosynthesis in leaves of tall fescue (*Festuca arundinacea* Schreb.). *Annals of Botany*, **35**, 311-322.

Woodward S.J.R. (1998) Bite mechanics of cattle and sheep grazing grass-dominant swards. *Applied Animal Behaviour Science*, **56**, 203-222.

Yearsley J., Tolkamp B.J. and Illius A.W. (2001) Theoretical developments in the study and prediction of food intake. In: *Proceedings of the Nutrition Society*, **60**, pp. 145-156.

Appendix 1 Distribution of sward surface height measurements cm^{-1}, Experiment 1 weeks 5 and 8

Height (cm)	% total measurements	
	Week 5	Week 8
1	0	0.0
2	0	0.0
3	1	0.3
4	4	1.4
5	4	1.4
6	12	4.1
7	18	6.2
8	18	6.2
9	27	9.2
10	20	6.8
11	29	9.9
12	31	10.6
13	21	7.2
14	26	8.9
15	13	4.5
16	15	5.1
17	9	3.1
18	11	3.8
19	15	5.1
20	7	2.4
21	4	1.4
22	3	1.0
23	2	0.7
24	1	0.3
25	0	0.0
26	0	0.0
27	1	0.3
28	0	0.0
Mean	9.5	13.1
s.d.	2.76	4.35
n	388	292
c.v. (%)	29.1	33.1

Appendix 2 Distribution of sward surface height measurements cm^{-1}, Experiment 2, weeks 4, 8, and 12

Height (cm)	% total measurements			
	22, 25 May	19, 22 June	17, 20 Jul	14, 17 August
1	0.0	0.0	0.0	0.2
2	0.0	0.0	0.0	0.0
3	0.3	0.0	0.4	1.0
4	1.6	0.4	2.1	4.1
5	2.9	2.0	4.4	6.0
6	8.7	2.2	5.9	11.8
7	10.0	6.2	7.5	13.2
8	11.3	10.7	11.9	16.1
9	12.0	11.1	14.0	9.9
10	14.9	15.3	10.3	5.8
11	9.4	11.9	9.2	7.0
12	6.1	9.3	7.1	6.3
13	10.7	5.8	6.7	4.8
14	5.8	7.8	2.7	2.9
15	2.6	3.6	4.0	4.3
16	1.6	3.6	3.6	1.7
17	1.0	2.4	1.9	1.2
18	0.0	1.2	1.7	0.7
19	0.3	1.2	1.9	1.0
20	0.0	0.6	1.3	0.7
21	0.6	0.8	0.4	0.5
22	0.0	0.6	1.5	0.2
23	0.0	0.6	0.2	0.2
24	0.0	0.6	0.4	0.0
25	0.0	0.4	0.4	0.5
26	0.0	0.6	0.0	0.0
27	0.0	0.2	0.2	0.0
28	0.0	0.2	0.2	0.0
29	0.0	0.6	0.0	0.0
30	0.0	0.0	0.2	0.0
31	0.0	0.0	0.0	0.0
Mean	10.7	12.3	11.5	10.1
s.d.	3.12	4.19	4.37	3.84
n	309	497	478	416
c.v. %	29.2	34.0	37.9	38.1

Appendix 3 Experiment 3, mean sward surface height treatment^{-1} week^{-1} (cm) (Barthram, 1986)

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Week 1	10.6	13.4	13.0	13.1	16.4	20.5	18.3	20.8
Week 2	10.6	13.7	22.1	21.6	17.9	23.3	28.2	30.2
Week 3	9.2	11.9	12.5	29.8	15.3	21.1	20.9	41.7
Week 4	9.7	13.0	22.7	12.9	15.7	21.0	34.2	17.4
Week 5	8.3	9.9	10.7	16.8	13.5	16.0	15.8	24.2
Week 6	7.4	10.3	15.7	23.7	13.5	16.2	21.0	29.9
Week 7	7.5	10.2	11.8	11.9	14.1	17.9	17.8	18.1
Week 8	9.7	11.4	18.7	18.1	15.5	21.0	25.9	25.5
Week 9	8.2	12.2	13.9	28.7	14.3	21.8	23.2	33.9

Appendix 4 Experiment 3, mean of maximum herbage height recorded from gripper samples treatment^{-1} week^{-1} (cm)

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Week 1	9.3	11.3	11.3	13.3	17.3	16.0	20.0	20.0
Week 2	10.0	14.7	24.0	25.3	18.7	24.0	25.3	33.3
Week 3	8.7	13.3	11.3	36.4	16.0	24.0	22.7	46.0
Week 4	9.3	13.3	22.7	13.3	16.0	24.0	34.7	22.7
Week 5	10.0	11.3	10.7	25.3	16.0	20.0	17.3	28.0
Week 6	10.0	12.0	18.7	25.3	16.0	20.0	24.0	33.3
Week 7	10.7	13.3	16.0	16.0	16.0	21.3	24.0	24.0
Week 8	11.3	14.7	25.3	21.3	16.0	24.0	29.3	29.3
Week 9	10.7	18.7	18.0	34.7	16.0	25.3	26.7	46.7

Appendix 5 Experiment 3, mean herbage mass to ground level calculated from sward gripper samples, treatment^{-1} week^{-1} (kg DM ha^{-1})

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Week 1	3543	4444	4086	4222	5679	7284	6173	6222
Week 2	3753	4556	5284	6296	7136	7901	6741	7309
Week 3	4000	4716	4864	8037	6370	6790	7457	10370
Week 4	4074	4506	5802	4167	7481	8642	8457	6765
Week 5	4809	4951	5265	4580	7407	8049	7358	8173
Week 6	4519	4926	4883	6383	9086	7457	8630	8383
Week 7	6519	5457	4309	4148	8790	7617	7222	7173
Week 8	4728	4321	5963	4815	8494	8012	7830	6568
Week 9	4531	5802	5444	7013	7728	8259	7049	9358

Appendix 6 Experiment 3, mean herbage mass above 4 cm calculated from description of vertical distribution of mass, treatment^{-1} week^{-1} (kg DM ha^{-1})

Residual height	6 cm				12 cm			
Cutting frequency	Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
Week 1	778	1284	1247	1383	2765	4025	3704	3778
Week 2	914	1617	3062	3407	3951	4938	4617	4889
Week 3	617	1432	1111	5272	3235	4123	4247	7605
Week 4	864	1074	2593	932	3728	4765	5741	3531
Week 5	685	1123	1438	1691	3630	4395	3235	4123
Week 6	667	1000	1401	3099	4148	3630	4481	5370
Week 7	914	1383	1123	1062	4148	3864	3617	3914
Week 8	926	1160	2235	1901	4741	4531	4447	3605
Week 9	901	1728	1407	4099	3556	4481	3593	6025

Appendix 7 Experiment 3, herbage mass per horizon; weeks 1, 2, 3 (g DM 135 cm^{-2})

Residual height		6 cm				12 cm			
Cutting frequency		Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
	Sward height (cm)								
Week 1	0-2	2.77	3.13	2.77	2.70	2.63	2.93	2.23	2.20
	2-4	0.97	1.13	1.07	1.13	1.30	1.47	1.10	1.10
	4-6	0.63	0.83	0.70	0.77	1.17	1.53	1.20	1.00
	6-8	0.33	0.53	0.43	0.47	1.03	1.23	1.10	1.03
	8-10	0.08	0.27	0.27	0.33	0.73	1.00	0.80	0.83
	10-12		0.10	0.20	0.20	0.40	0.73	0.60	0.70
	12-16			0.08	0.10	0.37	0.67	0.80	0.93
	16-20					0.03	0.27	0.50	0.60
	20-24								
Week 2	0-2	2.77	2.73	1.93	2.60	2.57	2.37	1.70	2.27
	2-4	1.07	1.23	1.07	1.30	1.73	1.63	1.17	1.00
	4-6	0.67	0.93	0.93	1.20	1.87	1.73	1.37	1.07
	6-8	0.43	0.53	0.63	0.77	1.27	1.27	0.83	0.97
	8-10	0.13	0.37	0.53	0.63	0.90	1.03	0.87	0.80
	10-12		0.27	0.53	0.57	0.63	0.80	0.67	0.57
	12-16		0.08	0.63	0.77	0.50	0.87	0.87	0.97
	16-20			0.37	0.43	0.13	0.63	0.87	0.87
	20-24			0.20	0.20	0.03	0.33	0.60	0.73
	24-28			0.13	0.03			0.13	0.33
	28-32			0.10				0.03	0.23
	32-36			0.07					0.07
	36+								
Week 3	0-2	3.33	2.83	3.60	2.57	2.67	2.27	2.87	2.53
	2-4	1.23	1.60	1.47	1.17	1.57	1.33	1.47	1.20
	4-6	0.60	1.13	0.90	1.20	1.77	1.57	1.77	1.30
	6-8	0.20	0.40	0.30	0.73	1.17	1.13	1.17	0.90
	8-10	0.03	0.27	0.23	0.67	0.83	0.90	1.03	0.80
	10-12		0.10	0.07	0.73	0.40	0.63	0.67	0.73
	12-16		0.03		1.03	0.17	0.73	0.67	1.30
	16-20				0.93	0.03	0.40	0.33	1.20
	20-24				0.87		0.20	0.10	1.23
	24-28				0.57				1.00
	28-32				0.27				0.77
	32-36				0.08				0.60
	36+				0.03				0.43

Appendix 8 Experiment 3, herbage mass per horizon; weeks 4, 5, 6 (g DM 135 cm^{-2})

Residual height		6 cm				12 cm			
Cutting frequency		Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
	Sward height (cm)								
Week 4	0-2	3.00	3.17	2.90	3.07	3.23	3.30	2.27	2.67
	2-4	1.33	1.47	1.43	1.30	1.83	1.93	1.40	1.70
	4-6	0.73	0.80	1.13	0.83	2.03	2.10	1.63	1.73
	6-8	0.27	0.30	0.63	0.17	1.27	1.30	0.97	1.10
	8-10	0.17	0.20	0.43	0.12	0.93	1.00	0.87	0.80
	10-12		0.10	0.40	0.08	0.57	0.77	0.73	0.47
	12-16		0.05	0.50	0.06	0.20	0.67	0.90	0.40
	16-20			0.27		0.03	0.47	0.93	0.20
	20-24			0.13			0.13	0.90	0.07
	24-28							0.50	
	28-32							0.23	
	32-36							0.07	
	36+							0.02	
Week 5	0-2	3.87	3.37	3.53	2.63	2.90	2.97	3.57	3.90
	2-4	1.70	1.80	1.63	1.27	2.20	1.97	2.00	1.57
	4-6	0.73	1.10	1.70	1.03	2.33	2.47	2.03	1.77
	6-8	0.15	0.23	0.13	0.30	1.23	1.40	1.07	1.03
	8-10	0.04	0.13	0.08	0.27	0.83	1.07	0.77	0.90
	10-12		0.05	0.03	0.23	0.33	0.53	0.33	0.53
	12-16				0.27	0.17	0.33	0.13	0.57
	16-20				0.12		0.13	0.03	0.43
	20-24				0.07				0.27
	24-28								0.07
	28-32								
Week 6	0-2	3.70	3.67	3.17	2.90	3.93	3.10	3.53	2.53
	2-4	1.50	1.63	1.53	1.53	2.73	2.07	2.07	1.53
	4-6	0.67	0.77	0.90	1.07	2.53	1.93	2.27	1.60
	6-8	0.17	0.30	0.30	0.60	1.40	1.17	1.33	1.00
	8-10	0.07	0.17	0.27	0.57	1.00	0.93	1.00	0.90
	10-12		0.08	0.17	0.47	0.47	0.47	0.50	0.70
	12-16		0.03	0.17	0.77	0.20	0.27	0.50	0.87
	16-20			0.08	0.47		0.10	0.30	0.80
	20-24			0.01	0.22		0.03	0.15	0.73
	24-28				0.03				0.37
	28-32								0.15
	32-36								0.07
	36+								0.07

Appendix 9 Experiment 3, herbage mass per horizon; weeks 7, 8, 9 (g DM 135 cm^{-2})

Residual height		6 cm				12 cm			
Cutting frequency		Twice	7 d	14 d	21 d	Twice	7 d	14 d	21 d
	Sward height (cm)								
Week 7	0-2	5.83	3.77	2.90	2.80	3.93	3.27	2.90	2.50
	2-4	1.73	1.73	1.40	1.37	2.33	1.80	1.97	1.90
	4-6	0.90	1.00	0.70	0.60	2.37	1.87	1.87	1.77
	6-8	0.20	0.40	0.43	0.33	1.57	1.23	1.10	1.13
	8-10	0.10	0.27	0.13	0.23	0.93	0.93	0.87	0.87
	10-12	0.03	0.13	0.17	0.17	0.50	0.53	0.40	0.63
	12-16		0.07	0.08	0.10	0.23	0.40	0.33	0.43
	16-20						0.23	0.20	0.27
	20-24						0.02	0.12	0.18
	24-28								
Week 8	0-2	3.70	2.77	3.60	2.60	2.90	2.80	2.77	2.43
	2-4	1.43	1.50	1.43	1.33	2.17	1.90	1.80	1.57
	4-6	0.80	0.77	1.00	0.83	2.33	2.00	1.87	1.63
	6-8	0.23	0.30	0.43	0.40	1.73	1.57	1.27	1.07
	8-10	0.13	0.23	0.40	0.40	1.80	1.47	0.73	0.57
	10-12	0.08	0.12	0.33	0.30	0.37	0.30	0.40	0.40
	12-16		0.15	0.40	0.50	0.17	0.37	0.53	0.47
	16-20			0.27	0.10		0.27	0.50	0.37
	20-24			0.15	0.03		0.15	0.40	0.23
	24-28			0.02				0.23	0.12
	28-32			0.02				0.07	0.02
	32-36								
Week 9	0-2	3.40	3.83	3.90	2.70	3.63	3.30	3.10	3.03
	2-4	1.50	1.67	1.55	1.23	2.00	1.80	1.57	1.47
	4-6	0.87	1.03	0.90	0.87	2.17	1.97	1.70	1.47
	6-8	0.23	0.43	0.30	0.63	1.20	1.33	1.03	1.03
	8-10	0.08	0.37	0.30	0.63	0.93	0.90	0.73	0.93
	10-12	0.03	0.23	0.15	0.57	0.30	0.50	0.37	0.63
	12-16		0.20	0.15	0.90	0.20	0.53	0.47	0.90
	16-20		0.07	0.08	0.77		0.33	0.33	0.77
	20-24			0.03	0.60		0.40	0.17	0.73
	24-28				0.30		0.08	0.05	0.57
	28-32				0.13				0.37
	32-36				0.13				0.37
	36+								0.37

Appendix 10 Experiment 3, relationship between cumulative herbage mass and sward height per treatment per week. y, cumulative herbage mass from ground level (g DM); x, sward surface height (cm)

	Week 1	r^2	Week 4	r^2	Week 7	r^2
T1	y = 4.78e-0.4569x	0.964	y = 5.5e-0.425x	0.995	y = 8.8e-0.5407x	0.996
T2	y = 6e-0.3785x	0.947	y = 6.08e-0.3863x	0.993	y = 7.37e-0.3692x	0.992
T3	y = 5.52e-0.3218x	0.980	y = 7.83e-0.1938x	0.993	y = 5.82e-0.3372x	0.993
T4	y = 5.7e-0.311x	0.979	y = 5.63e-0.39x	0.995	y = 5.6e-0.3196x	0.992
T5	y = 7.67e-0.2746x	0.902	y = 10.1e-0.3051x	0.925	y = 11.87e-0.2811x	0.940
T6	y = 9.83e-0.2003x	0.961	y = 11.67e-0.1982x	0.971	y = 10.28e-0.2603x	0.919
T7	y = 8.33e-0.1606x	0.977	y = 11.42e-0.1393x	0.893	y = 9.75e-0.2173x	0.995
T8	y = 8.4e-0.1482x	0.970	y = 9.13e-0.2137x	0.987	y = 9.68e-0.1922x	0.993

	Week 2		Week 5		Week 8	
T1	y=5.07e^-0.4124x	0.968	y = 6.49e-0.5927x	0.979	y = 6.38e-0.43x	0.999
T2	y = 6.15e-0.3087x	0.952	y = 6.68e-0.4622x	0.984	y = 5.83e-0.3101x	0.998
T3	y=7.13e^-0.1365x	0.994	y = 7.11e-0.5311x	0.960	y = 8.05e-0.2097x	0.978
T4	y=8.5e^-0.1877x	0.927	y = 6.18e-0.2255x	0.994	y = 6.5e-0.2356x	0.962
T5	y=9.63e^-0.2463x	0.947	y = 10e-0.2937x	0.934	y = 11.47e-0.2839x	0.863
T6	y=10.67e^-0.1553x	0.975	y = 10.87e-0.2504x	0.961	y = 10.82e-0.2083x	0.983
T7	y=9.1e^-0.1547x	0.883	y = 9.93e-0.3216x	0.957	y = 10.57e-0.1567x	0.965
T8	y=9.87e^-0.1239x	0.923	y = 11.03e-0.1876x	0.972	y = 8.87e-0.1855x	0.947

	Week 3		Week 6		Week 9	
T1	y = 5.4e-0.5746x	0.965	y = 6.1e-0.5436x	0.991	y = 6.12e-0.4957x	0.987
T2	y = 6.37e-0.4042x	0.959	y = 6.65e-0.4171x	0.993	y = 7.7082e-0.2871x	0.996
T3	y = 6.57e-0.4425x	0.932	y = 6.59e-0.2979x	0.971	y = 7.35e-0.2841x	0.991
T4	y = 10.85e-0.1273x	0.908	y = 8.62e-0.1877x	0.924	y = 9.47e-0.1203x	0.973
T5	y = 8.6e-0.3059x	0.935	y = 12.27e-0.2932x	0.937	y = 10.43e-0.291x	0.947
T6	y = 9.17e-0.1743x	0.977	y = 10.07e-0.266x	0.978	y = 11.15e-0.1791x	0.968
T7	y = 10.07e-0.204x	0.964	y = 11.65e-0.2084x	0.994	y = 9.52e-0.1977x	0.982
T8	y = 14e-0.0789x	0.941	y = 11.32e-0.1293x	0.972	y = 12.63e-0.0908x	0.987

Appendix 11 Distribution of sward surface height measurements cm^{-1}, Experiment 4

Height (cm)	% total measurements	
	Pre-grazing	Post grazing
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0.9
5	0	1.9
6	0	3.4
7	0	5.3
8	0	11.9
9	0	11.9
10	0	14.4
11	1.3	18.1
12	1.3	12.2
13	2.2	7.8
14	2.2	4.4
15	3.4	5.0
16	6.9	1.6
17	6.9	0.3
18	7.8	0.9
19	10.6	0
20	11.6	0
21	9.4	0
22	11.6	0
23	10.0	0
24	5.0	0
25	5.3	0
26	1.9	0
27	1.6	0
28	0.9	0
29	0.0	0
30	0.3	0
31	0	0
Mean	20.8	11.2
s.d.	3.54	2.61
N	320	320
cv %	17.1	23.3

Appendix 12 Experiment 4, grazing behaviour results cow^{-1} d^{-1}

	Paddock 1				Paddock 2
	Cow 1	Cow 2	Cow 3	Cow 4	Cow 1
Grazing time (min d^{-1})	12:26:08	5:57:45	9:08:09	8:20:31	11:02:21
Bites	38282	16641	30645	30451	33912
Chews	10224	6146	3582	1881	9116
Total GJM*	48506	22787	34227	32332	43028
Proportion GJM bites	0.79	0.73	0.90	0.94	0.79
Ruminating time (min d^{-1})	0:22:07	3:29:21	3:34:30	6:00:31	1:39:53
Mastications	1598	14238	15108	22796	6891
Boli	35	191	270	422	101
Idling (min d^{-1})	8:28:55	6:19:30	7:17:01	7:08:04	8:25:44
Mastications	1093	815	1082	1191	983
Other (min d^{-1})	1:37:20	2:05:36	2:44:08	1:02:27	1:50:02
Mastications	6736	8374	11435	3775	9828
Total eating time (min d^{-1})	11:28:04	5:45:55	8:22:16	7:44:18	10:12:36
Bites	37745	16553	30237	30014	33474
Chews	10386	6147	3641	1925	9257
Total GJM	48131	22700	33878	31939	42731
Proportion GJM bites	0.78	0.73	0.89	0.94	0.78

	Paddock 3				Paddock 4			
	Cow 1	Cow 2	Cow 3	Cow 4	Cow 1	Cow 2	Cow 3	Cow 4
Grazing time (min d^{-1})	11:07:22	8:26:07	8:19:04	8:26:48	10:55:27	9:00:50	8:46:26	10:31:41
Bites	34855	22979	29897	29231	32999	24781	31244	36929
Chews	9501	9511	2886	1162	10111	10544	2841	1636
Total GJM†	44356	32490	32783	30393	43110	35325	34085	38565
Proportion GJM bites	0.79	0.71	0.91	0.96	0.77	0.70	0.92	0.96
Ruminating time (min d^{-1})	1:01:05	4:09:02	3:42:34	4:20:57	1:43:36	5:17:05	5:39:23	3:32
Mastications	4120	16666	15872	16597	7060	21009	23885	1778
Boli	68	269	311	301	102	313	463	36200
Idling (min d^{-1})	9:05:09	9:05:09	7:16:45	8:59:51	8:54:31	8:11:13	8:37:09	7:56:57
Mastications	1589	1589	883	1417	1462	1105	1287	1235
Other (min d^{-1})	1:18:24	0:51:42	3:13:37	0:44:24	2:04:26	1:08:52	0:35:02	1:37:06
Mastications	6300	9734	14790	3711	12368	8360	6459	9809
Total eating time (min d^{-1})	10:41:14	8:03:31	7:52:06	7:28:51	10:19:54	8:44:29	8:20:50	9:23:16
Bites	34523	22751	29566	28544	32592	24651	30870	36200
Chews	9669	9528	2949	1345	10231	10560	2920	1778
Total GJM	44192	32279	32515	29889	42823	35211	33790	37978
Proportion GJM bites	0.78	0.70	0.91	0.96	0.76	0.70	0.91	0.95

Appendix 13 Experiment 4, data for calculation of bite mass and estimated number bites in aerials

	Cow	Total grazing time (s)	Total bites	Grazing time in aerials (s)	Estimated bites in aerials
Paddock 1	1	44768	38282	2480	2121
	2[†]	31409	23897	4412	3356
	3	32889	30877	4962	4658
	4	30031	30519	8813	8956
Paddock 3	1	40042	34972	6976	6093
	2	30367	23013	5063	3837
	3	29944	29963	5462	5465
	4	30408	25768	5869	4973
Paddock 4	1	39327	33021	4089	3433
	2	32450	24781	3760	2871
	3	31586	31273	4816	4768
	4	37901	36983	7673	7487

[†]Mean of days 3 and 4

Appendix 14 Experiment 4, estimated bites in aerials per period

	Bites per paddock per period		Grazing time per paddock per period		Grazing time in aerials per period	
	Total	s.d. cows	Total	s.d. cows	Total	s.d. aerials
Paddock 1						
15:00-19:00	24104	1105.0	463	10.6	81	2.8
19:00-08:00	61319	3300.8	1143	58.0	193	10.8
08:00-11:00	15238	2131.6	303	38.8	92	13.1
11:00-14:00	22732	993.5	406	23.0	50	3.1
Total	123393		2315		416	
Paddock 3						
15:00-19:00	23508	1307.2	446	20.9	65	2.7
19:00-08:00	56985	3642.4	1072	58.1	166	6.3
08:00-11:00	9281	486.0	192	15.1	42	6.8
11:00-14:00	23942	1380.3	443	33.1	116	17.6
Total	113716		2153		389.5	
Paddock 4						
15:00-19:00	29312	1407.2	542	18.1	81	3.8
19:00-08:00	61882	3232.8	1171	60.9	175	7.5
08:00-11:00	12014	611.6	228	3.8	31	2.0
11:00-14:00	22850	1214.1	430	15.7	51	5.9
Total	126058		2371		338	

Appendix 15 Experiment 4, mean sward surface height per paddock per recording and variability between aerials and individual height recordings

Paddock	Time (h)	Sward surface height (cm)	Variation between aerials			Variation between individual sward height recordings		
			s.d.	s.e.m.	c.v.	s.d.	s.e.m.	c.v.
1	15:00	20.1	1.18	0.42	5.85	3.63	1.28	18.04
	20:00	13.8	1.00	0.35	7.22	3.09	1.09	22.38
	08:00	12.5	0.63	0.22	5.08	2.99	1.06	24.00
	11:00	11.5	0.81	0.29	7.04	3.43	1.21	29.89
	14:00	10.1	0.97	0.34	9.59	2.52	0.89	25.00
2	15:00	19.7	0.94	0.33	4.80	3.27	1.16	16.66
	20:00	13.4	0.48	0.17	3.59	2.73	0.96	20.29
	08:00	12.1	0.42	0.15	3.44	2.53	0.89	20.94
	11:00	11.2	0.61	0.22	5.45	2.38	0.84	21.29
	14:00	9.6	0.50	0.18	5.25	2.66	0.94	27.64
3	15:00	19.4	0.84	0.30	4.34	3.85	1.36	19.81
	20:00	15.1	0.85	0.30	5.67	3.28	1.16	21.78
	08:00	12.6	0.78	0.27	6.14	3.19	1.13	25.24
	11:00	11.5	0.59	0.21	5.13	2.70	0.96	23.50
	14:00	10.8	0.64	0.23	5.94	2.58	0.91	23.90
4	15:00	20.8	0.59	0.21	2.85	3.25	1.15	15.60
	20:00	14.6	0.89	0.31	6.11	3.10	1.10	21.29
	08:00	11.7	0.45	0.16	3.84	2.88	1.02	24.72
	11:00	11.2	0.36	0.13	3.24	2.03	0.72	18.16
	14:00	10.5	0.63	0.22	6.05	2.54	0.90	24.27

Appendix 16 Experiment 4, estimated herbage mass removed per period per paddock from relationship between sward height measurements and vertical distribution of mass, and proportion herbage removed calculated from cut strips, per period

	Vertical distribution of mass ($g\ DM\ m^{-2}$)	% total herbage mass removed	Proportion herbage mass calculated from cut strips ($g\ DM\ m^{-2}$)
Paddock 1			
15:00-19:00	58.4	51.5	69.5
19:00-08:00	15.1	13.3	17.9
08:00-11:00	15.1	13.3	17.9
11:00-14:00	25.0	22.0	29.7
Total	113.6		135.0
Paddock 2			
15:00-19:00	59.8	50.9	50.9
19:00-08:00	16.2	13.8	13.8
08:00-11:00	13.3	11.3	11.3
11:00-14:00	28.1	23.9	23.9
Total	117.4		100.0
Paddock 3			
15:00-19:00	41.4	46.1	37.3
19:00-08:00	22.9	25.5	20.6
08:00-11:00	14.6	16.2	13.2
11:00-14:00	11.0	12.2	9.9
Total	89.8		81.0
Paddock 4			
15:00-19:00	47.4	48.1	37.0
19:00-08:00	32.0	32.5	25.0
08:00-11:00	7.0	7.1	5.5
11:00-14:00	12.2	12.3	9.5
Total	98.6		77.0