Investigations into soil nutrient and change in soil physical characteristics under complementary forage rotation in comparison to pasture systems for dairy cows

Bertin Kaboré

A thesis submitted in fulfilment of the requirements
for the degree of

Master of Science in Veterinary Science

Faculty of Veterinary Science
University of Sydney
July 2008

“To my Family”

Preface

I declare that I carried out the experimental work described in this thesis, with the assistance of the persons mentioned in the acknowledgements. This thesis has not been submitted previously, nor is it being submitted to any other institution for a higher degree.

Bertin Kaboré **Date**

Acknowledgements

I address my sincere thanks to my supervisor Professor Bill Fulkerson and my co-supervisors Dr Sergio Garcia and Mr Paul Milham for their generous guidance, advice and sense of orientation that facilitated my work.

I appreciate the financial support received from Dairy Australia for my study.

I also owe Professor Peter Martin, Dr Budiman Minasry, Dr Damien Field, Dr Vervoort R. Williem, and their colleagues from University of Sydney, a debt of gratitude for their technical support in their respective fields of expertise.

In the Mc Franklin Lab., (University of Sydney, Camden Campus), I would like to thank Ajantha Horadagoda and Sergio Suarez for providing great technical and laboratory facilities and support. I also extend thanks to my fellow students; Pancha Shrestha, Mariana Pedernera, and Ravneet Jhajj for their continual support and companionship. For other fellow students of MC Franklin Lab. and Camden Veterinary Science Library, I appreciate the help and dedication to help me in my work.

Valuable advice was provided by Roy Lawrie, Mark Conyers and Helena Warren (DPI NSW) and I especially thank Nawash Haddad for his great and continual help with the field work during these two years.

To Professor Peter Thomson, Dr Navneet Dhand (University of Sydney) and Dr Idris Barchia (DPI NSW), I acknowledge their advice and technical support in the treatment of my data.

My thanks especially go to the staff of FutureDairy, No 9 Dairy, Automatic Milking System (AMS) EMAI (DPI, NSW) for providing the facilities to run my field experiments, and the farm staff, for their help during my data collection in the field, especially Colin Spinks for his ingenuity in assisting with putting together my water runoff collection devices.

List of publications

Abstracts and Papers presented at conferences and symposia

B. Kaboré, W.J. Fulkerson, SC. Garcia, P. Milham and R.W. Vervoot (2006). Investigation into soil nutrient balance and change in soil physical characteristics under an intensive complementary cropping rotation. Dairy Research Foundation Symposium, (Camden, NSW) Volume 11, 139-141.

B. Kaboré, W.J. Fulkerson, S.C. Garcia, P. Milham and R.W. Vervoot (2006). Investigation into soil nutrient balance and change in soil physical characteristics under an intensive complementary cropping rotation in comparison to pasture. Postgraduate Conference 2006, University of Sydney, Faculty of Veterinary Science, (Camden, NSW) pp 33.

B. Kaboré, W.J. Fulkerson, S.C. Garcia and P. Milham (2007). Complementary Forage Rotation as the alternative pasture production for dairy cows. Dairy Research Foundation Symposium, (Camden, NSW) Volume 12, 52-55.

B. Kaboré, W.J. Fulkerson, S.C. Garcia and P. Milham (2007). Sustainability of a Complementary Forage Rotation and Pasture. Postgraduate Conference 2007, University of Sydney, Faculty of Veterinary Science, (Camden, NSW) pp 31.

B. Kaboré, W.J. Fulkerson, SC. Garcia, P. Milham and R.W. Vervoot (2007). Nutrient Balance for Complementary Forage Rotation and Pasture Systems. Australian Society of Animal Production Conference, University of Brisbane. (Proceedings in progess).

List of abbreviations

Al	Aluminium
ATP	Adenosine triphosphate
AW	Available water
BD	Bulk density
BEST	Beerkan estimation of soil transfer
C	Carbon
Ca	Calcium
$CaCO_3$:	Calcium carbonate
CaO	Calcium oxide
$Ca\ (OH)_2$:	Calcium hydroxide
$Ca,Mg(CO_3)_2$	Dolomite
CEC	Cation exchangeable capacity
CFR	Complementary forage rotation
Cl	Chlorine
cm	Centimetre
cm^3	Cubic centimetre
CO_2	Carbon dioxide
$C_6H_{12}O_6$	Sugar
CSIRO	Commonwealth Scientific and Industrial Research organization
CNREST	Centre National de la Recherche Scientific et Technique
C_3	Temperate plant species
C_4	Warm plant species
DAP	Di-ammonium phosphate
DPI	Department of Primary Industries
DD	Deep drainage
DM	Dry matter
ds/m	Deci-siemen/ metre
EC	Electrical conductivity
ECEC	Effective cation exchangeable capacity
EMAI	Elizabeth MacArthur Agricultural Institute
Etp	Evapo-transpiration
FAO	Food and Agriculture Organisation
FC	Field capacity
FDA	Fluoresein diacetate hydrolase
IBDU	Isobutylidine diureas
ICP	Inductively couple plasma
g	Gram
GDD	Growing degree day
K	Potassium
kg	Kilogram
Ksat	Hydraulic conductivity
K_2SO_4	Potassium sulphate
h	Hour
H_2O	Water
H^+	Ion hydrogen
OH^-	Hydroxide ion
ha	Hectare

HCl	Hydrogen chloride
L	Litre
lsd	Least significant difference
MAP	Mono-ammonium phosphate
meq	Milli-equivalent
Mg	Magnesium
mM	Millimole
mm	Millimeter
Mn	Manganese
Na	Sodium
NaCl	Sodium chloride
N	Nitrogen
NPK	Nitrogen- Phosphorus-Potassium
NSW	New South Wales
NUE	Nutrient Use efficiency
^{o}C	Degree Celsius
OC	Organic carbon
OGTR	Office of gene technology regulator
OM	Organic matter
ONCE	Urea nitrate, Ammonium nitrate fertilizer
P	Phosphorus
P	Probability
PE	Extensive pasture
PI	Intensive pasture
Pi	inorganic phosphorus
Po	Organic phosphorus
pH	Hydrogen ion activity
pHBC	pH buffer capacity
r	Correlation coefficient
PUE	Phosphorus used efficiency
PWP	Permanent wilting point
REML	Regression mixed model
SAR	Sodium absorption ratio
S	Sulfur
se	Standard error
sed	Standard error of difference
SB	Soil biota
SOM	Soil organic carbon
T	Treatment
TDS	Total disolved salt
T.P	Treatment.period
USAD	United State Department of Agriculture
yr	Year
wks	Weeks
WMP	Whole milk powder
WSC	Water soluble carbohydrate
WUE	Water use efficiency

Scientific names

Plants common names	**Scientific names**
Cocksfoot	*Dactilys glomerata*
Kikuyu	*Pennisetum clandestinum*
Lablab	*Lablab purpureus*
Lucerne (alfalfa)	*Medicago sativa*
Maize	*Zea mays*
Perennial ryegrass	*Lolium perenne*
Persian clover	*Trifolium resupinatum*
Phalaris	*Phalaris aquatica*
Paspalum	*Paspalum dilatatum*
Short rotation ryegrass	*Lolium multiflorum*
Subterranean clover	*Trifolium subterraneum*
Wheat	*Triticum aestivium*
White clover	*Trifolium repens*

Insects and diseases names	**Scientific names**
African black beetle	*Heteronychus arator*
Armyworm	*Persectaria ewingii*
Black leg	*Leptosphaeria maculans*
Sclerotinia	*Sclerotinia Clerotiorum*
Clover rot	*Sclerotinia trifoliorum*
Downy mildew	*Peronospora parasitica*
Endophyte	*Lolium endophyte*
Leaf spot	*Pyrenopeziza brassicae*
Leaf rust	*Uromyces trifolii-repentis*
Oomycete	*Verrucalvus flavofaciens*

Rhizobium	*Rhizobium trifolli*
Rust	*Puccinia spp.*
Sod web worm	*Crambus spp.*
Web worm	*Herpetogramma licarsisalis*

Summary

Facing rising resource costs and a relatively stable milk price, dairying in Australia may no longer be able to rely on a typical feed base of pasture supplemented with concentrate, unless the upper limit to pasture production of 20 t DM /ha/ yr can be increased in a sustainable way. The FutureDairy project has achieved over 42 t DM/ ha/ yr over the past 4 years using a Complementary Forage Rotation (CFR) comprising maize (*Zea maize*) as the bulk crop, forage rape (*Brassica napus*) as the break crop (biofumigation agent) and Persian clover (*Trifolium resupinatum*) to fix atmospheric nitrogen.

The CFR has very high fertilizer and water inputs and therefore there is a potentially high impact on the environment and this needs to be quantified; this was the overall goal of the present study.

Chapter 1 describes the importance of the dairy industry in the Australian economy.

Chapter 2 reviews the literature on sustainable cropping systems, nutrient and water flows within them and looks in more detail at the characteristics of the 3 crops used in CFR.

In Chapter 3, the objectives, hypothesis and general methods used are outlined. The broad approach has been to monitor key indicators of soil health status in the 3rd and 4th years of the FutrureDairy project, as well as the nutrient flows within the system to gauge the likely impact away from the CFR site, and to determine the nutrient and water use efficiency. Most sampling was in the topsoil (0-30 cm) but some samples were also taken to 100 cm to gauge deep drainage and nutrient movement into the subsoil.

The 2 years of study were climatically very different: a dry (drought) year followed by a normal year. Also, the 2 replicates (block) were carried out on different types of soil a comparison between years and blocks to be made.

The design was a split plot complete block randomized design with 3 treatments (CFR (3 crops), intensive pasture (PI) and extensive pasture (PE)) which repeated over 2 years (2006

and 2007) (dry and normal year). The treatment plots were paddock scale of 0.5 to 0.75 ha and were grazed by dairy cows (perennial pasture, clover and forage rape) or harvested for silage (maize). The fertilizer and water input to each treatment were 486, 190 and 433 kg /ha/ yr. N, P and K of fertilizer respectively, and 1334 mm /ha/yr of water for CFR plots; 494, 72 and 164 kg /ha/ yr respectively of N, P and K of fertilizer and 1319 mm /ha/yr of water for PI, and 1066 mm of water and no fertilizer for PE with the input into CFR and PI, being related to removal from the paddocks.

The results are outlined in Chapter 4. The physical characteristics of the soil (bulk density (BD), field capacity (FC), permanent wilting point (PWP), available water (AW) and hydraulic conductivity (Ksat) did not show any significant treatment effects. There were significant period effects due to the different levels of rainfall (rain representing 40% to total water input in year 1, against 77 % in year 2).

The change in rainfall pattern between the two years (464 mm in year 1 and 1030 mm in year 2) improved soil water storage (deep drainage) down the soil profile, with an increase from 89 mm in year 1 to 149 mm in year 2. The runoff water increased from 21 mm in year 1 to 156.6 mm in year 2 due to excess water received in year 2.

There were no significant changes in soil organic matter (OM) content between treatments, the variation being largely due to season and block (soil) effect, but all levels were of high OM content (4-7%). Soil OM content was greater for Replicate 2 (Black vertisol) (6.2 ± 0.4% of soil) than for Replicate 1 (Brown chromosol) (4.1 ± 0.3%).

Soil pH was significantly ($P = 0.04$) affected by treatment but only in the very topsoil (0-10 cm) and this probably related to the level of cropping activity and water input. Soil type had a significant effect on pH buffering capacity (Replicate 2 = 7.17 ± 0.65 Kmol H^+ /ha /pH; Replicate 1 = 5.89 ± 0.65 Kmol H^+ /ha /pH) with no effect of treatment.

The major change in “soil nutrients” (sodium (Na), magnesium (Mg), calcium (Ca) and chloride (Cl) and “nutrient loss” was due to the mineral content and the rate of application of irrigation water. The input of NaCl was markedly different between years (1578 kg NaCl in year 1 against 464 kg NaCl in year 2) due to less irrigation and lower mineral concentration in

year 2 due to high rainfall. This led to very different EC values of 0.16 ds/ m for year 1 against 0.12 ds /m in year 2 and ECEC values of 14 meq cation / 100 g soil in year 1 against 20 meq cation / 100 g soil in year 2.

The measurement of soluble P and K in the soil indicated that the input of P was adequate, but K input needs to be closely monitored in relation to soil capacity to supply K and fertilizer application as they were trending down. For both nutrients, the levels were lower than expected, and should be adjusted depending on crop need, soil type (clay nature and content), weather and availability of other nutrients (mainly N).

The loss of N, P and K from the treatment plots through surface runoff were similar between intensive systems (CFR and PI) with average of 20-4-26 kg of N-P-K/ ha/ yr, compared to the extensive pasture system (PE) with average of 1-0-4 kg of N-P-K /ha/ yr. The difference was probably due to the timing of fertilizer applications and of high water events (rainfall and irrigation).

A similar amount of both N and water were applied to the PI and CFR plots, and the CFR yield was twice that in PI (40.4 t DM/ ha against 20.2 t DM /ha). This resulted in increased N use efficiency for the CFR than for the PI treatments, respectively (51.5 kg DM/ kg of N fertilizer against 26 kg DM/ kg of N fertilizer) and water use efficiency (30.3 kg DM/ mm of water against 15.3 kg DM/ mm of water).

The results of this study show no adverse effects of high input systems (CFR and pasture) intensively managed after a 4 year period except for the slightly higher soil loss (representing less than 0.016% of the topsoil) for CFR, but even this would be reduced by direct drilling maize. The loss of soil nutrient through runoff was surprisingly low even in the relatively wet year compared to the average for pasture.

Overall, this study show that the increased intensification in home grown feed through CFR system can be achieved without adverse effects on soil physical and chemical properties, with greater yield (at similar input), compared to the typical intensive pasture production system.

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CHAPTER 1: INTRODUCTION

The dairy industry in Australia is the third largest rural industry in terms of value at the farm gate and employs more than 150,000 people directly and indirectly (farmers, farm hands and contractors). There are 8,840 dairy farms in Australia, mainly concentrated along the coast in South-Eastern Australia and the South-West of Western Australia, plus significant inland areas under irrigation (Goulburn and Murray valleys in Victoria, Riverina and the Hunter valley in NSW, and Darling Downs in Queensland). In 2004, there were 2 million milking cows or an average herd size of 216 cows /farm producing 10 billion L of milk annually. In 2005, dairy products added $ 3.2 billion to export income and $ 9 billion to the food industry (Dairy Australia 2005). Since 2004, there has been a steady decline in production and exports, mainly due to drought (Hogan and Delforce 2006). Over the same period, the real price of milk has decreased, except for 2007/08 when it rose substantially, while the input cost to produce milk (feeds, fertilizers) has increased. Therefore, the future viability of the dairy industry, at the farm level, will depend on the ability of farmers to maintain or to increase productivity (Bethume and Armstrong 2004).

Despite the overall decline in production over the past few decades, production/farm has increased, primarily due to the increase in production/cow, associated with improved genetic merit (Lindsay 2005) and feed management. Most of this increased production has come from brought in feed, not from increased forage production on-farm; despite the ample evidence that the best way to retain profitability is to increase the amount of forage grown on-farm. This is particularly true as the price of land, water and concentrates rise, and the real price of milk does not. In response to this cost price squeeze, the FutureDairy project (Garcia and Fulkerson 2006) was initiated with the objective of utilizing over 40 t DM/ha. yr of forage in an environmentally and economically sustainable way. The system likely to deliver such high yields in a sustainable way was considered to be a complementary forage rotation (CFR) using maize as the bulk crop, forage rape as a break biofumigation crop and clover (legume) to fix atmospheric nitrogen (N). The 40 t DM/ha target is more than 5 times greater than the average pasture utilized on dairy farms in Australia (Garcia and Fulkerson 2005). Such a system relies on high inputs of fertilizer and water, with the potential to have a high impact on the environment. However, the original plan for the CFR was to concentrate resources on more favorable agricultural land leaving the less desirable land to revert to nature; therefore the overall effect on the environment may be positive. In addition, the need for extensive monitoring of the system and its large plot size meant that the exact resource needs were able to be accurately applied. The efficiency of production (resource use) should increase as limitations to production are removed.

The objective of this study was to assess the major nutrient balances (nitrogen, potassium and phosphorus) in the CFR compared to both an extensively and intensively managed pasture in order to determine their relative nutrient use efficiencies and environmental sustainability. The hypothesis was that the CFR compares favourably with intensive pasture systems in terms of impacts on the major soil chemical, physical and biological properties and nutrient flow and has potential to significantly increase nutrient use efficiency (NUE) and water use efficiency (WUE) in terms of forage yield.

CHAPTER 2: LITERATURE REVIEW

Dairying is an intensive agricultural activity and often characterized by high use of inputs and generating substantial amounts of waste. The level of intensification and the degree of waste management varies from farm to farm. But generally, rising costs of inputs and static returns has led to increased intensification of dairy systems through higher use of fertilizer (Dorrogh *et al*. 2007), and improving productivity has necessitated significant increases in the amount of home grown feed. The high use of inputs in dairy and in pasture production and rising use of concentrates in herd diets have caused many environmental concerns due to rising nutrient loads (and on-farm nutrient imbalance) with negative impacts on the environment due especially to nitrogen and phosphorus (Bleken *et al*. 2005). The use of high input complementary forage systems may offer the prospect of achieving a significant increase in NUE and WUE compared with intensively managed pastures, but the long term sustainability in terms of nutrient balance and flow need to be measured and characterised. This chapter serves to provide background and introduce the key elements of this study and commences with reflection on the importance of dairy industry in the Australian economy. In addition the review explores what is understood about the concept of sustainability with particular relevance to agricultural systems, and focuses on sustainability in dairy pasture production systems by comparing typical intensive pasture systems with the CFR. Finally, the major soil fertility parameters (chemical, physical and biological), the major flows of nutrients and the possible chemical, physical and biological changes that characterize dairy pasture production systems, are described.

2.1. The Australian dairy industry

2.1.1. The industry

Dairy farming in Australia requires large financial investments in land and improvements, with access to ample water (high rainfall and/or irrigation) capable of supporting satisfactory pasture production though most of the year. These needs have seen the localization of dairy farms along the coast, where rainfall is better, and inland under irrigation (Figure 2.1). Victoria and New South Wales have 65% and 13% of registered farms, respectively, and more than 72% of the national dairy herd (Dairy Australia 2005). In these states, dairying has developed along the Murray River in Victoria and in the Riverina region of NSW, where there was ample water for irrigation, but also in the relatively higher rainfall regions of Gippsland and south-Western Victoria. Dairying is also scattered along the Coastal high rainfall area of Tasmania, South Australia and Western Australia. The location of major dairy regions is shown in Figure 2.1.

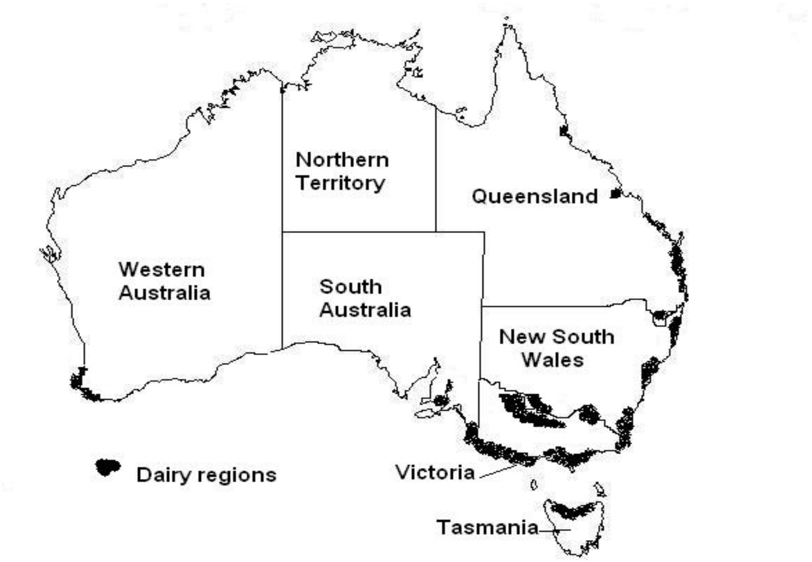


Figure 2-1 Australian dairy regions (source ADC 1999).

From 1979 to 2005, the number of dairy farms has halved while herd size and milk yield/cow increased by 75% and 7%, respectively. These increases in output have countered the cost price squeeze and illustrate the need for farmers to grow their enterprise to remain viable. The dairy industry in Australia is one of the major providers of employment in rural areas employing over 40,000 people directly while service providers and sub-contractors comprise another 100,000. The national dairy herd of 2.01 million milking cows is located on

8,840 registered dairy farms and produces more than 10.1 billion L of milk annually (Dairy Australia 2005).

2.1.2. Marketing of dairy products in Australia

The average herd size is about 216 cows/herd producing an average of 4,983 L milk/ cow/ yr in 2006. Dairy production is valued at $3.2 billion annually at the farm-gate. The milk is processed into cheese (38%), skim milk powder and butter (24 %) and milk for drinking (20%), with the rest diverted into milk powder, yogurt and ice cream (see Table 2.1). Half of the milk produced is exported as products, principally into Asia, placing Australia as the third biggest exporter of dairy products in the world, after the European Union and New Zealand. The balance of the production is sold domestically. Furthermore, the diversification of milk products through processing adds $ 9 billion to the industry.

Table 2-1 Breakdown of the milk industry in 2005 (source Dairy Australia)

Subject	Comment
Value-added food industry	$ 9 billion at wholesale
Milk utilization	Drinking milk 20% Cheese 36% Butter 25% WMP 15% Other 4%
Export proportion	50%
Annual production of main commodities	Milk powder 378,500 t Cheese 385,500 t Butter 147,000 t
Dairy- Major export industry	$ 2.6 billion /year (13% of world market)
Number of industries involved	357 companies
Destination of dairy production (excluding milk and ice-cream)	Australia 378,000 t Japan 155,500 t Singapore 79,500 t Philippine 70,000 t Malaysia 68,100 t Indonesia 53,900 t

The biggest issue to be addressed by the industry is milk price, which has only increased by 15% over the past decade. However, the recent global shortage of dairy products saw the price nearly double in 2007. The recent water crisis (drought) is also critical for the future of the dairy industry, which is the biggest user of water in agriculture (40%). Access to water for irrigation is likely to constitute the major long-term constraint to profitability for Australian dairy farmers (Bethume and Armstrong 2004).

2.1.3. Forage production systems in Australian dairy regions

Four distinct dairy regions have been identified in Australia and these are defined by climate and feed base differences as described below. These factors also dictate the type of management adopted (extensive or intensive) to meet year-round forage demands.

2.1.3.1. Inland irrigation region

The inland irrigation region is located along the Murray River in north-west Victoria and the Riverina in the south-west of NSW. The 3,000 dairy farms in the region produce 26% of Australia’s milk. The presence of rivers is critical to the provision of irrigation water in this semi-arid region. The decrease in the available water for irrigation, due to a persistent drought, has led to moves to improve water use efficiency (WUE).

The region receives 350-550 mm rainfall annually. Pasture grows from spring to autumn, and irrigation is used to complement seasonal rainfall. The soils are heavy red-brown clays with pH_w ranging from 6.0-7.0 on the surface and 8.5 at 1 m depth. Major nutrients are often deficient and annual application of N, potassium (K) and phosphorus (P) (34-46-52 kg /ha) is required to sustains pasture production.

Perennial pastures, notably paspalum (*Paspalum dilatatum L.*) and perennial ryegrass (*Lolium perenne L.*), are the 2 most common pasture species. Together they represent up to 75% of total pasture production of 10-19 t DM /ha/yr (Doyle *et al.* 2000). In contrast, rain-fed perennial pastures produce 2-9 t DM /ha /yr. In some cases, these grasses are grown in association with white clover, which can comprise up to 50% of the sward during spring in favorable years (Fulkerson and Doyle 2001) as indicated in Figure 2.2. Maize is commonly grown for silage to fill the perennial grass deficit. Pasture production can be increased by improving nutrient recycling (NUE) and also by subsoil drainage.

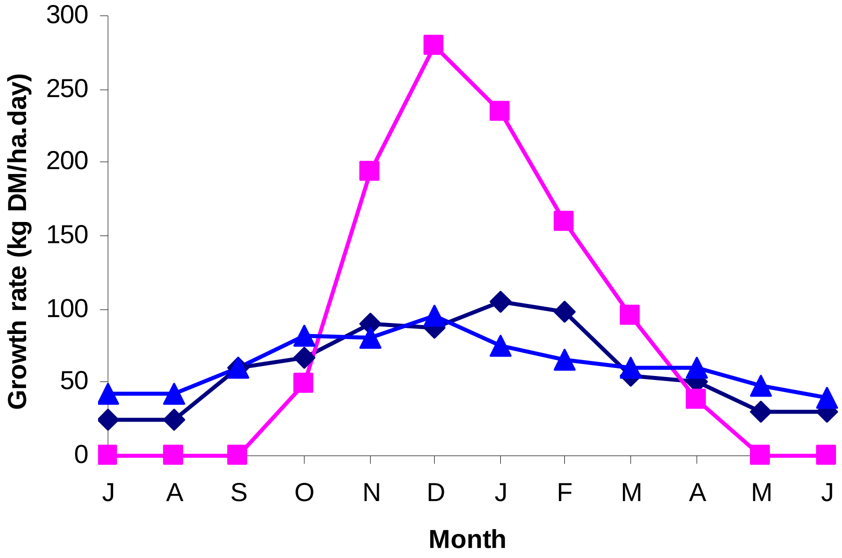


Figure 2-2 Monthly growth rates (kg DM/ ha/ day) under mowing management of paspalum (Δ), ryegrass (◊) and white clover (□) grown in pure swards with "ideal" management (Fulkerson and Doyle 2001).

2.1.3.2. Subtropical region

Stretching along the east coast from north of Sydney in NSW to Cairns in northern Queensland, the subtropical region is characterized by a dry winter-spring and a wet humid summer-autumn. The rainy season is governed by tropical cyclones in summer, and strong south-easterly winds from May to September.

The dominant soil type is of volcanic origin and has good fertility to suit both rain fed and irrigated pastures. Soil pH ranges from neutral to slightly acid and may require liming for certain temperate species. Due to its high clay content, soil compaction can be a problem when grazing in wet conditions.

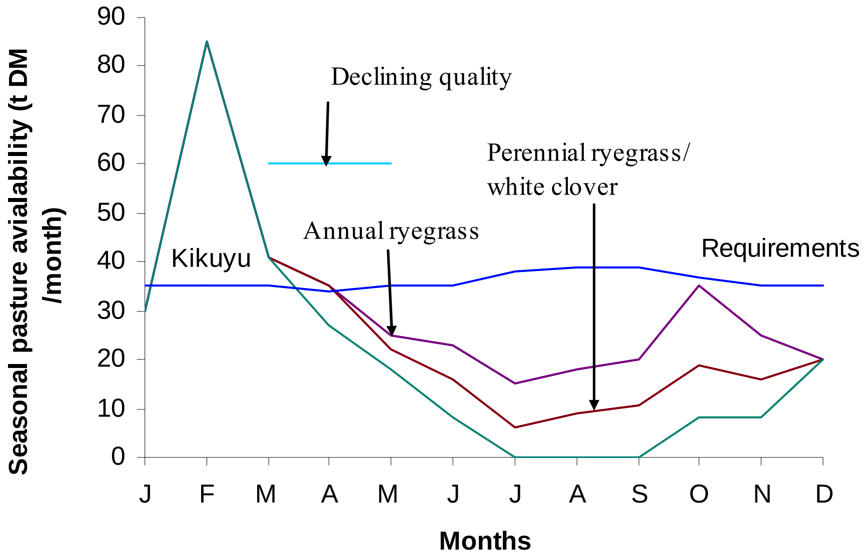


Figure 2-3 Seasonal pasture availability on a NSW north coast dairy farm (Fulkerson and Doyle 2001).

Depending on soil and water availability (irrigation and rain), various forage species can be grown. Generally, in the temperate part of the region, oats is grown in winter and various crops in summer, including maize (*Zea mays)*, lablab **(***Lablab purpureus***)** and lucerne (*Medicago sativa L.*), with the legumes reducing N use. The perennial pastures kikuyu (*Pennisetum clandestinum*) and paspalum are commonly oversown with winter species (short rotation ryegrass, *Lolium multiflorium* and Persian clover, *Trifolium resupinatum*) as shown in the Figure 2.3. The high winter temperatures allow high growth rates of pasture and crop species.

2.1.3.3. Cool temperate region

This cool temperate region includes southern Victoria (Gippsland and south west Victoria), Tasmania and the south coast of New South Wales (NSW). The region hosts more than 5,000 farms which produce about 39% of Australia's milk, making it the top milk producing area in Australia. Farm size is ranges from 50-150 ha with stocking rates of < 1 to 2.7 cows /ha.

The region is known for its cool wet winters and two distinct feed-bases:

1. The low rainfall region with a maximum annual rainfall of 800 mm; here supplemental irrigation is often provided.
2. The higher rainfall region (>1,000 mm/ annum) which usually has a longer pasture growing season.

In Gippsland, dark and loamy clay soils, and grey clayey gravel soils, dominate the region with a pH_w ranging from 5.6-6.0. Phosphorus and K are deficient in most soils. In the south west, deficiencies of N, P, K sulfur (S) and calcium (Ca) on the loamy sands are common. In Tasmania, red Krasnozem loam to clay soils are more frequent.

Perennial pastures (clover associated with rye grass/paspalum), produce 6.5-9.7 t DM/ha / annum in Gippsland and <14 t DM /ha/ yr under irrigation in Tasmania (Doyle *et al.* 2000). The high rainfall on Krasnozem soils in Tasmania has meant the application of high rates of fertilizer (600- 800 kg /ha .yr of mixed P and K) to get good yields.

2.1.3.4. Mediterranean region

The Mediterranean dairy region is located in the south-west of Western Australia and South East of South Australia, where the climate is characterized by dry and hot summers and wet winters. The region has some of the highest milk yields / cow due to the need to feed high levels of supplement during the dry summer.

The region has a 700 to 800 mm annual rainfall. In the low rainfall area (< 550 mm), irrigation is practiced on 20% of the total pasture area. The dominant duplex soil is moderately acidic and deficient in N, P, and K, requiring annual applications of mixed fertilizer.

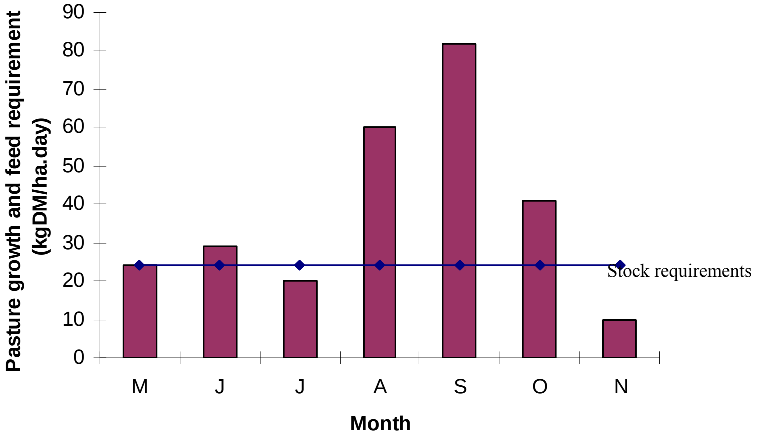


Figure 2-4 Pasture growth and the stock requirements (kg DM /ha /day) in south west, Western Australia (Fulkerson and Doyle 2001).

Annual pastures (annual rye grass/subterranean clover (*Trifolium subterranum*)) are common but phalaris (*Phalaris spp.*) and cocksfoot (*Dactilys glomerata L.*) are also grown in summer. Under irrigation, species such as ryegrass, white clover, paspalum and kikuyu are grown to secure high yields. About 65% of the total annual pasture growth is in the 3 spring months and much of the surplus is conserved as hay and/or silage to fill the summer feed gap (Figure 2.4).

2.2. Farming systems

Much of modern agriculture is based on monoculture cropping. This is also true for dairying in Australia, where perennial ryegrass is the predominant pasture species. In fact, perennial ryegrass - white clover pastures are the basis of most dairy farming systems in the world. These pastures provide high quality forage throughout most of the year, but poor persistence can be a problem. Even under ideal management, the yield is limited to 20 t DM /ha /yr. The limitations to yield of ryegrass, combined with the need to increase productivity as the price of land and water rise in many dairy regions, raises the question of whether a more appropriate forage base can be grown. The growth of a diverse range of species is one way to maximise the opportunities for the soil to be productive. This strategy would at the same time, ensure long term sustainability and be expected to minimise the build up of crop specific pathogens. The FutureDairy project is trialling a complementary forage rotation (CFR) system which has produced over 40 t DM /ha /yr for 3 successive years in replicated, paddock scale plots. The CFR has a bulk crop (maize), a "break" crop (forage rape) and a legume (Persian clover). Yields of a typical intense kikuyu pasture (*Pennisetum clandestinum*), oversown with short rotation ryegrass in autumn, produced nearly 18 t DM/ha.

In the following section, the agronomic specifications of each crop used in the CFR in the FutureDairy project, and the pasture control are described, in order to illustrate the limitations and advantages of each crop in terms of contributing to total productivity and conferring sustainability.

2.2.1. Maize

Maize has been grown as a grain crop for human consumption since antiquity in Latin America and constitutes the third largest grain harvest in the world (CNREST 1991). Maize is increasingly grown as an animal feed and this use consumes 80% and 92% of total maize grown in Australia and the USA, respectively (Berger 1962). The strong demand for maize has improved crop production techniques with yields increasing from 6.33 t grain /ha in 1978 to 8.6 t grain /ha more recently in USA (Smith *et al.* 2004). The peak yield of 9.5 t grain /ha was recorded in France (White and Johnson 1987). The whole maize plant is used for silage to feed dairy cattle (Kaiser *et al.* 1997). The high yields and nutritive value of maize silage have led to its use as the bulk crop in FutureDairy CFR, with maize contributing up to 65% of the total yield of the system (Garcia and Fulkerson 2006)

Maize grows a warm (21 to 32°C for optimum growth) and humid climate (White and Johnson 1987). The crucial growth period is from germination to tasselling (Kaiser *et al.* 1997), when soil moisture adequacy is critical. Any water stress during this period reduces yields. Photoperiodicity also determines the number and size of plant leaves (Freeding and Walbot 1993), and therefore productivity of the plant. According to Kucharik (2003), hybrid maize must receive at least 900 growing degrees days (GDDs) to maturity, where GDD is the sum of the difference between mean maximum and mean minimum daily temperatures above 10^{o} C during the growth period.

Maize is grown successfully on a large range of soil types. However, the optimal conditions include pH 6-7, good aeration and drainage and an abundance of organic matter (OM) in order to facilitate extensive root development. Its strong root system (up to 2 m depth) can actively explore to a depth of 50 cm in a radius of 70 cm (Berger 1962). Maize is sown at a density of 45,000 to 90,000 plants /ha but can reach over 109,000 plants /ha for forage production (White and Johnson 1987). The maize is sometimes grown as a single crop, but more commonly in a rotation with other crops such as barley, oats and soybean. In order to obtain high yields, large amounts of fertilizer must be applied (Table 2.2). The rate of N and K application should be related to soil test results (Frank and Roeth 1996) in order to optimize nutrient use efficiency (NUE). In Australia, N is applied at 200-260 kg /ha to achieve a yield of 25 t DM/ha or 10-12 t grain /ha (Kaiser *et al.* 1997). The high inputs of water and N increase the risk of loss of N through leaching, denitrification and volatilization.

Table 2-2 Nutrient content (kg of nutrient/ t DM) of maize (Andrade *et al.* 2000)

	N	P	K	Ca	Mg	S
Grain	14	3.2	4.2	0.16	1.2	1.3
All plant	21	4	20.7	4.3	4.7	2.3

Maize is subject to infestation diseases and pests (African beetle, cutworm, armyworm and heliothis grub) through the growth cycle. Defoliation is the most common symptom (Kaiser *et al.* 1997) and can reduce maize yields by up to 10%.

The root system of maize can access nutrients deep into the soil profile to retrieve nutrients lost to shallow-rooted crops (Reidell *et al.* 1998) and therefore is useful in a rotation with other crops to increase NUE. The deep root profile encourages organisms, e.g. earthworms and OM mineralization at depth, and improves the physical status (by increasing water storage capacity, infiltration rate, and roots penetration) and chemical fertility of soil (by leaving substantial root material for further OM recycling).

2.2.2. Brassica

As part of the Brassicaceae family, the *Brassica genus* includes the species-nigra, oleracea and conysestris. Brassica seed is appreciated for its high oil content for industrial and domestic consumption (oil and mustard seeds), for medical use (the by-products) and for animal feed. Industrial use of brassica began after the 1960's in the cosmetics, pharmaceutical, chemical and hydraulic fluid industries, and animal feed due to its high energy and protein content. The biggest rapeseed producing countries are China (6,506 000 t /yr.), the European Union (6,161 000 t /yr.), and Canada (3,758 000 t /yr.) accounting for 89 % of total world production in 1993 (Kimber and McGregor 1995). Representing only 5% of the oilseed production in 70's, brassica's share has doubled in a decade (Duke 1983) in relation to other seed oils. Because of its high content of protein (15-28%) (Ayres and Clements 2002; Najda 1991) and fatty acids, brassicas have been cautiously introduced into animal feed products due to potential goitrogenic (L-5-vinyl-2-thiooxazolidone) toxicity. For this reason, the dairy industry prefers to use the vegetative material rather than the seed for cattle feeding. Brassicas also have biofumigation properties which have the capacity to reduce pathogenic fungi and nematodes in the soil (Hugo *et al.* 2004; OGTR 2002). The brassica species, such canola, is used as a break crop in cereal rotations (Garcia and Fulkerson 2006) and in the triple crop CFR developed by FutureDairy, providing 25% of total DM production.

Brassicas are C_3 plants that require cool climates (5-27^{o}C) (Duke 1983) for optimum growth but are tolerant of frost. The *Brassica napus L.*, commonly called forage rape, is grown for forage production. There are two types of forage rape: the giant leafy species used to feed cattle (Najda 1991), which can grow to 1.5 m under irrigation (Hannaway and Larson 2004), and the dwarf species which are generally used to feed lambs.

Forage rape grows over a large range of fertile soils provided they are well aerated, with pH of 4.2-8.2 (Duke 1983), and provided they receive over 300 mm of rainfall during the growing period. The crucial growing period corresponds to the pre- and post-flowering stage, if the plants are grown for seed production. Forage rape should be sown at less than 2 cm deep at a rate of 3-4 kg/ha (Najda 1991) with row spacing of 30-70 cm (50-70 plants /m^2). Excessive surface crop residue at sowing severely reduces rape germination (Kimber and McGregor 1995).

A basic sulfur (S) amendment of 22 kg/ha (Hannaway and Larson 2004) and up to 70 kg/ha of N (Ayres and Clements 2002) are required annually to achieve best results. The N is applied at sowing (with molybdenum) and 50 kg /ha after the first grazing to increase the crude protein content. Depending on soil P and K content, a top dressing of K and P is often necessary (Kimber and McGregor 1995). Rape production is variable ranging from 10-12 t DM /ha under grazing (Garcia and Fulkerson 2006) to 10 t DM/ha for crops grown in Alberta (Najda 1991) to 14.3 t DM /ha in a cut plot experiment in Camden NSW (Shrestha *et al.* 2006).

Brassicas are affected by diseases and insect attacks including sclerotinia stem rot caused by *(Sclerotinia clerotiorum*), black leg caused by *Leptosphaeria maculans* (Ayres and Clements 2002), light leaf spot (*Pyrenopeziza brassicae*) and downy mildew (*Peronospora parasitica*).

The major contribution of brassicas to soil health is biological rather than chemical or physical, due their biofumigant properties which assist in the control of soil parasites (Stirling and Stirling 2003). Brassicas release isothiocyanates that target some nematodes, fungi, oomycetes and bacteria (Smith and Kirkegaard 2002). Reducing pathogenic agents in the soil impacts positively on soil biota mineralization efficiency and results in release of more nutrients (Angus *et al.* 1994). However, Oswald (2002) strongly advises against growing brassica for a maximum of 2 years on the same site to avoid black leg outbreak, and this has been confirmed in our studies with forage rape at Camben.

2.2.3. Persian clover

Persian clover is a legume and therefore is capable of fixing atmospheric N through a symbiotic relationship with rhizobia bacteria. It is the third species of FutureDairy's CFR system and contributes up to 10% of the total yield (Garcia and Fulkerson 2006). In the system, clover is considered more as a soil improver rather than a quality feed, fixing N for the current, and the future crops.

Persian clover is an autumn to spring growing species which grows in a range of alkaline soils from loam to clay (pH of 6-8) (Lacy 2003), but adapts to low fertility soils. It is also heat tolerant and its roots can explore a fairly large volume of soil (60 to 90 cm deep) (Verhallen *et al.* 2001), making it drought and waterlogging tolerant (OGTR 2002). It requires 450-650 mm of rainfall in its growing season to obtain high yields.

Persian clover is sown at less than 2 cm soil depth through direct drilling or broadcasting at a the rate of 4-20 kg/ha (40 plants /m^2) (Lacy 2003). The seed is generally inoculated with *Rhizobium trifolli* and coated with lime. Annual applications of a 67-23 (P-K) mixed fertilizer /ha are generally recommended (Hall 2006). When Persian clover comprises over 30% of the sward, it can supply an adequate level of N for the total sward. For reasonably rapid establishment, 50 kg N /ha are needed at sowing. The N contribution of clover is estimated to range from 10 kg N /ha /yr for poor soils to over 380 kg N/ ha/ yr in fertile soils (Fulkerson and Lowe 2002b).

The productivity of clover grown in a monoculture is generally greater than when grown in association with grasses (Elgersma and Hassink 1997). Reed (1999) estimated that 3-5 t DM /ha is generally achievable with some species at the first cut, compared to 1-3 t DM /ha in a mixed sward with grass. Like the other crops, clover can be affected by a number of diseases and insects such as leaf rust (*Uromyces trifolii-repentis*) and clover rot (*Sclerotinia trifoliorum*), more commonly found in dense irrigated swards (Lacy 2003).

2.2.4. Pastures

2.2.4.1. Kikuyu

Kikuyu is the second only to ryegrass in the dairy industry throughout Australia because of its remarkable adaptation to a large range of soils and climates (Moore 1970). Kikuyu originated in East Africa and has reasonable quality for a C_4 grass. The original kikuyu cultivar brought to Australia was “common” kikuyu which seldom seeded and was propagated largely by stolons. Subsequently, a seeding cultivar of kikuyu, Whittet, was selected, and the seed is now commercially available.

Kikuyu belongs to the Poaceae family and Panicoideae subfamily. With its powerful root system of rhizomes it propagates rapidly through the soil (Whittet 1969) and can withstand substantial trampling during grazing. Kikuyu is capable of exploring a large volume of soil (to 3 m soil deep) and therefore has a greater capacity to recover nutrients lost beyond the root zone of more shallower rooted species and its colonizing nature means it is used as a protection against erosion (Whittet 1969).

Kikuyu is suited to a large range of climatic zones from 1000-1500 mm rainfall in the tropical and sub-tropical regions and can be found above 3000 m altitude (Pearson and Ison 1987). It has remarkable water logging tolerance (Rotar and Kretschmer 1973) and can grow in an extreme temperature range from -2°-38°C. Kikuyu enters into dormancy below 9°C. The kikuyu growth period extends from late spring to autumn, with optimum temperature for growth below 30°C but above 15°C.

Kikuyu can adapt to a wide range of soils, but prefers alluvial loams and clay soils. Kikuyu is tolerant to low pH (< 4.5) and therefore high aluminum (Al) and manganese (Mn) levels (Cook *et al.* 2005). Kikuyu is also moderately salt tolerant and is often used to re-colonize saline soils. Kikuyu pastures can be established by direct seeding at rates of 1-3 kg/ha or by using stolons.

Kikuyu responds very well to N (50 kg N /ha /month) and P fertilizer application during its growth period (summer to autumn), where NUE of 15-30 kg DM /kg N can be expected, if moisture is adequate. Excessive N fertilizer application can cause luxury plant uptake that causes toxicity in cows and also increases soil nitrate leaching. Applying N after every second grazing is the best way to avoid this. Under optimum conditions, kikuyu is capable of producing 30 t DM /ha /yr (Cook *et al.* 2005), but in Australia, yields are limited to 12-14 t DM /ha /yr of utilized forage under best management grazing practice (Fulkerson and Lowe 2002b).

Kikuyu can be attacked by several insects and diseases such as African black beetle (*Heteronychus arator*), web worm (*Herpetogramma Licarsisalis*) and the oomycete, *Verrucalvus flavofaciens,* can devastate the root system and the plant, and has been recorded in coastal subtropical regions of Australia.

2.2.4.2. Ryegrass

Ryegrasses (*Lolium spp.*) are cool season temperate grasses originating from Europe. Ryegrass is divided into two major groups: short rotation and perennial, with similar agronomic features. In Australia, short rotation ryegrass is often oversown into a kikuyu or paspalum base pasture in autumn, to provide winter feed (coastal regions of NSW and southeastern Queensland).

Ryegrass develops a fibrous root system to a maximum depth of 80 cm (Jones 1988) and an average of 40 cm. Ryegrass requires fertile soils (pH 5.5-7) and liming should be considered to keep Al level less than 10% of effective cation exchange capacity (ECEC) (Fulkerson and Donaghy 1998). Ryegrass grows well in regions with a well distributed rainfall pattern and total rainfall above 800 mm.

Ryegrass is sown in autumn at a rate of 15-20 kg/ha for perennial ryegrass and up to 30 kg/ha for short rotation ryegrass. Nitrogen fertilizer is applied (50 kg N /ha) after each 2nd grazing (Sale 1996) and an annual top-dressing of P and K. Ryegrass is grazed at the 3 leaf stage of growth when water soluble carbohydrate reserves are optimal (Fulkerson 1997).

During growth, *Lolium spp.* can be subject to fungal infestation, e.g. by an endophyte (*Lolium endophyte)* and rust (*Puccinia spp.*), chewing insects such as sod web worm (*Crambus spp.*) and the armyworm (*Persectaria ewingii*), causing yield losses.

Ryegrass is an excellent sodium remover from the soil compared to kikuyu (0.15 g vs. 3.67 g sodium (Na) /kg DM in kikuyu and ryegrass, respectively) (Reeves *et al.* 1996).

2.2.5. Advantages of the Complementary Forage Rotations

The high worldwide demand for cereals, due to population increase and the diversion into a multitude of other uses such as biofuels, has increased monoculture practices. As the consequence, more cultivated lands fertility have been progressively deteriorating, despite high inputs of fertilizers and water. Crop rotations have been re-introduced to counter these negative effects, to restore soil fertility and to achieve sustainable production systems. In the case of FutureDairy, the sustainability of CFR trial is being assessed in comparison to a pasture control system.

Crop rotation is the use of different crops systematically and in a recurring sequence on the same land as opposed to continual cropping of monocultures (Dyck and Liebman 1993). The CFR is a special type of crop rotation where the crops comprising the crop rotation complement each other at the soil/plant level. In this case, the CFR system uses maize as a bulk crop; the root crop Brassica is also a "break crop" and Persian clover as the legume to provide a diverse combination of species which optimize forage. The specific advantages of the CFR are:

-The rotation of diverse forage species helps to reduce pressure on specific soil nutrients, thus micro-nutrients are replenished through OM mineralization. For example, N need is lower during Brassica-clover (replenished) than maize, but the maize is more capable of recovering N leached beyond to shallow root zones of brassica and Persian clover. In fact, several studies have demonstrated that maize has higher NUE in a rotation compared to in a monoculture (Florin *et al.* 2000; Raun and Johnson 1999; Reidell *et al.* 1998), highlighting the complementary role of rotations in NUE. Also, crop rotation reduces N leaching (Wen-Juan *et al.* 1996).

- Crop rotations contribute to improved soil structure by returning diverse crop residues (OM) to the top soil (Martinez *et al.* 2004), and improving soil water status at variable soil depths due to variable root structure (Masri and Tyan 2005). The availability of OM at variable soil depths may encourage soil biotic activity down the soil profile, and improve soil structure (Collett and McGufficke 2005) and nutrient recycling. Table 2.3 summarizes some of the benefits and disadvantages of each crop in the CFR system.

Table 2-3 Advantages and disadvantages of the CFR and perennial forages.

Type of crop	Advantages	Disadvantages
Maize	-Deep OM accumulation -Recycling of deep nutrients -Increase infiltration and water distribution -Good NUE in rotation and high yield	-Poor surface coverage -Low residue return (silage) -Increased evapo-transpiration -Could accelerate water percolation -More labor required
Brassica	-Soil biofumigation -Reduced S induced by low pH -Debris protects soils	-Probable soil compaction by grazing -More labor required -Buildup of diseases in long-term
Clover	-Improved soil N and OM content -Good soil coverage	- Probable soil compaction by direct grazing

- Crop-rotations can contribute to control of soil-borne diseases by interrupting their life cycle (suppression of hosts) (Alabouvette *et al.* 1996); although some pathogens, such as *Pythium spp.,* have a wide range of hosts. Brassica can biofumigate the soil through the release of isothiocyanates which inhibit the growth fungi and nematodes.

- Crop rotations allow better control of weeds because there are more options to target different weed species (Dyck and Liebman 1993)

The bigger challenge of “intense” rotations remains the difficulty of managing the residues of the previous crop which may compromise the establishment of the next crop.

In section 2.2.6, the following section the concept of environmental sustainability in agriculture and nutrient flows and balances which determine environmental sustainability are reviewed.

2.2.6. Sustainability in farming systems

2.2.6.1. Origin and concept of sustainable farming systems

Sustainability originated from the Latin word “sustinere”, which means permanent or long-term support. Sustainable agriculture refers to a system with the capacity to support and maintain productivity indefinitely to meet society’s needs. The term of sustainability was defined in the Brundtland Report on World conservation as “*development which meets the needs of the present generation without compromizing the ability of future generations to meet their own needs”* and was adopted by the United Nations Conference on Environment and Development (the Rio Earth Summit) in 1987 (Stoneham *et al.* 2003).

The notion of sustainability in agriculture focused on the soil’s capacity to “indefinitely” support production increases, or the ability to indefinitely support crop growth (Chataway 2004). In the actual context of increasing demand for food to satisfy the global population growth, the intensification of agriculture leads to more land already degraded and the need for more fertile lands at the detriment of natural reserves (grass lands and forests). In this context, agriculture intensification should be socially supportive, commercially competitive and environmentally compatible (Ikerd 1990). This justifies the necessity of redefining sustainability by emphasizing the role of these additional parameters.

2.2.6.2. Difficulties surrounding the concepts of sustainability

Since the introduction of the concept of sustainability in the early 1980’s, several innovative concepts and contradictory ideas have emerged to support or promote growth of resources (Chataway 2004). This has been debated world wide in order to reach a consensual definition of sustainability. The long absence of consensual definition of sustainability among scientists and rural actors poses the problem of its applicability on the field. The great confusion comes from the fact that sustainability has generally been taken as a “new outcome” and not as something that already exists, such as sustainable farming systems (Ison 1990). In view of this confusion, Herdt and Steiner (1995) concluded that sustainability is a complex idea involving many different aspects of human activity which are linked to many levels and dimensions of the global system, causing a continual mutation of the concept.

2.2.6.3. Sustainability of farming systems

The FAO definition of sustainability is: *sustainable development is the management and conservation of the natural resource base and the orientation of technological and* *institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for the present and future generations. Such sustainable development conserves lands, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable* (F.A.O. 1995). Based on this definition, sustainability in agriculture has emerged as a concept of ensuring essential food production with minimal impacts on the environment (Davis and Trebilcock 1999). Figure 2.5 illustrates the main factors impacting on sustainability during agricultural intensification. The main challenges to intensification is disruption of ecological balance that results from nutrient pollution and massive land clearing, and the integration of economic profitability, social and economic equity (Tilman *et al.* 2004).

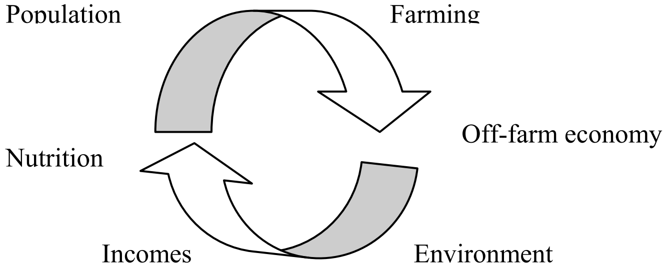


Figure 2-5 Dynamic links of farming practices and population growth (Clay and Reardon 1998).

The absence of a global approach to the sustainability concept at the farm level makes it difficult for farmers to integrate all aspects of sustainability (social and economic) towards healthy ecosystems, based on soil fertility indices only (Schroth and Sinclair 2003). Based on the FAO definition, special mention is given to land preservation and conservation in the agricultural context to counter land degradation that often occurs under increasing intensification of farming practices. That calls for elaboration of simple and comprehensive guidlines for farmers to assess their soil fertility (physical, chemical and biological components) and the sustainability of their practices as suggested by Byerlee and Murgai

(2000). The following part of the review describes soil fertility indicators for dairy farmers in order to strength their management practices.

At the farm scale, the current definition of sustainability is usually assessed through the soil's capacity to sustain crop yields over time. However, this is a narrow vision of sustainability because yield increases can be obtained by using high inputs in a monoculture system without meeting sustainability requirements. Monitoring the seasonal variation in soil fertility indexes of biological, physical and chemical components on-farm, could help farmers establish sustainable land management practices, and this is as summarized in Figure 2.6.

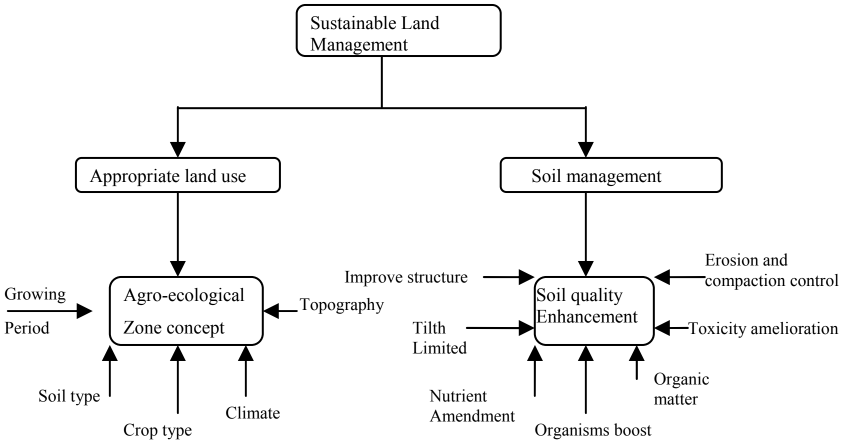


Figure 2-6 Components of sustainable land management (modified from Raman 2006).

Sustaining agricultural systems is synonymous with solving soil degradation problems induced by agricultural practice.

2.2.6.4. Conclusion

The sustainability of dairy farming systems is strongly influenced by three interacting factors which are: economic, social and environmental. However, the present study will limit the investigation of sustainability to the agronomic aspects of pasture-based dairy production systems, and compare a common intensive forage production system (ryegrass/kikuyu) with the CFR.

The dairy industry is striving to improve management practices to support more sustainable production systems. This may be realised by having a clearer understanding of the major nutrient cycles and the way to optimize their use in an environmentally efficient manner, without compromising on quality. Doing this requires an understanding of basic monitoring of soil components associated with soil fertility. In this regard, Australian farming systems appear to be far from being sustainable, due to massive imbalance in the nutrient and water cycles, which often leads to land degradation. The recent moves to higher rates of use of fertilizers has introduced negative impacts in nutrient balance (massive nutrients loss and environmental pollution) affecting the long-term sustainability of farming. Furthermore, safe farming practices would certainly contribute to improve economic and social aspects and meet the general vision of sustainability.

2.3. The soil /plant relationships of the dairy production system

The productive performance of a pasture-based dairy farm depends on the flows of water and nutrients in the plant/soil system. The movement of water and the balance of nutrients in the soil are primarily influenced by the soil moisture status.

2.3.1. The water cycle

2.3.1.1. The water cycle in the plant

Water assures the transport of the mineral (nutrients) and elaborated substances such carbohydrates to the entire the plant. Carbohydrates are the main source of energy (non-structural carbohydrates) and cell wall structure (structural carbohydrates).” Carbohydrates are formed by the process of photosynthesis, from CO_2 using water, and energy from solar radiation to produce simple sugars and O_2, as shown in Equation 2.1

Equation 2-1 Photosynthesis

$$6H_2O \;+\; 6CO_2 \xrightarrow{\text{Solar radiation}} \underset{\text{Simple sugar}}{C_6H_{12}O_6} \;+ 6O_2$$

2.3.1.2. The water cycle in the soil

In the soil, water is redistributed by gravity and diffusion through the profile depending on availability, weather (evaporation and rain), crop demand (transpiration) and soil type (infiltration, deep percolation and capillarity ascension). In the soil, the active water dissolves nutrients and facilitates their transport to, and absorption by, plant roots (Teixeira *et al.* 2003). Water is essential to sustain biological life in the soil, which is the basis of nutrient recycling from OM that plays such an important role in plant nutrition. The soil macro/micro-pores, combined with the OM can hold substantial quantities of water which can be gradually released to supply the plant. The distribution of water down the soil profile is correlated to soil physical characteristics (texture, compaction) surface crusting, infiltration and erosion), OM content (crop residues and roots) and the quantity of water available for infiltration. If there is excess water, soluble nutrients may be leached out of the root zone by deep drainage and /or lost in surface run off (Beetz 2002). In normal soil conditions, where there is sufficient water, the greater the hydraulic conductivity, the greater will be the water flow down the soil profile (Hanks and Cardon 2003). Some factors which increase water movement in soil include: land slope (contouring); cultivation system (bedded surface, drainage, ploughing); surface cover and; infiltration in combination with aggregate stability (soil organic matter and humus content). Surface runoff is low from soils that are well covered by perennial grasses. The balance of water in the soil can be described by Equation 2.2:

Equation 2-2 Soil water balance

$$\text{Soil water balance} = (\mathbf{W_r + W_i} + W_f + W_m + W_u + W_l + W_c + W_g) - (\mathbf{W_e + W_t + W_{of} + W_d} + W_o)$$

Where W_r = Rain, W_i = irrigation, W_f = frost, W_m = Water mobilized by organic matter, W_u = Urine, W_l = lateral infiltration, W_c = capillarity ascension, W_g = groundwater inflow, W_e = evaporation water, W_t = transpiration, W_{of} = Runoff water, W_d = deep drainage and W_o = groundwater outflow)

Bold characters indicate contributions and groundwater flow (in and out) may be balanced

Seasonal forage production needs to match the seasonal availability of rainfall, whilst irrigation is used to minimize water deficits (unpredicted or seasonal drought). If sufficient water is supplied by rain or irrigation, the water is distributed through the soil profile, at a rate depending on soil type. It refills the soil water reserve (macro-pores) and stabilizes in 24-48 hours after the excess water has been removed (by drainage or runoff). The soil water saturation point is related to soil texture (proportion and type of clay, loam and sand, and soil OM content). Plant root penetration increases water storage (by increasing the soil porosity). The root density is proportional to plant density and growth. Most soil water for growth is stored in the top 30 cm which also corresponds to the most active root zone for most plant species (hosting the majority of soil biota and nutrients), but the gradual water supplied during the crop cycle will boost root development and improve nutrient absorption (mass flux and diffusion) (Foth and Ellis 1988). Other sources of soil water come from the capillaries e.g. the ascension from deep water reserves to recharge top-soil storage. The rate of movement of water from the lower to upper profile by capillary action increases with increasing dryness (Hanks and Cardon 2003). Dew or frost may also contribute a significant amount of water, but this is difficult to estimate. Evaporation and transpiration are weather-induced water loss factors which increase with temperature and wind speed. The "crop" factor, which depends on canopy cover, is usually used to estimate or predict crop water need. Thus, C_3 and C_4 plants evapo-transpiration (Etp) varies depending on plant species, environment and soil type (Ward *et al.* 1999). Crop characteristics such as crop height, leaf thickness (cuticle) and ground cover can induce different levels of Etp in different crops under identical environmental (weather and management) conditions (Allen *et al.* 1998).

2.3.1.2.1. Surface water loss

Surface water runoff occurs when the rate of application (rain/irrigation) is greater than the infiltration rate. The excessive water often causes soil surface erosion (particularly on sloping surfaces) leading to soil loss (nutrients) and gully erosion.

Infiltration of water or leaching is also related to the soil characteristics. Infiltration rate is faster in sandy soils which generally have lower OM content. Water movement in the soil profile may be increased at depth as crops grow and the extended root system opens macro-pores in the soil. However, the greater infiltration rate may lead to more rapid movement of water out of the root zone if the subsequent crop has shallow roots.

2.3.1.2.2. Managing dairy water

Rural activities produce waste water which can pollute streams and ground water (Sala and Mujeriego 2001). Pollution of waterways by P and N compromises nutrient cycling and causes serious concerns to production systems (nutrient losses and explosion of algae in the effluent) and also to public health, threatening the integrity of the ecosystem. Point source pollution from agricultural land (Dunne *et al.* 2005) often causes eutrophication of dams and rivers, compromising water purification and public amenity.

On dairy farms in Australia, waste water must be recycled on the farm. This increases NUE and lowers the environmental impact, while improving water quality (Dunne *et al.* 2005). Generally, dairy effluent (dung and urine) is treated in a 2 pond system. The first pond is deep and anaerobic where bacteria break down most OM. The effluent then moves into an aerobic pond which is relatively shallow (1 to 2 m) for further purification with the resultant water being re-used for irrigation. The use of dairy waste water should be monitored periodically because of the seasonal variation in nutrient content (Wrigley 1996).

To reduce the possibility of nutrient overload, the treated waste water might undergo further nutrient purification by applying it to a wetland system (Dodds 2003) and incorporating periphton and plankton (Hanes *et al.* 2001). These two groups of plants remove substantial amounts of P (and N) in water, and can then be harvested for composting and used as organic fertilizer (Wrigley 1996), optimizing P and N cycling.

2.3.2. The nutrient cycle and soil fertility

The fertility or health of a soil reflects its capacity to host living functions in natural or managed systems, to sustain plant and animal productivity, while maintaining or enhancing water and air quality (Foth and Ellis 1988). To optimize the positive effects of soil fertility, (Schaller 1993) suggested that all the components of soil should be considered as a unique system interacting with each other in complex ways, where one defective factor could affect the whole ecosystem balance. At the farm level, the monitoring of soil health/fertility should always be based on periodic soil assessment (basic soil components), in order to improve management practices and sustain production, where nutrient cycling plays an important role.

In the following sections, the basic indicators of the biological, physical and chemical components of the soil are described, together with their potential to interact to limit production and an understanding of this interaction may affect sustainable management systems.

2.3.2.1. Chemical components of soil

The soil is a chemical laboratory where a myriad of reactions happen between natural and added components (fertilizers, pesticides, compost materials, etc) in a complex and often unpredictable way that could benefit or harm soil nutrient status. Table 2.4 summarizes some of indicators that reflect soil chemical status.

Table 2-4 Proposed minimum data set of soil chemical indicators required to screen for quality and soil health (Lal, 1999).

Indicator	Relationship to soil condition and function; rationale as a priority measurement
Soil organic matter (total organic C and N)	Defines soil fertility, stability and erosion extent; used in process models and for site normalization
pH	Defines biological and chemical activity thresholds
Electricity conductivity	Defines plant and microbial activity threshold, soil structure stability, water infiltration. Can be a practical estimator of soil nitrate and leachable salt
Extractable N, P and K	Plant-available nutrient and potential loss from soil; productivity and environment quality indicator
ECEC (exchangeable cations)	Nutrient availability and potential impact on soil pH

2.3.2.1.1. Soil pH

Soil pH is commonly used to assess the soil health/fertility components such as its physical and biological activities. Soil pH is measured in either calcium chloride (pH_{CaCl2}) or water (pH_w). Soil is considered acid when the pH ranges from 1 to < 7 and alkaline > 7 to 14 with 7 being neutral. In the natural state, most species are found over a large range of pH_w (3.5-10.5) with optimum pH for most plant species being 5.3 to 6.7 (Goulding 1999).

Soil acidification is a natural process that changes with time and space due to internal and external factors. The mechanism balancing acidity and alkalinity (neutralization) is a natural process, but is quickly interrupted by agricultural activities. Generally, acidity starts in the top-soil before moving deeper into the sub-soil where it is more difficult to correct. This phenomenon of sub-soil acidification is wide-spread in agriculture and will potentially increase with intensification of the system of production. Hundreds of thousands of ha of arable land are lost every year to soil acidification (pH < 4.8). In Australia, 29 million ha are considered to be acidified, of which more than 9.5 million ha are in NSW (Evans 1991).

2.3.2.1.1.1. Mechanisms causing soil acidification

Harvesting and removal of crops exports nutrients, including cations and factors soil CEC, inducing a decrease in pH (Lesturgez *et al.* 2006). The most important elements generating soil acidity are leakage of C, N and S (Conyers *et al.* 1995) (see Equations 2.3, 2.4 and 2.5) and the absorption of nutrients by plant roots leaving an excess of H^+ ions in the soil matrix.

Equation 2-3 Nitrogen oxidation

$NH_4^+ + 2O_2 \rightarrow\rightarrow NO_3^- + \mathbf{2H^+} + H_2O$

Equation 2-4 Carbon oxidation

$C_xH_{2x}\text{-}Ox^- + \mathbf{H^+} + xO_2 \rightarrow xCO_2 + xH_2O$

Equation 2-5 Sulfur cycle

$R\text{-}SH + H_2O \rightarrow R\text{-}OH + H_2S \leftrightarrow \mathbf{2H^+} + S^{2-} + H_2O$

The key factors that determine the level of soil acidity are:

The farming system. The wide-spread use of fertilizer, particularly N, is the primary cause of soil acidification. The use of correct fertilizers such as cyanamid (22% N) which has a low salinity index can minimize acidification affect as indicated in the Table 2.5 (MCF 1993). These types of fertilizer are also more suitable for seedling establishment as they do not lead to root burning. However, cost prohibits their extensive use.

Table 2-5 Acidity or alkalinity expressed in kg of CaCO3 /100 kg fertilizers used (MCF 1993).

Fertilizer	Salinity Index	Acidity effect	Alkali effect
Nitrogen -			
Anhydrous ammonia 82% N	47%	148	
Ammonium sulfate 20.5 % N	69%	110	
DAP 16.5 % N	30 %	88	
Urea 46 % N	75 %	75	
Ammonium nitrate 33.5%	105%	60	
MAP 11% N	30%	59	
Potash nitrate 14 % N	46 %		25
Sodium nitrate 16 % N	100 %		29
Cyanamid 22 % N			63
Phosphorus			
Superphosphate 14 -48 %	8 for single P	0	0
Bi calcite phosphate 37 %			25
Natural phosphate <35 %			Alkaline
Murate of potash	114 %		

Rainfall. The weathering of soil is a natural acidification process. The rate is high in tropical or high winter rainfall regions which increases nutrient leaching and runoff (N, S, K and P) (Carl 1983).

Soil base material. Some soil parent materials, such as feldspar and granite naturally contain minerals which free more H^+ during weathering than others, producing acidic conditions.

Organic matter. Organic matter is well known as being of benefit to soil structure by supplying nutrients to plants through nutrient cycling. However, it also has a disadvantage in contributing to soil acidification (Goulding 1999). The decomposition of OM generates humic acid that contributes to raise soil acidity (Valarini *et al.* 2002). In contrast to OM, the build up of manure seems to have a reverse effect by inducing a slight pH increase (Bellows 2001).

Direct consequence of Soil acidity. Soil pH remains the best indicator of change in soil status. It gives a quick indication of the activity of microorganisms in the soil; reflecting the status of nutrient availability or level of toxicity which influences soil physical characteristics. In this way, changes in pH alter the availability of nutrients for the plant. Favorable pH supports biodiversity in the soil, increases the microorganism count and the efficiency of mineralization of OM, and therefore improves nutrient cycling (for macro- and micro-nutrients). According to the USDA (1998), the optimum pH_w for bacterial activity is 5.5-7.3. At low pH, activities of fauna and fungi are reduced, affecting their ability to grow and to transform OM into available nutrients for plants. Rhizobia, the bacteria responsible for fixing N in legume nodules, develop poorly at low pH and fail to establish the strong symbiotic relationship with the plant required to efficiently fix atmospheric N (Graeme 1991). In the N cycle, pHs below 6 show the nitrification process which becomes negligible at pH 4.5. In contrast, the ammonification process is not disrupted by variation in pH (Ulrich and Sumner 1991).

Low soil pH has an adverse impact on soil texture. In fact, in heavy clay soils, low pH causes the soil surface to crack when drying and this becomes extreme when OM content is also low. This has a negative impact on rate of water infiltration and porosity of soils reducing the plant's ability to explore soil volume (Collett and McGufficke 2005) and microorganism growth. In conclusion, the chain of events described above reflects the real impact of low pH on soil fertility.

2.3.2.1.1.2. pH and nutrient availability

Soil pH is the principal factor influencing mineral availability or solubility in soil. Figure 2.7 shows the influence of pH on the availability of minerals. At low pH, P becomes less soluble and therefore less available to plants (Bellows 2001). In acidic soils ($pH < 4.5$), solubility of some minerals starts to rise, viz. Mn and Al to concentrations that can be harmful (toxicity) to plant growth. Most nutrients are available in the pH range of 6-7.5.

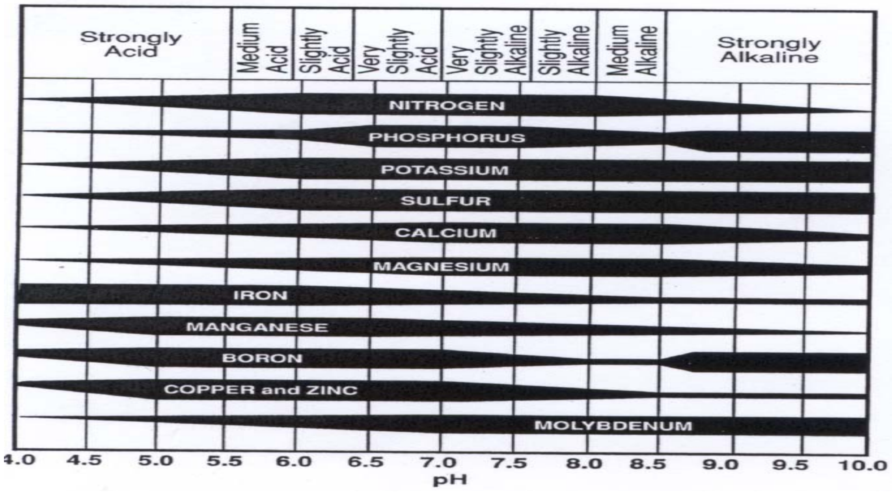


Figure 2-7 Influence of pHw on nutrient availability (Goulding 1999).

2.3.2.1.2. Soil organic matter

Soil OM comes from crop residues, compost, root material, animal excreta and dead soil organisms. Organic matter is the most dynamic soil component (Masri and Tyan 2005) because it decomposes into a variety of sub-components that contribute to improved soil fertility. The degree of decomposition of OM, and its effective contribution to soil structure, depends on its origin. Organic matter improves soil physical properties and hence soil water retention (Masri and Tyan 2005) (limitation of evaporation). Organic matter hosts microbial life and the activities as summarized in Table 2.6 and Figure 2.8.

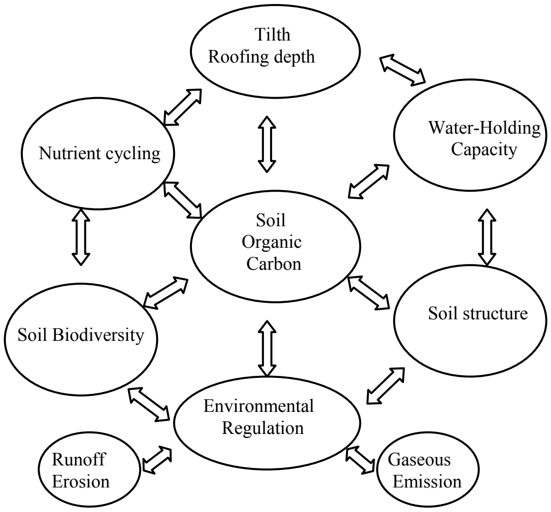


Figure 2-8 Beneficial effects of soil organic matter (Raman 2006).

Thus, OM will stimulate plant production and therefore yield (Traore and Harris 1995). According to Foth and Ellis (1997) old and well decomposed soils OM can enhance soil ECEC to levels greater than 291 cmol/ kg. Successively, soil OM is decomposed into semi-decomposed matter such as humic and fluvic acids, before total mineralization freeing soluble nutrients. Humic acid is the main component enhancing soil ECEC and may increase soil water holding capacity by 20 fold (Kahattak 1996). The rate of decomposition of OM depends on soil conditions (clay, moisture, aeration and pH), the carbon (C): N ratio (OM in young plants are more easily decomposed due to their higher C: N), climate (warm weather accelerates microorganism activity) and management (tilling /no tilling practice). Mineralization is faster in the tropics than in temperate regions. Usually, the rate of decomposition can be gauged by the C to N ratio which frees a substantial amount of N for the current crop.

Table 2-6 Summary of physical, chemical and biological impacts of organic matter on soil status (Michelle 2004)

Summary by Waksman (1936)	Summary by Frank and Roeth (1996)	Summary by Stevenson (1994)
	Physical function	
Modifies soil colour, texture, structure, moisture-holding capacity, and aeration	Water storage, transport and potential erosion, productivity, soil compaction and leaching, SOM and Microbial	Colour, water retention, helps prevent shrinking and drying, combines with clay minerals, improves moisture retaining properties, stabilize structure, permits gas exchange
	Chemical function	
Solubility of minerals, formation of compounds with elements such as Fe, making them more available for plant growth; increase the buffer properties of soil	Soil fertility, stability and erosion extent, thresholds of microbial and chemical, balance between cation and H^+, productivity and N loss	Chelation improves micronutrient availability; buffer action maintains uniform reactions in soil and increases cation exchange
	Biological function	
Source of energy for micro-organisms, making the soil a better medium for the growth of plants; gradually supplies nutrients for plant growth	Nutrient pool, productivity and N supply, biomass activity	Mineralization is a source of nutrient; combines with xenobiotics, influencing bioavailability and pesticide effectiveness

2.3.2.1.3. Effective Cation Exchange Capacity (ECEC)

Organic matter in the soil comprises a complex of humus products that are negatively charged due to their carboxyl (-COOH), hydroxyl (-OH) (Huang 1980) and amino ($-NH_2$) groups (Blair and Sale 1996). Apart from soil temperature and moisture, the status of OM depends on available soil air which sustains micro-organism activity. When soil OM combines with clay minerals, also negatively charged, they form colloidal complexes capable of fixing and storing cations (Na^+, K^+ Ca^{2+}, Mg^{2+}, $Mn^{2+)}$) which are used by plants. The more OM that is decomposed, the more colloidal complexes are formed, resulting in an increase in CEC in the soil (Valarini *et al.* 2002) and the less cations are liable to be lost through leaching and runoff. The complete cation complement in soil is referred to as the ECEC and includes beneficial (to plant growth) and toxic cations. The ECEC is also related to the type of clay in the soil. For example, kaolinite has the lowest ECEC (3-15 cmol/ kg) compared to vermiculite which has the highest CEC content (100-450 cmol/ kg). The CEC value is considered to be acceptable when it is above 6 cmol/ kg (Havilah *et al.* 2005). The Ca^{2+} cations form a stronger bond in the soil than Al and therefore Al is easily substituted by Ca^{2+} during liming hence increasing pH. Soil ECEC is positively correlated to the soil pH. In an acidifying soil, ECEC levels are low and the freed negative sites on the clay matrix are quickly occupied by H^+ ions produced by oxido-reduction processes (Conyers *et al.* 1995), or in the worst case scenario (low ECEC), cations can be displaced by H^+ ions.

The absorption of cations by the plant must respect a certain balance: such is the case for Mg, Ca and K. The priority for availability of cations has also been observed in relation to plant uptake. An increase in Mg uptake may reduce Ca uptake; when Mg uptake increases, K uptake decreases (Marschner 1991).

2.3.2.1.4. Effect of liming on ECEC

The amount of base required to increase the pH by one unit is called the pH buffering capacity. The soil's pH buffering capacity is the best index of the potential ameliorating effect of lime on soil pH. Lime works to increase pH in soil by substituting Ca or Mg ions for H^+ ions in the clay matrix. Liming restores soil health and thus plant growth, particularly of legumes (Moore 1970), and boosts beneficial microbial activity. For example, an increase in soil pH will increase the availability of molybdenum, a critical nutrient required for rhizobia development in the nodules of the roots of legumes. Increased soil pH also improves soil structure and, as a consequence, increases the drought tolerance through better developed root systems. The palatability of herbage to stock also increases as soil pH rises (Beetz 2002). Liming also reduces toxicity due to excess Al^{3+} and Mn^{2+}, again increasing overall plant growth. For ideal plant growth, soil exchangeable Ca, Mg and K concentration should be 65%, 10% and 5%, respectively, of CEC (Kopittek and Menzies 2007). As a consequence dolomite is often preferred to limestone as it supplies both Mg and Ca avoiding an imbalance in the soil, even if the Ca: Mg ratio has not been clearly established yet (Fenton and Conyers 2002). Several studies on the impact of the Ca: Mg ratio on yield of cotton and alfalfa (Kelling *et al.* 1996; Stevens *et al.* 2005) have shown no effect. There are several sources of Ca that can be used for liming including calcium carbonate ($CaCO_3$), dolomite limestone (($CaMg, (CO_3)_2$ containing 10% Mg), calcium oxide (CaO), calcium hydroxide ($Ca (OH)_2$), slag (an industrial product) which has a variable neutralizing value (CSIRO 1999). Calcium oxide and $Ca(OH)_2$ have faster action (1-2 weeks) compared to $CaCO_3$ (Heanes 1981).

2.3.2.1.5. Salinity

Soil salinity is the second major problem affecting agricultural land. Salinity has two origins; the main source of salinity is rising salty water due to agricultural activities (e.g. water quality, fertilizer) (Barrett-Lennard 2002). Soil salinity affects soil structure causing dispersion of clay minerals, decreasing water holding capacity and compromising nutrient cycling and therefore NUE. It affects crop growth, particularly in species sensitive to salinity in contrast to halophytes plants which are tolerant to salinity (Bee and Laslettb 2002). An acceptable soil salinity level depends on soil type and crop species as summarized in Table 2.7. For example, white clover and maize are sensitive to salinity compared to kikuyu grass, which is moderately tolerant, and ryegrass which is even more tolerant.

Table 2-7 Electrical conductivity level in the soil in ds/m (Havilah et al., 2005).

Texture	Not saline	Weakly saline	Moderately saline	Strongly saline
Sandy loam	<0.11	0.12-0.23	0.24-0.45	>0.45
Loam	<0.12	0.13-0.35	0.36-0.79	>0.79
Clay loam	<0.18	0.19-0.42	0.43-0.85	>0.85
Clay	<0.24	0.25-0.56	0.57-0.94	>0.94

2.3.2.2. Soil fertility and major nutrient cycles

Soil fertility is the sum of the physical, chemical and biological characteristics which ensure continual nutrient supply to the plant. Organic matter plays a role in storing nutrients and limiting their losses through runoff and deep drainage. The activities of micro-organisms that recycle minerals by breaking down OM into soluble nutrients for plant uptake and immobilizing excess nutrients in the soil help improve soil fertility. In the case of intensive production systems, the rapid recycling of nutrients is vital and can be achieved by creating favorable conditions for micro-organism activity in soil. In this regard, the monitoring of macro-nutrients (N, P, K, Ca, S and to a lesser extend Cl and Na) should improve NUE. Micro-nutrients or trace elements including iron (Fe), Mn, zinc (Zn), copper (Cu), molybdenum (Mo), nickel (Ni) and boron (B) also play important roles in the soil-plant relationship (Marschner 1991). The major nutrients N, P and K will be reviewed in the next section with particular interest in the most effective fertilizers to use to support sustainable production.

2.3.2.2.1. Nitrogen cycle in dairy

Nitrogen is an important component of plants, animals and all living organisms, including bacteria, fungi and other microbes. Nitrogen is necessary for the formation of protein, amino acids and nucleic acids (genetic material). The ultimate source of N is N_2 which comprises 78% of total atmospheric gasses. **Legumes** partially satisfy their daily N needs through the symbiotic fixation of atmospheric N by rhizobia (Karel 1986). Most N in the soil is recycled through OM and constitutes the stable and labile form of N for plant nutrition. In dairy soils, the N cycle follows complex pathways as summarized in Figure 2.9.

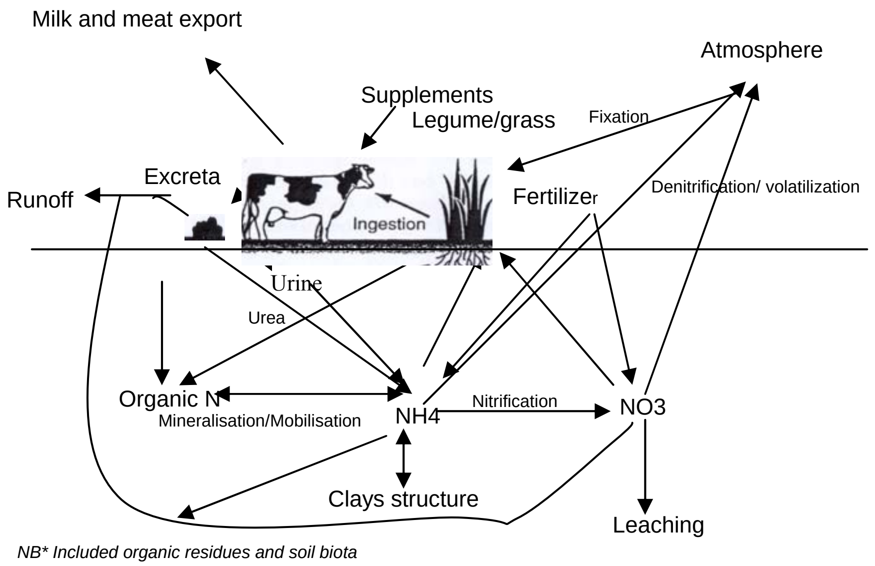


Figure 2-9 Nitrogen cycle on a dairy pasture (modified from Jarvis 1998).

2.3.2.2.1.1. Sources of N on a dairy farm

The N budget for pasture is summarized in Equation 2.6:

Equation 2-6 Nitrogen cycle in dairy farm

$$\text{N balance (pasture)} = \mathbf{N_f} + \mathbf{N_w} + N_{at} + N_{om} + \mathbf{N_{lg}} - (\mathbf{N_{ex}} + \mathbf{N_v} + \mathbf{N_d} + N_{of} + \mathbf{N_l})$$

where N_f = Fertilizer, N_w = farm waste, N_{at} = atmospheric fixation, N_{om} = OM mineralization, N_{lg} = legume fixation, N_{ex} = crop export, N_v = volatilization, N_d = denitrification, N_{of} = runoff and N_l = leaching

where the bold fractions represent key components of the cycle.

The main sources of N used in agriculture come from: inorganic fertilizers, OM and atmospheric N fixed by legumes and animal excreta (dung and urine). Fertilizer, as a source of N (inorganic) comes in various forms. The most commonly used inorganic fertilizer is urea, with monoammonium phosphate (MAP), diammonium phosphate (DAP), ammonium sulfate and ammonium nitrate used less commonly. The choice of the type of N fertilizer is not

without consequence, because of their variation in cost and the potential to generate soil acidity and salinity. Once urea fertilizer is applied, it undergoes a series of transformations in the soil, being converted into ammonia, nitrite and lastly nitrate. Ammonium can be temporally adsorbed onto clay minerals until nitrification is completed (Inglett 1970) increasing the soil's CEC and may range up to 10% of total N in the soil (Foth and Ellis 1997)
.

2.3.2.2.1.2. Organic matter N

The N present in OM (plant material, and deceased animals) is decomposed into nitrate (mineralization) by bacteria. The degree of mineralization of OM in the soil is indicated by C: N ratio. A satisfactory level of soil OM content ranges from 2 to 4% for most soil types. A proportion of mineralized N will be immobilized by micro-organisms for their own use (multiplication) and later released for plant growth (Jenkins and Lines-Kelly 2003) and this is part of the N cycle.

2.3.2.2.1.3. Legumes and nitrogen fixation

Another way of introducing N into the soil is by legumes fixing atmospheric N through a symbiotic relationship with rhizobia located on the roots of the plant in nodules (Fulkerson and Lowe 2002b). According to Bellows (2001), atmospheric N fixed by the plants contributes between 112-190 kg N /ha /yr, of which 20-40% is immediately available for current grass growth, the rest is progressively released for the next crop. However, the rate of fixation varies greatly depending on soil temperature, plant species, soil pH, soil fertility (particularly NO_3 content) and type of rhizobia.

2.3.2.2.1.4. Nitrogen pathways in the soil

The transformations that N undergoes in the soil is governed by physical, chemical, biological and climatic conditions and also known as the “N Cycle”, and are summarized by Equation 2.7 and Figure 2.10:

Equation 2-7 Nitrogen pathways

Soil N = $N_f + N_{lg} + N_{om} + N_{at} - (N_d + N_{ex} + N_{ex} + N_{of} + N_l)$

where N_f = Fertilizer, N_{lg} = legume fixation, N_{om} = OM mineralization, N_{at} = atmospheric fixation, N_d = denitrification, N_{ex} = crop export, N_v = volatilization, N_{of} = runoff and N_l = leaching

The pathways that N takes in the soil is summarized in Figure 2.10:

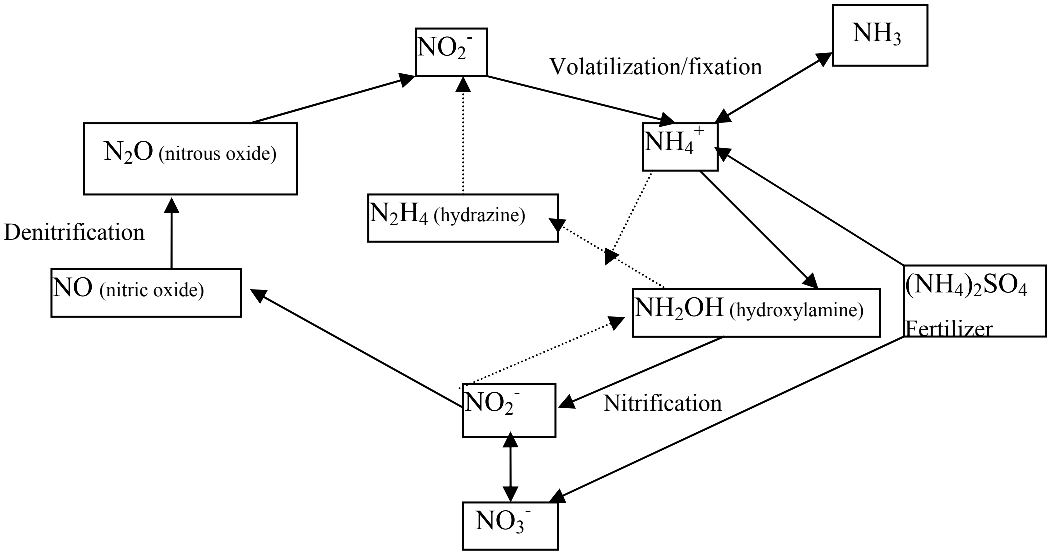


Figure 2-10 Possible pathways for N components in the soil (Dunne et al., 2005).

Denitrification is the reaction converting nitrates in an anaerobic phase into gaseous N (N_2O/N_2). Denitrification is affected by soil type, water content and temperature (Foth and Ellis 1997). The losses of N through denitrification/volatilization from applied fertilizers can reach 21% (Egginton and Smith 1986) and over 50% from urine patches (Fulkerson and Lowe, 2002b), particularly when the soil is wet after a long period of dry, and from wetlands

(Dunne *et al.* 2005), especially in summer (Sahrawat and Keeney 1986). There is also a complex aerobic denitrification process (see Equation 2.8) the effect of which is difficult to measure.

Equation 2-8 N denitrification

$NO_3^- \dashleftarrow\dashrightarrow NO_2^- + \frac{1}{2} O_2 \longrightarrow \frac{1}{2} N_2^- + O_2$

Ammonification occurs naturally when atmospheric N is fixed through lightning or legumes. The rate of N fixation in the latter is greater when soil conditions are favorable for the microbial activity (moisture, temperature and availability of organic residues). Nitrogen fixation by lightning and legumes may be important in some situations but is very difficult to measure.

Nitrification is biological oxidation which transforms ammonium into nitrate by bacteria. The first step is carried out by nitrosomonase bacteria which produce sequentially hydrazine, hydroxalamine, N, hyponitrous oxide, nitric oxide, nitrous acid and nitrogen dioxide. Then nitrobacter bacteria convert nitrogen dioxide into nitrate by secondary oxidation (Inam-ul-Haque and Jakhro 1996) as summarized in Equation 2.9.

Equation 2-9 N nitrification

$NH_4^+ + O_2 \longrightarrow NO_2^- + O_2 \longrightarrow NO_3^-$

Nitrification is the principal cause of N loss in agriculture when the rate of nitrification e.g. of urea, is greater than plant uptake. To reduce this, slow release N fertilizers (see Table 2.6) can be used as well as nitrification inhibitors, such as dicyandiamide (Di and Cameron 2004).

Mineralization is the transformation of organic N into a variety of other forms including NH_4^+, NH_3, NO, N_2O and atmospheric N_2. This reaction can also happen when the soil is over supplied with nitrates, or when the plants have low N uptake (low plant density or slow plant growth) relative to N availability. This can be minimized by appropriate timing of N fertilizer application when there are high rates of OM decomposition e.g. autumn after a dry summer. Substantial amounts of OM are mineralized every year with peak activity in summer (high soil temperatures and moisture). Its contribution has been estimated to be 20-120 kg N/ha /yr (Fulkerson and Lowe 2002a) and should be part of annual N calculations (Frank and Roeth 1996). Frank and Roeth (1996) have proposed the following model for N contributions to maize growth (Equation 2.10).

Equation 2-10 OM N contribution for maize

$$N_{rec} = 39.2 + (0.02141 \text{ x } EY) – (8.96 \text{ x } NO_3\text{-}N) – (0.00025\text{x } EY \text{ x } SOM) – \text{Other N credits}$$

Where N_{rec} = fertilizer N recommendation in kg/ha; EY= expected yield kg DM/ha, NO_3-N = average NO_3-N in root zone to depth of 46 cm or greater (mg/ kg), SOM = soil organic matter in the top soil (g/ kg); other credit = legume or NO_3-N irrigation water.

Thus, the N cycle in the soil is a very complex process depending on climatic, microbial and soil conditions as summarized (Figure 2.10).

Nitrogen Losses Leaching of N from fertilized pasture, and clover-based pasture (Ruz-Jerez *et al.* 1995) occurs when N (as nitrate) moves below the plants root zone, causing ground water pollution. Understanding the dynamics of NO_3 formation and movement in the soil will help to reduce leaching effects (Gasser *et al.* 2002). Generally, the lysimeter is used to assess nutrient leaching (Bredemeier *et al.* 1990), which is higher in sandy soils than clayey soil. Leaching from excreta (urine patches) and fertilizer usually becomes more significant in winter when plant growth is slow (Powlson 1993). Overall, the total N loss (denitrification, volatilization and leaching) can reach 20-50% for cereal (Francis, *et al.* 1993, Wienhold *et al.* 1995, Karlen *et al.* 1996). To optimize NUE on dairy pastures, targeted fertilizer application should be practiced, or alternatively the use of waste water (see above) can be used in irrigation especially during the periods of fast pasture growth (Landman 1990). Substantial N is also lost through fertilizer and excreta when excessive irrigation is applied. Thus poor irrigation and fertilizer management may increase both N loss through leaching and runoff (Qian *et al.* 1997).

2.3.2.2.1.5. Soil and plant nitrate content

Under intensive pasture management, N is typically the first limiting nutrient for plant growth. Correct N management is essential to ensure NUE and environmental safety (Barnes *et al.* 2003). Agronomists like to see N levels in soil above 10 mg /kg (Reid 2004) for pasture land. Available N in the soil for plant nutrients comes from OM which constitutes 95%, the reserves that are gradually released by mineralization. In this review, only the major forms of N (NO_3^- and NH_4^+) in the N balance will be discussed. Optimum soil N content depends on the type of activity (crop or fallow, fertilizers' history) and species (legume or not), but Barnes (2003) gives some estimates in Table 2.8.

Table 2-8 Average concentration of nutrient in soil (Barnes *et al.* 2003)

Element	Absorption form by plant	Average in soil (mg/kg)
Nitrogen	NO_3^-, NH_4^+	1-50*
Potassium	K^+	50-200
Calcium	Ca^{2+}	500-8000
Phosphorus	$H_2PO_4^-$, HPO_4^{2-}	2-100
Magnesium	Mg^{2+}	0-1000

* For nitrate form only

Plant N content is variable and depends on plant species, stage of growth and plant part. Keeping the nitrate level within a satisfactory range is beneficial to plant growth. Young grass shoots contain high levels of N (Reuter and Robinson 1986) compared to older leaves. Plants will take up N to luxurious amount if available in the soil, but this should be avoided to reduce health problems for livestock (nitrate toxicity).

2.3.2.2.1.6. Strategies to improve N use efficiency for plants

The application of N in agriculture should be based on the plant growth requirements in order to achieve sustainable dairy farming with minimal environmental impacts. Several strategies have to be considered to maximize N use efficiency including the most appropriate form of fertilizer.

Table 2-9 Characteristics of nitrogen fertilizers (Swift 1995).

Fertilizer	Analysis	Source of N	Moisture dependence for availability	Response at low temperature	Residual N activity	Salt index (per N unit)	Leaching potential
			Rapidly available				
Ammonium-nitrate	33-0-0	Ammonium nitrate	Minimal	Rapid	4-6 wks	3.2	High
Ammonium-sulfate	21-0-0	Ammonium sulfate	Minimal	Rapid	4-6 wks	3.3	High
Ammonium-phosphate	18-46-0	Di-ammonium phosphate	Minimal	Rapid	4-6 wks	1.6	High
Urea	46-0-0	Urea	Minimal	Rapid	4-6 wks	1.6	Moderate
			Slow release				
Sulfur-coated urea	22/38 %	Urea	Moderate	Moderately rapid	10-15 wks	Not applicable	Low
ONCE	24/24%	Urea nitrate, Ammonium nitrate	Moderate	Moderately rapid	15-38 wks	Not applicable	Low
			Available				
IBDU	31-0-0	Isobutylidine diurea	High	Moderately rapid	10-16 wks	0.2	low
Nitroform	38-0-0	Ureaformaldehyde	High	Slow	10-30 wks	0.3	Very low
Nutralene	40-0-0	Methylene ureas	Moderate	Medium	7-12 wks	Not applicable	low
Methylene urea	39-0-0	Methylene ureas	Moderate	Medium	7-9 wks	0.7	low
Coron	28-0-0	Urea/methylene ureas	Minimal	Moderately rapid	7-9 wks	Not applicable	moderate

Table 2.9 summarizes the types of N fertilizer available and their properties which relate to NUE. Choosing slow release N fertilizers (Swift 1995) with low salt index, can be financially beneficial and environmentally friendly. The IBDU (isobutylidine di-urea) or nitroform listed in Table 2.9 is used on rice crops and fits both criteria of slow release and low losses (runoff, denitrification and leaching). It can be easily reduced while optimizing plant nutrient uptake.

Optimizing NUE is impossible if there are critical limitations on the availability of other nutrients. In addition, the use of species that have high NH_4^+ absorption capacity will contribute to reduce losses, e.g. wheat can absorb more than 35% of its N needs as NH_4^+ from fertilizer containing 25% NH_4^+ (Raun and Johnson 1999). Another possibility is to choose (for equal yield) species or cultivars with high N use efficiency such as maize, or alternatively use crop rotations which include legumes (Reidell *et al.* 1998). Animal excreta can be a substantial source of N and can be effective if optimal grazing management practices are adopted which ensure more uniform distribution of N over the farm.

2.3.2.2.1.7. Conclusion

Nitrogen is the first limiting factor in agricultural production and the most complicated nutrient to manage due to the multiple forms that this element can take in the N-cycle. Under field conditions, the best way to minimize N losses (volatilization and leaching) and increase NUE is to use plant species which can absorb a greater proportion of their uptake as NH_4^+ rather than NO_3^-, while enhancing microbial activity vital to N mineralization from OM. Also, the plant should have a well developed root system to maximize N uptake. Nitrogen use efficiency can also be improved by monitoring soil N. The establishment of an N balance is generally assessed from easy measurable components and then estimating the ones that are more difficult to measure (gas exchange and mineralization).

2.3.2.2.2. The phosphorus cycle in dairy

In Australian soils, P is as likely to limit plant production as N. Phosphorus plays an important role in seed and fruit formation and in the development and strength of root structure, leading to better plant growth and increased drought tolerance. It is used in the genetic coding system (nucleic acid synthesis) and in energy transfer as adenosine triphosphate in cells. Phosphorus also intervenes in mitochondria formation, which powers the cell. Phosphorus contributes to the plant's disease resistance and is often a limiting factor involved in plant growth (Speir and Cowling 1991). The cycling of P on a dairy farm is complex, due to its reactions with other soil components. The P cycle is summarized in Figure 2.11 and by Equation 2.11

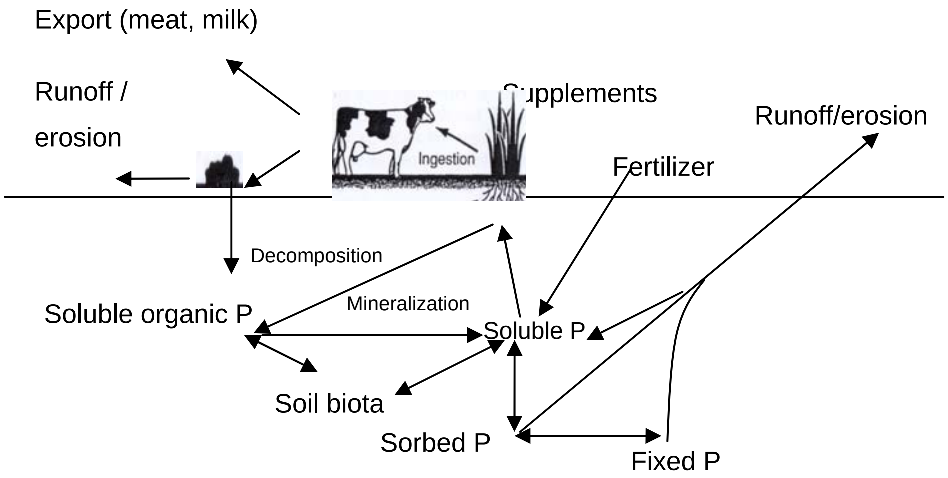


Figure 2-11 Phosphorus cycle in a dairy pasture (modified from Mathews *et al* 1998).

Equation 2-11 Phosphorus cycle in dairy

$$\textbf{Soluble soil P} = \mathbf{P_f} + \mathbf{P_{om}} + \mathbf{P_s} - (\mathbf{P_{ex}} + \mathbf{P_{of}} + P_l + \mathbf{P_{sf}})$$

Where P_f = Fertilizer, P_{om} = organic matter, P_s = soil release, P_{ex} = product exported + P_{of} = runoff, P_l = leaching and P_{sf} = soil fixation

2.3.2.2.2.1. Phosphorus chemistry in the soil

The P cycle is governed by complex chemical reactions affecting its solubility. In the soil, total P comprises organic P (Po) and inorganic P (Pi). In the P cycle, it is important to consider Po (from OM mineralization) which is can constitute up 50% of the P in some arable soils (Mattingly and Chater 1982). In moist soils, P moves by diffusion, making it vulnerable to loss through soil surface runoff. Phosphorus is present in three pools: soluble (ortho-phosphates), sorbed (reactive pool) and stable. At low pH, the soluble P is bound to Fe and Al ions, but when the soil is alkaline, P is bound to Ca and Mg ions. Keeping soluble P at adequate levels will avoid its intensive use through fertilization. Phosphorus fixation is the major concern in the cycle and could constitute 17-50% of soil P (Gil-Sotre *et al.* 2002). The capacity of the soil to retain P depends on clay type, OM content, and soil moisture and microbial status. Soil P levels can be related to the type of parent rock, with Histosol, Mollisol and Ultisol being rich in P (Gil-Sotre *et al.* 2002). In these soils, substantial amounts of P may be released through weathering (Mathews *et al.* 1994).

2.3.2.2.2.2. Sources of P on a dairy farm

The main source of inorganic P in agriculture is supplied by through the application of fertilizers, the characteristics of which are summarized in the Table 2.10. Shortly after P fertilizer is applied to soil, Pi starts progressively binding to soil and can become totally unavailable at the end of the crop cycle. During this time, available Po (from OM decomposition) will represent the available P and is the largest components of available P (Chaplin *et al.* 1978; Walbridge 1991), so it is critical to take account of Po when calculating annual P requirements.

Table 2-10 Phosphorus content in fertilizer (Mylavarapu *et al.* 2006).

	Chemical formula	Analysis (NPK)	Management factors
Ammonium	$NH_4H_2PO_4$ +	10-34-0	N improves P
Polyphosphate	$(NH_4)_3HP_2O_7$	15-62-0	solubility
Diammonium phosphate	$(NH_4)\ H_2PO_4$	18-46-0	Alkaline pH
Monoammonium phosphate	$(NH_4)_2HPO_4$	11-48-0	Acid pH
Superphosphate	$Ca(H_2PO_4)_2$ /Ca SO_4	0-20-0	Low solubility
Rock phosphate	$Ca_3(PO_4)_2CaF_2$	0-34-0	Low solubility
Triple superphosphate	$Ca(H_2PO_4)_2$	0-46-0	Available as per analysis

*NPK: Nitrogen, phosphorus and potassium

2.3.2.2.2.3. Role of soils microorganisms in the transformation of P

Biological P transformation influences the P content of the soil (Steward and McKercher 1982) by playing a direct and indirect role in P immobilization, mineralization and redistribution (Steward and Tiessen 1987). The contribution of each of these activities is not clearly distinguishable and difficult to isolate. Several studies (Magid and Nielsen 1991; MCF 1993; Saunders and Metson 1971) have observed a seasonal peak in P availability which can be attributed to weather conditions (soil temperature and moisture) but may also be due to microbial activity (Hanes *et al.* 2001; Harrison and Pearce 1979). The action of phosphatases from microorganisms (e.g. symbiosis between mychorrizae and plants) gradually dissolves and releases esters of P into the soluble pool (Mathews *et al.* 1994; Walbridge *et al.* 1991). Gil-Sotre *et al.*, (2002) found a strong correlation between phosphatase concentration, microbial activity and soluble P in the soil. Among these phosphatases, Speir and Ross (1978) identified phosphamonoesterases as being primarily responsible for P release from the bound form. This release mechanism can be a source of unexpected and substantial P into the cycle and can therefore modify the P balance in the soil. It has also been reported that sorghum grew faster when it was grown on land previously growing pigeon pea (Ae *et al.* 1990) with the pea presumed to be responsible for the release of organic acids from the pea roots which released the bound P. As all these mechanisms release soluble P, P use efficiency could be increased by creating conditions that favour these mechanisms.

2.3.2.2.2.4. *Phosphorus losses from dairy farms*

Another P input into the P budget comes from supplementary stock feeds brought onto the farm. Concentrate feed may be high in P due to inaccurate estimation of P needs for cows (Powell *et al.* 1998), or due to low costs of high P feed ingredients. For example, of the 1.5 t concentrate/ cow fed annually, 66% (see Table 2.11) of the ingested P was excreted in the faeces and 26% was removed in the milk (Wheller *et al.* 1987). Accurate allocation and formulation of feed may reduce P concentration in animal excreta, therefore reducing potential P loss without compromising milk yield (Ebeling *et al.* 2002).

Table 2-11 Nitrogen, phosphorus and potassium (%) in the faeces, urine and milk from a typical dairy cow (Pearson and Ison 1997).

Nutrient	Faeces	Urine	Milk	Retained by cow
N	26	53	17	4
P	66	0	26	8
K	11	81	5	3

In the paddock, runoff of soluble P is the main source of P loss on dairy farms in contrast to P loss in particulate form in bare soil (Dougherty *et al.* 2008). Hopkins (1999) found that water in effluent ponds on dairy farms contained up to 31 mg P /L. The loss of P through runoff is accentuated if P fertilizer is applied shortly before irrigation or heavy rainfall events. Bush and Austin (2001) and Dougherty (2004) recorded a considerable decrease of P loss when pastures were irrigated more than three days after P application. Heavy applications of manure can also lead to high levels of P loss (Sharpley *et al.* 2003; Vervoot *et al.* 1998). Phosphorus loss through runoff can be minimized by its direct incorporation into the soil (ploughing). However, the ability of P to be leached can be temporarily reduced if soil P is bound to Ca, Fe and Al (Gil-Sotre *et al.* 2002) and this can be increased by adjusting soil pH. Plant density and herbage cover play important roles in increasing P loss from runoff (Dougherty *et al.* 2008; Mathews *et al.* 1994). Phosphorus can be subjected to considerable loss in sandy soils.

2.3.2.2.2.5. Conclusion

The P cycle in the soil is complex, due to the multitude of pools in which P is present. Phosphorus availability and balance for a crop can be largely affected by the bound forms. Phosphorus buffering capacity changes with pH, OM and mineralization and so may change from one season to the next. In addition to P cycling in the soil, a full assessment of the biological factors that modify soluble P in the soil will help to refine the possible pathways of P in the soil. This can be done in 2 ways; firstly, to assess total P, but this would be of limited use, as total P is poorly related to available P, and secondary, to assess available P during the crop cycle.

To optimize P use efficiency, storage P can be made more accessible by improving conditions which induce its release, such as mineralization and enzymatic processes e.g. raising the pH. But the best way to increase P use efficiency by crops is to apply an accurate amount of P fertilizer based on annual soil and foliar tests, by monitoring the P-budget.

2.3.2.2.3. Potassium cycle on the dairy farm

Potassium is the third major nutrient required for plant growth. It is characterized by greater solubility in water (mobility) than P. Potassium moves in the soil by slow diffusion. Potassium plays key role in the plant’s photosynthesis and respiratory processes. It is involved in protein synthesis, carbohydrate oxidation, regulation of the cells’ osmotic pressure, and plant resistance to disease and drought. Potassium status in some Australian soils is quite acceptable with few showing deficiency, but K is deficient in most coastal (dairy) soils with high rainfall (> 500 mm/ yr), due to K leaching (Moore 1970).

2.3.2.2.3.1. Potassium in the soil

Potassium is stored in the soil in 3 different forms (Malavolta 1985):

- ✓ <u>Readily exchangeable K</u> is also gradually available to plants, with rate of availability depending on soil OM and clay content.

- ✓ Non-exchangeable K is mainly trapped within the clay minerals and organic compounds. It released through weathering into the readily exchangeable pool.
- ✓ Matrix or lattice K represents primary K in the rock (feldspars and micas), where weathering can gradually release K into the available K pool.

Commonly, exchangeable K represents the sum of soluble and readily exchangeable K. Exchangeable K, non-exchangeable K and matrix K represent respectively, 2% and 10% and 88% of soil K

The K budget on a dairy farm can be summarized by Equation 2.12:

Equation 2-12 Potassium cycle in dairy

$$\textbf{Soluble soil K} = \mathbf{K_f} + \mathbf{K_u} + K_{om} + K_{sr} + \mathbf{K_i} - (\mathbf{K_{ex}} + \mathbf{K_{of}} + \mathbf{K_l} + K_{sf})$$

where K_f = Fertilizer, K_u = urine K, K_{om} = organic matter (manure), K_{sr} = soil release, K_i = irrigation water, K_{ex} = product exported + K_{of} = runoff, K_l = leaching and K_{sf} = soil fixation and bold items indicate a major contribution.

In the following section, K balance in the soil and its sustainability in dairy production systems is review.

2.3.2.2.3.2. Sources of potassium on a dairy farm

Potassium fertilizers remain the largest source of K supply to the dairy farm for pasture production. Potassium is the second largest amendment applied to soil and plays an important role in soil ECEC. Potassium chloride or Muriate (KCl) is the most common K fertilizer used and it has the highest solubility in water (Eatock 1985). High levels of use of this K fertilizer may cause the build up of chlorides in the soil profile and increase salinity. Other K fertilizers are also used as indicated in the Table 2.12, including potassium sulfate (K_2SO_4). The K in various K fertilizers is shown in Table 2.12.

Table 2-12 Proportion (%) of minerals in various potassium based-fertilizers (Mylavarapu *et al.* 2006)

Fertilizer	Mix (NPK)	Formula	Solubility in water
Muriate of potash	0-0-60	KCl	100
Potassium sulfate	0-0-22	K_2SO_4	43
Potassium / magnesium sulfate	13-0-44	$K_2/MgSO_4$	74
Potassium nitrate	0-0-50	KNO_3	46

The second major source of K on dairy farms is from excreta produced by the cow and the level is related to diet (Beetz 2002). On a predominantly grazed pasture diet, 81% of the K ingested is excreted in urine (Pearson and Ison 1997). The urine patches are highly concentrated in K and accumulate in stock camps, troughs, shade and laneways. Potassium in urine is 50 to 90% more efficient than K in fertilizers because it can last for up to two years in the soil (Cherney and Cherney 1998). This illustrates the importance of managing urine distribution through appropriate grazing management (see under N cycling). The liquid effluent waste from dairies is also a good source of K and can be recycled onto pasture as irrigation water.

Cattle manure (slurry) is also a good source of K, with 11% being K. The K secreted in manure or OM is released gradually into the soil solution through mineralization. Soluble K can also attach to colloidal complex structures enhancing soil ECEC.

Potassium can also be slowly released from weathering of parent rock, but this can be negligible in relation to the total annual K input on a highly productive dairy farm.

Irrigation water can be a significant source of K, depending on the water source (river, dam etc), and the surrounding level of agriculture. Generally, water from upper to down stream of the river (Dunne and Luna 1978) can carry substantial amounts of nutrients originating from runoff from upstream. In the South West of Western Australia, high K concentrations (420 mg /L) have been recorded in dairy pond water (Hopkins 1999). This may become a serious concern during drought periods when river and pond water are used for irrigation.

2.3.2.2.3.3. Potassium in the soil in dairy farm

Potassium is abundant in the top 15 cm of soil where the majority (70-80%) of K moves by diffusion and mass flow (Malavolta 1985). The minimum exchangeable K in the soil to support plant growth is estimated to be 50-200 mg/kg (Table 2.8), but this depends on the crop, and OM content. Like P, equilibrium is reached between the soluble and exchangeable pools. Soil capacity to buffer K varies with type of clay (ECEC) and is weak for kaolinite (oxisols) and strong for vermiculite (Foth and Ellis 1997).

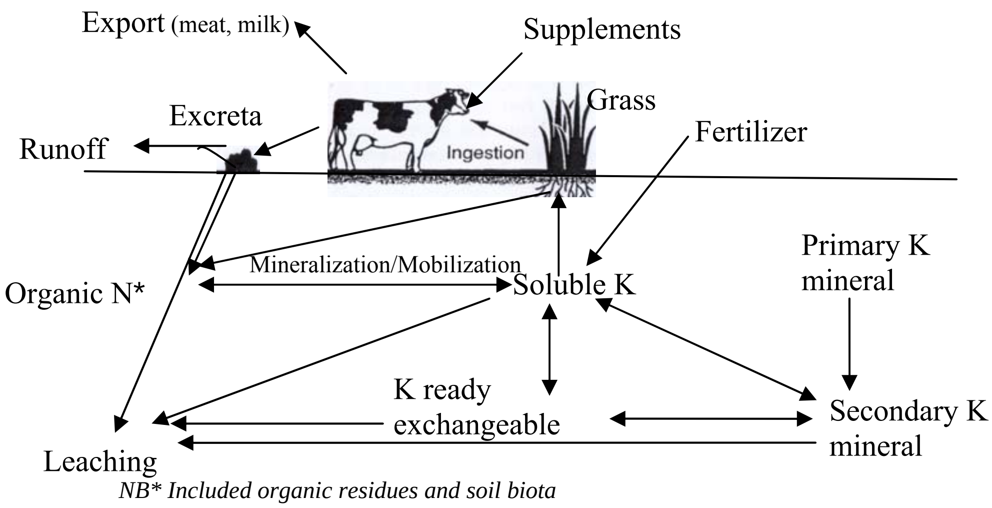


Figure 2-12 Potassium cycle in a dairy pasture (modified from Cherney *et al.* 1998).

Excess K from fertilizers immediately increases the available pool and luxurious K uptake by grass. Split application of K fertilizer in appropriate timing could avoid the high concentration of K in grass (Cherney and Cherney 2005). Also, the contribution of K by OM mineralisation can also increase periodic K availability and possibly induce luxurious grass uptake and should be considered in the inorganic K fertilizer **estimation (Figure 2.12).** Also, some soil rich in K can release substantial K to replenish soil soluble K from non-exchangeable pool under cropping conditions (Marta *et al.* 2004; Nebies *et al.* 1993). Potassium movement is restricted in dry soils and reduces plant capacity to take up K (Cherney and Cherney 1998).

2.3.2.2.3.4. Potassium losses

Like other soil nutrients, K is subjected to losses (leaching and runoff) from the soil, especially from animal manure (Alfaro *et al.* 2004a). Soil properties seem to play important roles in these losses (clay minerals). Clay with a high ECEC fixes more K (Foth and Ellis 1997), therefore K losses are relatively low. In soils with a poor microbial activity, excess K may not be able to be immobilized, resulting to more K loss. Heavy clay soils and increased water flow (from severe rainfall events) increase K loss from runoff (Alfaro *et al.* 2004b). Excessive NH_4^+ in the soil may also displace K in soil complexes (Johnson *et al.* 1985), hence the need to apply the correct amount of fertilizer (Dobb and Thompson 1985) and work on a NH_4^+/K ratio of 2/1 in the soil.

2.3.2.2.3.5. Conclusion

The mechanism that leads to K loss in the soil has not been investigated as widely as N. Frequent application of K and improving water management (on and in the soil) is a key means of minimizing losses (Johnston and Goulding 1992). In despite of such uncertainty, K uptake by plants seems to be better in grasses than for arable cropping systems (Pearson and Ison 1997), especially when N availability is sufficient (Bolton *et al.* 1970). The mineralization of OM can be supplemental sources of K in active soils when crop residues are not removed. Potassium demand varies from time to time depending on crop performance, weather, and microbial status. Limiting the possibility of competition between NH_4^+ and K is crucial, without compromising plant N and K uptake, and avoiding luxurious K uptake. Once again, gradual fertilizer (N and K) applications are necessary to avoid their losses. Potassium balance on dairy farms is the main focus of reducing nutrient load in waste water even if K negative effect on the ecosystem is not actually a major problem in comparison to N and P, but could be economically significant for dairy farmers.

2.3.2.3. Physical characteristics of soil and fertility

Soil is the main support for all kinds of life, therefore we need to conserve or improve its fertility in order to sustain production and ecosystem dynamism. Several criteria, such as the biological activities and chemical properties of soils have been used to assess soil fertility, but physical properties also play an important role in defining soil productivity and fertility (Foth and Ellis 1988). Decreasing physical fertility has a direct impact on nutrient availability of arable soils by increasing its risk of soil degradation (water and wind) which may lead to its agronomic decline. Soil physical properties such as soil bulk density, infiltration rate, texture, depth of top soil and water holding capacity are vital to soil performance (Table 2.13).

Table 2-13 Proposed minimum data set of soil physical indicator for screening the condition and health of soil (Lal (1999).

Physical indicators of soil condition	Relationship to soil condition and function; rational as a priority measurement
Texture	Retention and transport of water and chemicals, need for many process models; estimate of degree of erosion and field variability of soil type
Depth of soil, top soil and rooting	Estimate of productivity potential and erosion, normalizes landscape and geographic variable
Soil bulk density and infiltration	Indicator of compaction and potential for leaching, productivity and erosivity; density needed to adjust soil analyses to field volume basis
Water-holding capacity	Related to water retention and erosivity; available water can be calculated from soil bulk density, texture and soil organic matter

2.3.2.3.1. Texture and soil water storage capacity

Soil texture is defined as the proportion of clay, silt, sand and coarse sand (Tagar and Bhatti 1996). It also indicates available pore space for water, air and root penetration in the soil. The proportion of air in the soil depends on pores (created by soil particles), bioactivity and OM. The more porous the soil, the faster water infiltrates and the easier it is for roots to penetrate. Clay soil has smaller and lower infiltration rates and therefore stores less water available for plant absorption, exposing more of the applied water (after intense rainfall events and or irrigation) to runoff. During intense rainfall events, low infiltration rates induce runoff and therefore nutrient and soil loss. Such soils will also be subjected to water erosion by causing surface degradation (loss of top soil) and formation of gullies. As a consequence, potential nutrient cycling in the soil will be compromised, and water storage diminished. In contrast, in sandy soil, with high soil permeability, water accessibility by plants is easier, but the water drains quickly due to the high infiltration rate, thus reducing nutrient use efficiency. A balanced soil with adequate OM content, dynamic microbial activity and good vegetative cover will maximize soil fertility and grass production.

2.3.2.3.2. Depth of the top soil and soil fertility

The depth of top-soil depends on parent material, weathering processes and the system of agriculture practiced. Top-soil is the layer of the soil profile that hosts most functional parts of the soil governing soil fertility and its components (biology, chemistry and hydrology). Larney *et al.,* (2000) showed that the removal of 20 cm of the topsoil, reduced wheat (*Triticum aestivum*) yield by 53%. Deep topsoil stores more nutrients down its profile and can be explored by roots for better nutrient absorption and hence better NUE. The depth of topsoil plays an important role in plant growth and needs to be improved by agricultural practice such as by increasing soil OM, and less soil disturbance to minimize erosion and microbial activity, resulting better NUE.

2.3.2.3.3. Bulk density and infiltration

Soil bulk density (BD), is often used as an indicator of soil fertility, reflecting the change in soil properties such OM accumulation and infiltration rate that accompany compaction. In this regard, BD has been successfully correlated to key soil functions such as soil water profile (infiltration, soil holding capacity and wilting point) (Franzliebbers 2002). This confirms once again the important role that OM plays in soil fertility, and therefore nutrient balance. Less soil disturbance helps to build up soil structure through improvement in soil porosity necessary for root penetration, and the movement of air and water. Infiltration is the essential feature that controls runoff, leaching and water availability for the plant (Franzliebbers 2002). Soil compaction (machineries and animals) produces reverse effects, destroying soil structure (Lowery *et al.* 1996). The decrease in OM by erosion, impacts negatively on water infiltration thus increasing runoff and leaching.

2.3.2.3.4. Soil erosion

Soil formation naturally occurs at an extremely slow rate from 0.0025 to 0.1mm / yr or 0.3 to 1.3 t /ha /yr (Raman 2006). Compare to this the speed of erosion which degrades agricultural land only moderately in the United States of America and in Europe with 17 t / ha/ yr and in severe cases in Asia at 30-40 t /ha /yr (Zhang and Wang 2006). The loss of the top few cm of soil, which hosts most of the OM and nutrients, has a negative impact on nutrient cycling, and microbial activity that govern soil water recharge (Kirchhof and Daniells 2001). Faced with the impossibility of completely stopping erosion, the soil must be managed to minimize soil erosion (Reeve and Brouwer 1992) and Table 2.14 gives some maximum acceptable values for erosion.

Table 2-14 Erosion rate (t/ ha/ yr.) target for different type of pastures (Reeve and Brouwer 1992).

Soil and fertility	Acceptable erosion rate (t /ha /yr)
Fertile soil with rooting depth exceeding 1.5 m	Less than 10
Fertile soil with rooting depth between 1 and 1.5 m	Less than 5
Fertile soil or infertile soils with rooting depth < 1 m	Less than 1

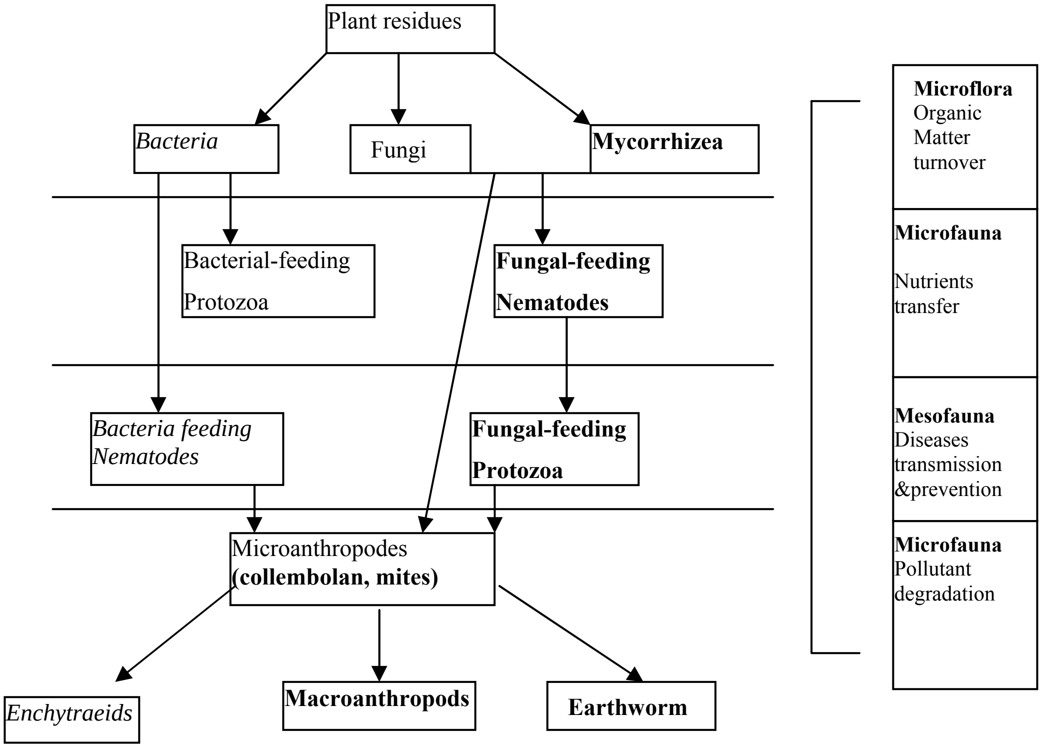
2.3.2.4. Biological properties and soil fertility

Soil micro, macro-fauna are important active soil components which have the ability to improve soil structure. The level of soil biota (SB) is strongly related to the carbon cycle and depends on the quality of soil OM. The soil biota colonize different stratus of the soil (3 -25 cm) (Farooq-e-Azam and Memon 1996) being most abundant in the organic horizons.

Microbial communities can be limited by specific management and the toxins (pesticides) used in agriculture. The ratio of N: C is usually used as a guide to soil biota status, but the level of specific enzymes such as fluorescein diacetate hydrolase (FDA) is a better indicator of microbial activity (Gillian and Duncan 2001).

2.3.2.4.1. Classification of soil biota

Soil biota are classified into 4 groups-micro-flora, micro-fauna, meso-fauna and macro-fauna (Hignett 1998) depending on their size, function and role in the soil. The capability of soil biota to establish in the soil depends on agricultural practices such as tillage and this is summarized in Figure 2.13:



NB: *Conventional tillage soil in Italic* and **No tillage soil in bold**

Figure 2-13 Different production systems alter the breakdown food-web for plant residues (Hignett 1998).

Macro-fauna (lumbricid, macroarthropodes etc) considered as the soil engines, they have a role of fragmenting the OM into small pieces that can be easily incorporated into the topsoil to improve soil texture (pores and aggregate stability) (Lavelle *et al.* 2003). The action of macro-fauna, combined with soil OM, can improve the soil physical properties such as water movement.

- Meso-fauna (Acari, nematodes, collembolan) are responsible for further fractioning of OM and hence mineralization. This group includes fungal predators, which regulate soil biota growth (in relation to reserves). In this way, the assessment of C: N ratio in OM indicates the stage of decomposition (soil OM quality) of OM and overall soil biota dynamism.

- Micro-fauna (protozoa). This class of micro-organisms constitutes the transition class between the micro-flora and the large size biota and contributes to OM mineralization and nutrient release. They regulate the proportion of bacteria and fungi.

- Micro-flora (bacteria, fungi and mycorrhyzae) directly improve nutrient flux in the soil (symbiotic action) and indirectly assist in fractioning and mineralization of OM. They have the capacity to turn organic residues into stable soil components which help soil structure.

2.3.2.4.2. Soil biota and their contribution to nutrient cycling

Soil biota are recognized as the platform for N, P, C and Ca cycling in the soil (Farooq-e-Azam and Memon 1996). They also contribute to the degradation of toxins and pollutants, such as pesticides. Specific enzymes such as urease and phosphatases convert and release N and P from organic sources. Optimum soil conditions for biotic activity and high OM content, will boost the soil's biodiversity and therefore the number and strength of microbial communities and will affect further nutrient release through the recycling process. Perucci (1992) found a correlation between enzyme activity, biomass-C, FDA, deaminase, protease and seasonal diversity for other enzymes such arylsulphatase), and phosphomonoesterase, due probably to the seasonal change of soil conditions (soil moisture, temperature and C content) (Uckan and Okur 2000). The OM content in soil is considered to be satisfactory when OC carbon ranges from 1 to 4% (Sparling 1992). This ratio tends to be greater under pasture because of the restricted physical disturbance.

2.3.2.4.3. Conclusion

This section has highlighted the role of soil biota in the cycling of OM and therefore in soil fertility, by replenishing nutrient pools improving soil stability (aggregates). Micro-organisms play important roles in regulating the fluxes and storage of soil nutrients that meet plant demands (mobilization/immobilization). They also recycle micro-nutrients which are absent in most fertilizers. Some soil biota are capable of improving soil fertility through aggregate stabilization, which increases water retention and inhibits natural and artificial toxins. The function of soil biota regulators sustain soil functions (physical, biological and chemical) in the whole system, and are indicative of fertility and soils ability to sustain crop growth. The exhaustive assessment of microbial activity is difficult, but measurements of enzymatic activity in the soil can be made. In the interest of sustainability, the conditions (temperature, pH, moisture, aeration, OM etc) which enhance soil biotic activity and diversity, should be primary considerations in soil management.

CHAPTER 3: METHODOLOGY

The current FutureDairy investigation of a new model of forage production uses maize as a bulk crop, forage rape as a break crop and clover to fix atmosphere nitrogen. Four consecutive cycles have yielded over the 40 t DM/ ha/ yr and has effectively doubled the yields possible under an optimally managed high input pasture system producing 20 t DM /ha /yr (utilized). However, the sustainability of such system is still not known, and it was the aim of this study to determine the impacts of the CFR on soil physical properties and major nutrient flows. The design of the study aims to compare soil and nutrient outcomes in the CFR system with current intensive forage production systems (PI), and with an extensive pasture system (PE) used as a control.

The objective of this study is to assess the major nutrient balances (nitrogen, phosphorus and potassium) in the CFR compared to pasture in order to determine their respective nutrient use efficiencies and likely sustainability in terms of local environmental impacts.

3.1. Hypothesis

To investigate the sustainability of the CFR systems compared to typical dairy pasture systems, the following hypothesis was used:

The CFR compares favourably with intensive pasture systems in terms of impacts on the major soil chemical, physical and biological properties and nutrient flow and has potential to significantly increase NUE and WUE in terms of forage yield.

3.2. Experimental approach

Nutrient/mineral balance studies provide valuable information on the amount of nutrient/mineral movement and their pathways on farm (Williams and Haynes 1991). Such studies also allow assessment of NUE and analyze the long-term sustainability and the environmental impact of farming systems (Fortune *et al.* 2001). The better understanding of nutrient/mineral flows can lead to improve management systems that minimize potentially harmful effects on the environment.

Intensive forage production systems require high rates of application of inorganic fertilizers and irrigation with the quantities dependent on the type of forage and its season of growth. In dairy pasture systems, several quantifiable sources of nutrient/ mineral input may be defined (see Equation 3.1).

Equation 3-1 Nutrient inputs for dairy pasture

Nutrient/ mineral input = $M_f + M_{ax} + M_i + M_{at} + M_{om}$

where M_f = inorganic fertilizer, M_{ax} = animal excreta, M_i = irrigation water, M_{at} = atmosphere fixation , M_{om} = mineralization of soil OM.

In the present study, inorganic fertilizers were applied at a rate of application designed to replace 100% of the P and K removed and 80 % of the N removed.

The contribution of animal excreta to nutrient return is inversely related to digestibility, therefore for dairy cows, the return varies from 20-34% of ingested nutrients (Aarons *et al.* 2004) and for sheep 35-81% (Wilkinson and Lowrey 1973). This input provides most of the organic fertilizer direct to the pasture where distribution (management techniques) and cow diet play important roles in its effectiveness as a source of plant nutrient. Mechanical harvesting of crops removes more nutrients from the paddock than direct grazing as there is no return of animal excreta.

Irrigation water is not a negligible source of nutrient input to pasture (Allan 1995) with the amount depending on the quality and quantity of water used.

The outputs of nutrients from the system relate to product removal (meat and milk), loss from the soil surface as runoff, soil fixation and/or deep drainage (see Equation 3.2), P sorption and (for N) also from volatilization.

Equation 3-2 Nutrient outputs for dairy pasture

Nutrient output= $M_{ex} + M_{of} + M_{l} + (N)\ M_{v} + M_{fx}$

where M_{ex} = export, M_{of} = runoff, M_{l} = deep drainage, (N) M_{v} = Volatilisation and M_{fx} = soil fixation

The extent of the non-productive losses (run off, deep drainage and N volatilization) relate to management practice, season, landscape (slope), crop coverage and timing of fertilizer application (in relation to water input), targeting the most soluble nutrients such as K, N and Na (Aarons *et al.* 2004). Nutrient losses through deep leaching are influenced by soil texture and also by timing of fertilizer application (plant uptake capacity) and water management.

In the context of dairy pastures, estimation of nutrient balances should take into account parameters which play key roles in the overall balance of nutrient movement. Those that make a substantial contribution but are difficult to quantify, were estimated from data provided in the literature. This is the case for N as it relates to unmeasured losses from volatilization, and gains from environment fixation and mineralization.

3.3. Location

This study was conducted over a 2 year period on 2 of the original 4 replicates forming part of the FutureDairy CFR forage project (Garcia 2007). The original project commenced in March 2004, with the sowing of the first forage rape crop at the Elizabeth McArthur Research Institute (EMAI). The study reported in this thesis covers the years 2006 and 2007. This experiment was conducted at the EMAI which is located at Camden, 55 km southwest of Sydney, New South Wales (latitude 34^{o} 06’ S, longitude 150^{o} 42’ E) (see Figure 3.1).

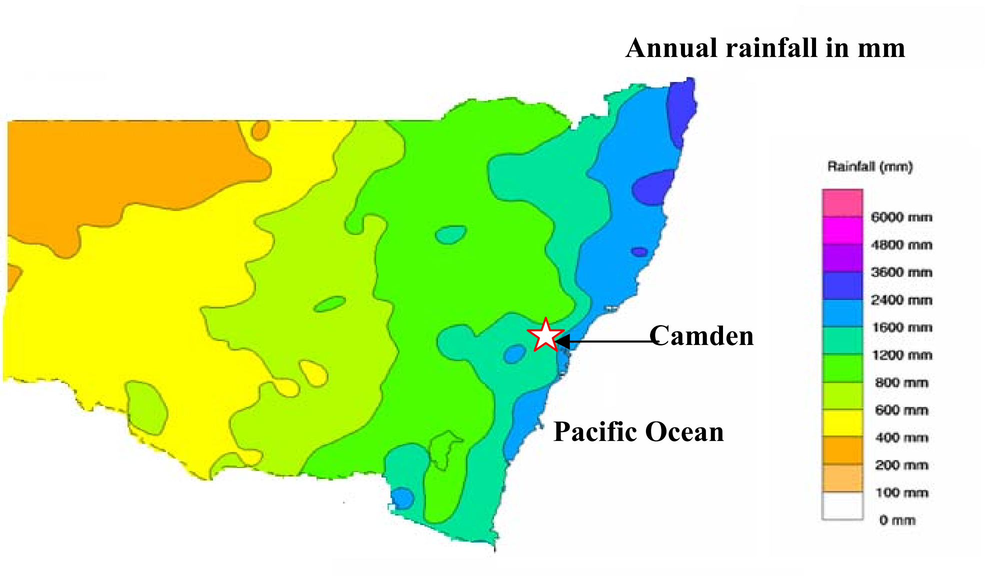


Figure 3-1 The location of Elizabeth Macarthur Agriculture Institute and annual rainfall for NSW

3.4. Climate

Climate along the South East Coast of Australia is governed by a low pressure belts which move from the Indian Ocean and cross the country from West to East. This movement generates a temperate climate on coastal NSW which is subdivided into hot-dry inland, highland and higher rainfall coastal climates, such as Camden. The climate at Camden is characterized by an average annual rainfall of 828 mm (see Figure 3.2) but reliability is low and hence irrigation is required to undertake dairy farming. The long term rainfall pattern (Figure 3.2) indicates a summer-autumn peak-associated with high temperatures (where the maximum daily temperature can exceed 40^{o} C). In contrast, in winter and spring the rainfall is low and so are temperatures, with a mean minimum in July, the coldest month of the year, of 5^{o} C (see Figure 3.2). However, drought has seen the rainfall as low as 465.5 mm in 2006. On average there are 18.5 (1943 to 2004) frost days/year.

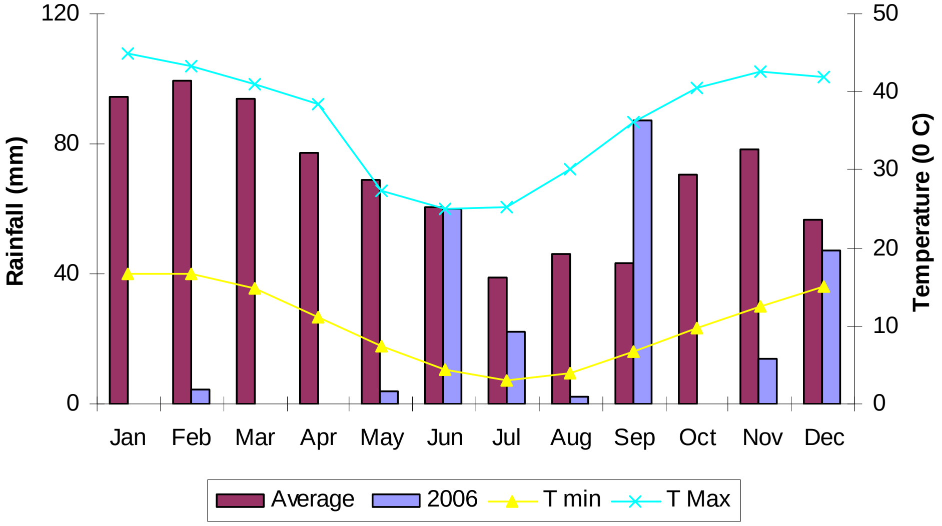


Figure 3-2 Mean long term monthly rainfall (🟪) annual minimum and maximum temperature (^{o}C) and actual rainfall (🟦) in 2006

3.5. Site history

To limit the residual effects of variations in past fertilizer use across the site, locations with similar soil nutrient status were selected based on soil tests. A bulk dressing of 600 kg of superphosphate /ha (or 54kg P/ha) was applied over the whole area at the commencement of the trial so that P availability would not limit forage growth in the CFR and PI plots.

3.6. Soil description

The 2 replicates were located on 2 different soil types. Replicate 1 was on a yellow duplex soil and Replicate 2 was on a dark cracking clay soil (Lawrie *et al.* 2004), located on sloping and flat landscapes, respectively. The depth of the top-soil was variable and ranged from less than 25 cm, for the duplex soil, to over 30 cm for the dark soil. Both soils were moderately acidic (see Table 3.1). The dark soil has higher clay content than the duplex soil (see Figure 3.2) and this is reflected in differences in the rate of infiltration of water (drainage), gaseous exchange and root penetration.

Table 3-1Characteristics of brown chromosol and black vertisol soil of the study site

	Soil characteristic	Chromosol (brown) soil	Vertisol (black) soil
In Topsoil (0-30 cm)	**pH $_{(CaCl2)}$**	5.7	5.5
	Electrical conductivity 1:5 (ds/m)	0.137	0.16
	Organic carbon (%)	2.13	3.13
	Colwell K (mg/kg)	153	213
	Colwell P (mg/kg)	31	55
	Total Nitrogen (%)	0.16	0.27
	Total P (mg/kg)	390	563
	Ca (cmol/kg)	7.03	13.3
	Mg (cmol/kg)	3.06	5.63
	K (cmol/kg)	0.23	0.33
	Na (cmol/kg)	7.33	13.3
	Al (cmol/kg)	0.5	0.67
	Bulk density (g/cm^3)	1.46	1.23
	Total porosity (%)	53	44
	Color	10YR2/1	7.5YR2/5
	Slope (%)	5-6	<0.5
	Particles size		
	Clay content (%)	30	39
	Silt content (%)	34	42
	Sand content (%)	28	15
	Coarse (%)	8	4
	Smectite (%)	17	32
Subsoil (31–100 cm)			
	Bulk density (g/cm^3)	1.39	1. 61
	pH $_{(CaCl2)}$	7.2 – 8.3	6.5 – 8.0
	Electrical conductivity 1:5 (ds /m)	0.47	0.21
	Clay (%)	>48	>53
	Macroporosity (%)	40	39

Figure 3-3 Cracking black soil on Replicate 2 (size of the cracking compared the ruler)

The proportion of smectite, the major clay mineral in the soil, is nearly twice as high in the dark soil as in the duplex soil and this explains its higher capacity to retain nutrients and to crack (see Table 3.1); therefore the dark soil is considered the more fertile. The sloping aspect of the duplex soils helps with surface drainage compared to the black soil site. The subsoil of both soil types has similar characteristics, with a rise in pH and clay content with soil depth while porosity decreases. This is reflected in a decrease in deep drainage and a decline in the ability of roots to explore the deeper soil profiles. The electrical conductivity is also higher in the subsoil than in the topsoil indicating a rise in salinity with soil depth.

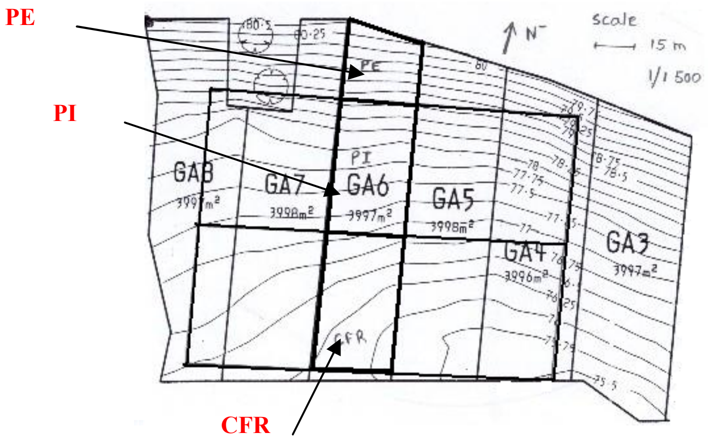
3.7. Experimental design

The experimental design is described in (Garcia *et al.* 2008). "The design was a complete randomized block design with four replicates (blocks) over two soil types and with two treatments. The soil types were yellow duplex soils on two of the blocks, I and II, and gradational on the other two blocks, III and IV.

There were two treatments. The intensive pasture control treatment (PI) represented a typical pasture system with a C4 grass (kikuyu grass, Penisetum clandestinum) in summer over-sown with a C3 grass (short-rotation ryegrass, L. multiflorum L. cv 'Surrey') in early autumn. The pasture was fertilized, irrigated and managed to maximize herbage production and utilization. The CFR treatment represented an intensive system with an annual sequence of forage crops grown in a rotational way and designed to complement the needs of the soil, plants and dairy cows. Initially, the rotation comprised three crops per year with a brassica (forage rape, Brassica napus L.) sown in late February–early March as a break crop; an annual legume [either Persian clover (T. resupinatum L.) broadcast sown after the first grazing of the forage rape or maple peas (Pisumsativum L., sown in early August); and maize (Zea mays L., a forage crop for silage) sown in early October and harvested in February." More detailed observations reported in the present study were conducted on blocks I and III only (see figure 3.4). An additional treatment (PE) was added on each block.

The CFR treatment included a 3 crop rotation (maize, Brassica rape and clover) in year 1 and 2 crop rotation (maize and clover) in year 2 due to increase in soil born diseases**.**

Replicate 1: Brown chromosol (block I of original layout)



Replicate 2: Black vertisol (block III of original layout)

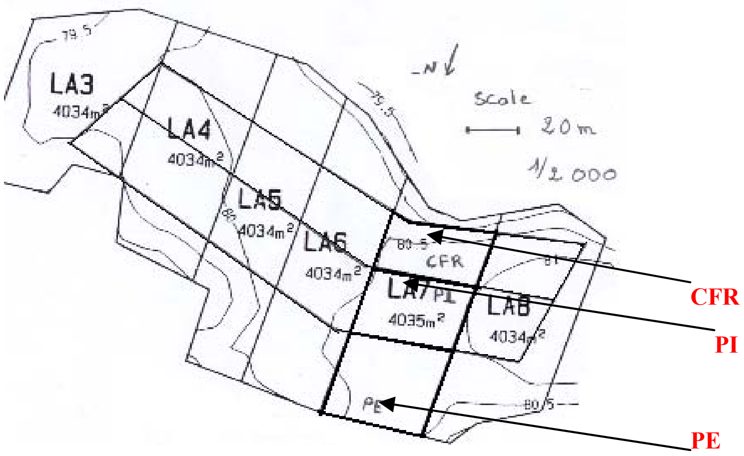


Figure 3-4 Location of treatments: Complementary Forage Rotation (CFR), intensively managed pasture system (PI), extensively managed pasture system (PE) and replicates.

3.8. Measurements and collection of samples

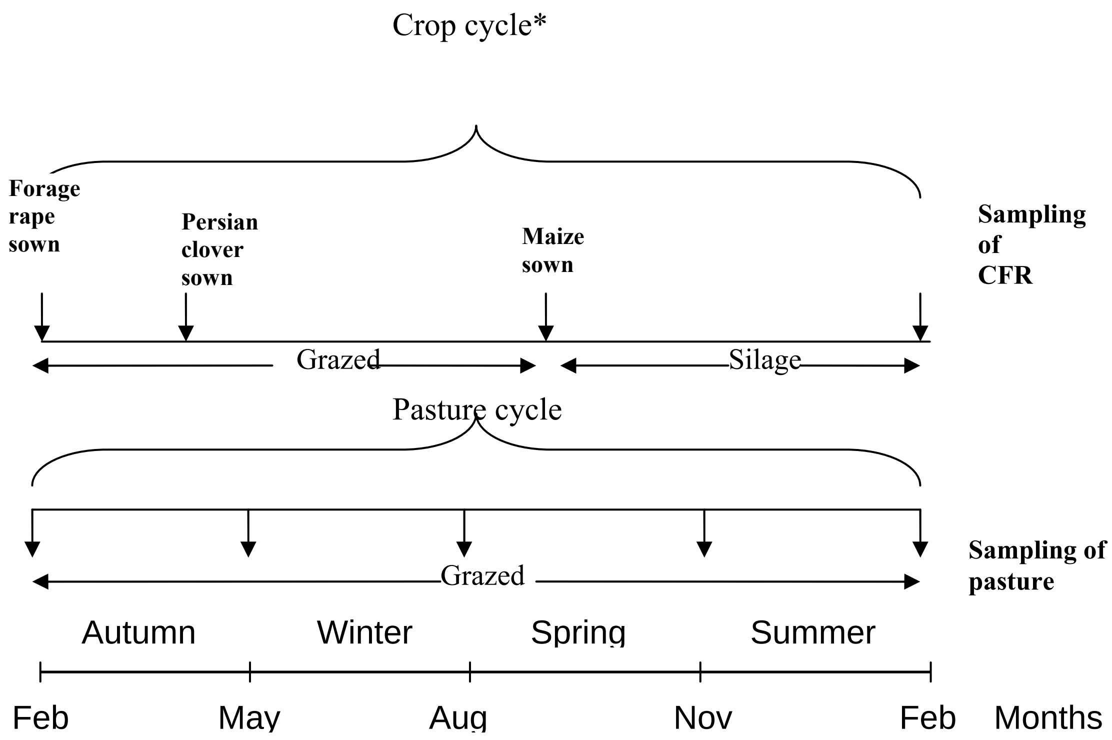
For the major nutrients, inputs from fertilizer, faeces, urine and irrigation, and output from crop removal, runoff and deep drainage of water were monitored intensively over a 3 year period. In addition, on the 2 replicates of CFR and PI, but not PE, soil sampling for the determination of some baseline parameters was undertaken in August 2003 before the trial commenced and hence long term the changes in soil status in these plots for the 4 years to March 2008, were available.

3.8.1. Soil samples

In 2006, 2007 and 2008, the topsoil was sampled to a depth of 30 cm in 5 cm increments for each of the three treatment locations, as shown in Figure 3.5.

Figure 3-5 Mechanical soil sampling device

A pooled soil sample constituted a minimum 24 cores taken to 30 cm soil depth randomly across each replicate at the times indicated in Figure 3.6. Thus, soil samples were taken at the commencement of each of season in the pasture plots and after each crop in the CFR treatment.



NB * Year 1 crop cycle, (rape-clover-Maize) and year 2 crop cycle (clover-Maize)

Figure 3-6 Timing of sampling and crop cycles/seasons

Simultaneously, a separate soil sample to 10 cm depth was collected for FDA analysis to assess microbial activity in the soil. Bell *et al.* (2006) previously demonstrated that assessing the soil FDA accurately reflects microbial biomass carbon in the soil in the short and medium-term. To determine nutrient leaching through the soil, 4 core samples over depths of 30 to 70 cm and 70 to 100 cm were taken using the mechanical soil core sampler (see Figure 3.5).

3.8.2. Runoff water collection devices

In order to determine the quantity of nutrient leaving the CFR plots in run off water, collection devices were installed at each replicate, with the design depending on landscape, as shown in the Figure 3.7 and 3.8. The devices made of plumbed buckets and drums were located at the end of a plot. This collection device enabled water to be collected from the specific area isolated from the main drainage water.

Figure 3-7 Device to collect surface runoff water from the CFR plots

In the pasture plots, an area of 25 m^2 each was isolated by sinking a sheet of plastic to 30 cm soil depth re-inforced externally with hard plastic and wooden logs. This restricted movement of external water to a specific outlet, from where the water was drained by underground pipe to collection tanks whilst still allowing the plots to be grazed (see Figure 3.8).

Figure 3-8 Device for collecting runoff water from pasture plots

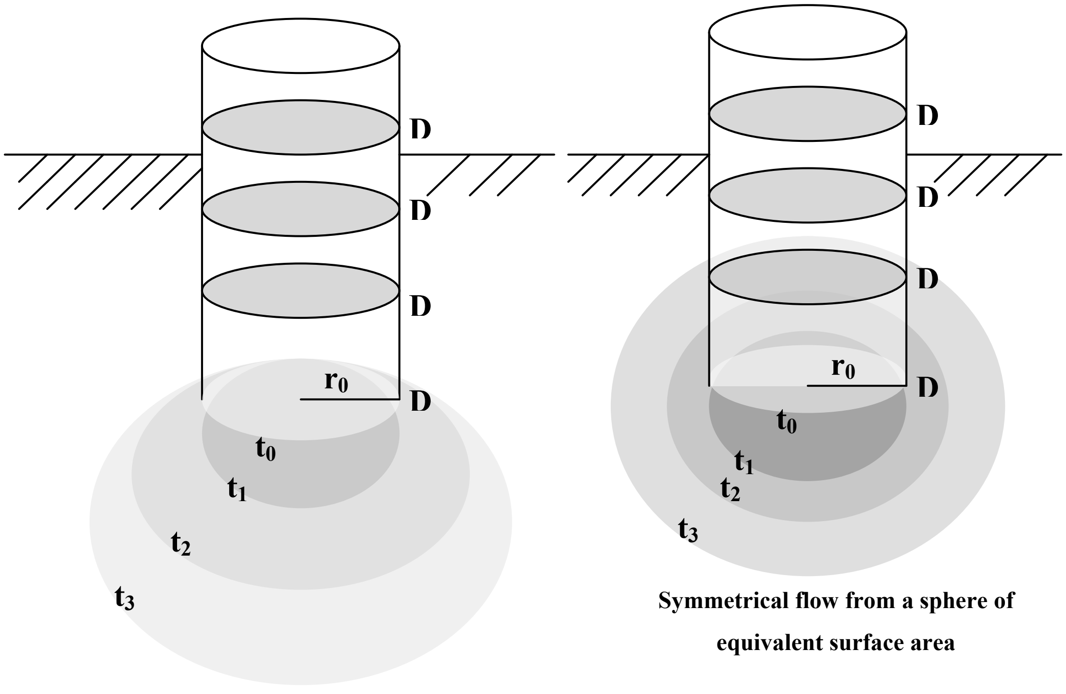
3.8.3. Deep drainage and nutrient leaching

Deep drainage was estimated from the computer program “Neurotheta” (Minasny and McBratney 2002). This program uses soil characteristics (BD, particle size) to estimate potential soil water parameters (field capacity, hydraulic conductivity and available water) and deep infiltration, using the falling-head lined-borehole method (drainage), (Regalado *et al.* 2005) in relation to surface water events (from irrigation and rain). Soil moisture was monitored 3 times/wk using a Diviner 2000, and deep infiltration was measured using the borehole method (Philip 1993). Nutrients leaching were estimated from deep drainage of water and soil analysis for various nutrients over the soil profile. This method was preferred to the lysimeter method used to estimate leaching, because of the high clay content at depth of these soils (see Figure 3.3 and Table 3.1) and the lack of capacity to fully saturate the soil (Hansen *et al.* 2000).

3.8.3.1. Borehole method

Philip falling-head lined-borehole method for determination of deep infiltration consists of assessing subsoil hydraulic conductivity (*in situ* measurement) at different depth without disturbing the soil. Water infiltration is measured in deep soil by inserting a PVC pipe tube (50 mm) to 1 m depth, corresponding to the limit of the active root zone. Beyond this limit, water and nutrient were considered to be lost out of the root system. The PVC pipe is filled initially with a known quantity of water (height and volume) then infiltration is monitored by using a graduated wooden stick until saturation. In our case, the daily water level was used because of the low infiltration rate due to the high clay content.

Figure 3.9 illustrates the dynamics of water diffusion down the pipe into the soil (D_o-D_3) over time (from t_0-t_3) and diffusing through the soil (r_0-r_3) that is used to express deep hydraulic conductivity (K_{sat}) through the Green-Ampt Model.



Actual 3-D elliptical flow

Symmetrical flow from a sphere of equivalent surface area

Figure 3-9 Actual and assumed flow from base of borehole

Trainer (2005) deducted these formulas from Green-Ampt model (see equation 3.3):

Equation 3-3 Green-Ampt model

$$K_{sat} = \frac{-\frac{dD}{dt}\left(R_{\max} - r_0\right)}{R_{\max}\left(\frac{8C}{\Pi^2 r_0} + 1\right)}$$

where K_{sat} is the saturated hydraulic conductivity (cm/min), $\frac{dD}{dt}$ is the steady-state infiltration rate (cm/min), r_0 is the initial radius of the sphere from which infiltration is being modeled, C is the wetting front potential, which models capillarity and is the final radius of the wetted bulb given by (see equation 3-4):

Equation 3-4 Green-Ampt radius

$$R_{\max} = \left[r_0^{\,3} + \frac{3D_0 r_0^{\,2}}{\Delta\theta}\right]^{\frac{1}{3}}$$

where $\Delta\theta$ (cm^3/cm^3) is the volumetric variation of moisture content over the period of infiltration and D_0 is the initial water depth in the permeameter . The value of c is 83.3 for most structured soils from clays to loams; and is most frequently applicable for agricultural soils (Trainer 2005).

The deep drainage formula was deduced from K_{sat} which is expressed in number of days (N_s) needed for the soil to reach saturation as shown in equation 3-5:

Equation 3-5 Deep drainage

$$DD = K_{sat}.N_s$$

3.8.4. Forage production

The pasture utilized by grazing was determined from the difference between pre-and post-grazing pasture mass obtained by an Ellinbank rising plate meter (Earle and McGowan

1979) (see Figure 3.10) calibrated for each pasture type. The amount of Persian clover and forage rape utilized was determined by cutting to ground level 2.5 m^2 randomly placed quadrants pre-and-post grazing. The yield of maize was determined by cutting 12 x 8 m rows of maize to harvest height / replicate.

Figure 3-10 Measuring pasture mass using the rising plate meter

Herbage samples from each forage were dried in a forced-draught oven at 60°C for 48 hrs and then pooled over the growing season and analyzed for nutrient content.

The pasture contained some white clover which contributed to yield in late spring and therefore contributed to soil N supply.

3.8.5. Urine and faeces estimation

Return of animal excreta by the grazing cow is a substantial source of nutrient input, with the ratio of pasture to other feeds, and the digestibility of the feeds, being important determinants as to the quantity of nutrients returned. The number of dung pats over a specific area was counted after each grazing and the average dry weight determined, with a representative sample of faeces analyzed for chemical composition. The quantity of urine excreted was estimated by establishing a correlation between dung and urine excreted during a period when cows were observed during the day and night (Ayantunde 1998; Betteridge *et al.* 1986). Representative urine samples were collected during milking and analyzed. The faecal samples were pooled seasonally and sent for analysis.

3.8.6. Irrigation and runoff water sampling

Irrigation water was applied frequently on the CFR and PI plots. A travelling irrigator was used in replicate 1 with water sometimes applied beyond the PI plot to the PE plot. In this case, the PE plot received substantial irrigation water depending on the wind direction. In Replicate 2, set sprinklers were used to apply irrigation water with much less drift to the PE plot.

The irrigation and drainage water were sampled within 24 hrs of irrigation and analyzed for pH and electric conductivity. Water samples were then pooled seasonally and analyzed for chemical composition (pasture) or after each crop cycle (CFR) (Figure 3.6).

3.9. Analysis of samples

3.9.1. Analysis of soil samples

After sampling, the soil samples were air dried, cleaned of roots and stones before sending for analysis. The samples were analyzed for ammonium, nitrate, P (Colwell method), K (Gilman method), organic carbon (by the oxidation method; Leco carbon analyzer) (Rayment and Higginson 1992), soluble salt, pH (in water and in 10 mM calcium chloride), electrical-conductivity (on 1:5 ratio for EC and pH), chloride and sodium. Soil ammonium and nitrate was assessed by Lachat flow injection analyzer and total nitrate by the Leco FP nitrogen analyzer. Soil fertility was assessed annually and included total P and N as well as soil cation exchanges capacity (Gilman method - prewashed). Only N, P, K, pH and EC were assessed for deep drainage samples.

3.9.2. Analysis of water samples

Pooled water samples from irrigation and runoff water for each plot over each season were analysed for N (ammonium and nitrate using the Inductively Couple Plasma (ICP) method) P, K, carbonate, sulfate and calcium (through chromatogram method) concentration and pH_w and EC.

3.9.3. Analysis of forage

Pre-harvest or pre-grazing, plant material was dried in a forced-draught oven set at 60^oC for 48 h, before grinding to pass a 1 mm sieve. These samples were pooled seasonally in proportion to their relative yield, and analyzed for N, P, K, Ca, Na, S, and Cl content. The N content was obtained by the Leco method, and the other minerals were digested in nitric acid then measured on ICP-AES. The Lachat Flow Injection Analyzer was used to determine nitrate and chloride content. The analyses were undertaken by DPI Victoria (Werribee) and CSBP South Australia laboratories.

3.9.4. Particle size determination

The determination of soil particle size was based on a modified version of method size by Dane and Topp (2002). Analysis was undertaken in the Agriculture, Food and Natural Resources Laboratory of Sydney University.

An air dried soil sample (30 g) (> 0.2mm) was mixed with a 50 mL solution of Sodium hexametaphosphate (5%) (pH 8.5) in a 500 mL bottle, then made up to 400 mL with distilled water. The bottles were then rotated for 3 days at 50 rpm. A blank sample was also prepared with 50 mL of sodium hexametaphosphate and distilled water only. The density of each suspension was measured with a hydrometer (ASTM 152 H Bouyoucos). After the third day, the content of each bottle was poured into 1 L beaker and made up to 1 L with distilled water. The density of the silt and clay fraction were read after shaking the solution in the beaker and leaving it to rest for 4 minutes and 45 second at 20^0C (time for coarse and sand particles to settle). The same process was repeated to obtain only the clay density by leaving for 8 h. The contents of the beaker were then washed, dried and sieved through a 200 µm mesh to separate sand and coarse particles.

3.9.5. Soil surface infiltration measurement

The infiltration rate of the surface soil was measured in the field to determine potential water movement using Beerkan estimation of soil transfer single ring method (Lassabatere *et al.* 2006). A single ring (20 cm height and 30 cm radius) was inserted into the soil and the water topped up (8 refills minimum with constant volume of water) and the amount of water loss over a given time was recorded. The soil hydraulic conductivity (K_{sat}) was estimated from an infiltration chart. This method could not be used on all plots: the failure was due the presence of expanding clay stopping water infiltration before reaching the 8 refills as required by the BEST method. Due to the unsuccessful surface water measurement, the estimation of $K_{(sat\ )}$ were obtained by using the Neuro-theta model (Minasny and McBratney 2002) which is capable of predicting soil water parameters.

3.9.6. Soil pH buffering capacity assessment

Soil pH buffering capacity assessments were carried out to quantify the acidity down the soil profile, by using a modification of the titration method described by Conyers *et al.* (2000). In this method, 5 g of soil was mixed with 25 mL of $CaCl_2$ (0.01 M) and left for 1 hr before measuring the pH. The solution was then titrated against $Ca(OH)_2$, standardised with 0.1 M HCl, past pH 7 on day of addition to soil sample with methyl red indicator to provide the endpoint (red) sequentially using 1 mL of $Ca(OH)_2$ (0.01 M) and shaken (30 min) and pH measured. The data were then plotted on a polynomial graph to estimate the pH buffering capacity (pH(y) as per Equation 3.6.

Equation 3-6 pH buffering capacity

pH (y) = OH meq/100g(x)

where x is the number of mL of $Ca(OH)_2$ added.

3.9.7. Resistance to soil penetration

Soil resistance to penetration was measured with penetrometer cone resistance, which seemed to reflect the resistance that the plant roots should develop to penetrate the soil. This resistance is variable with the time depending on soil moisture content (Topp *et al.* 2003; Vaz and Hopmans 2001), but also with the soil BD (Vaz *et al.* 2001). The measurement is done by dynamic hammer (hammer drop gravity) developing energy which drives the cone down the soil. Minasny and McBratney (2005) deduced the penetration resistance (R) to the following formula (see equation 3.7):

Equation 3-7 Penetration resistance

$R = Mgh /(Ax) \times [M/(M + m)]$

Where R is the resistance (MPa), M is the hammer weight (kg), g (kg/m) the earth gravity, h the high of the falling hammer (m), A*x* the surface of the cone section (m^2) and m, the mass of the axle (kg)

3.9.8. Estimates of input and output of nutrients / minerals

1. *Animal excreta* (see section 7.5). The assumption was that all dung collected is mineralized during the season or crop cycle as the previous dung drops were presumed to be (not counted) active in the soil (progressively in mineralization) and as any identifiable organic material was avoided during soil sampling (discrepancy over time).
2. *Irrigation water* (see 7.6 and annexes)

3. *Mineralization*. OM mineralization was assumed after Condron *et al.* (2000), to be 105.9 mg/kg of N, 19.6 mg/kg and 1 cmol/kg of extractable P and K, respectively. According to Anderson *et al.* (1998), the mineralization could supply 80-130 kg N /ha yr. The difference between soil OM content between periods was used in the calculation (with 10% of OM for continual mineralization).

4. *Legume N fixation* - estimated from field legume fixation in pasture (Ledgard 1991; 2001; Ledgard and Steele 1992; Peoples and Baldock 2001; Peoples *et al.* 1995), where average of 20-200 kg N /ha yr (with 8-28% of white clover contribution into the swards) was fixed and 3-103 kg N/ ha yr, transferred from root decomposition. The range could be higher depending on P fertilizer and pesticides, grazing pressure and environmental conditions (Anderson *et al.* 1998). This estimation was also revised by the seasonal legume N fixation in PE treatments (with no N fertilizer input) to cover plant N removal, as the treatments (PE and PI in each Block) were adjacent, and therefore were subjected to clover rate which varied with the seasons.

5. *Change in soil*- calculated from the difference in nutrients content between two sampling times (at the beginning and end of season or crop cycle) and the volume of soil in question.

6. *Water runoff* – calculated from section 7.6, based on individual sampling of each runoff event and then a composite sample was sent for analysis.

7. *Plant removal*- calculated from plant samples taken before each grazing or harvesting and seasonal / crop composite was sent for testing

8. *Change in subsoil*- calculated as change in soil.

3.9.9. Data analysis

The seasonal data collected during the 2 years were analyzed using Genstat version 9. The crop cycle (3 crops) for the CFR was an unbalanced data set. To handle the periodic disparity of the forage crop between systems, the Mixed Model (REML) treatment and time as fixed effect, and block (replicates) as the random effect were used to test the treatment and period effect, and also the block effect by using treatment and block as the fixed effect and treatment as the random effect to highlight the soil type effect. Simple variance analysis was also used to test the single recorded data. Also, correlation was used to analyze the seasonal effect of each forage production system and also to test for site effects on the change of soil fertility in relation of the management practice. Correlation analysis was used to test the existence of relationships between different variables during the monitoring periods.

The nutrient balance, calculated on a per hectare basis, was established for each season and crop cycle in order to assess NUE and WUE. The calculation of N balance required the consideration of 2 extra non measurable parameters: the contribution of atmospheric fixation of N by the legume component in the CFR (Persian clover), and in the mixed pasture sward (white clover) from the literature, and N loss by volatilization into the atmosphere.

3.10. Systems management

3.10.1. Grazing

Pasture was grazed to best practice. Thus, the interval between grazing was based on the principle of allowing sufficient time for the plant to replenish its water soluble carbohydrate (WSC) reserves but before the older leaves began to senesce with a consequent drop in quality, with timing of events based on leaves/tiller stage of growth (3) or pasture on offer (2700 kg DM/ha) (Fulkerson and Donaghy 2001), which ever came first. Grazing on a given area was restricted to 24 hrs to prevent new regrowth being grazed, which would be expected to set back regrowth. The pasture was grazed to 6-7 cm stubble height, a height which maximizes pasture utilization without appreciably depressing milk yield/cow. The all systems were grazed excepted for maize which was cut for silage.

3.10.2. Fertilizers statistic

In these intensive production systems, a substantial amount of fertilizer was applied at the beginning of the study, and then periodically to replace nutrient removed by stock as shown in Table 3.2, except for N where only 80% of the net removal was returned. In contrast, in the PE system, no fertilizer was applied. The types of fertilizers used were urea for

N, muriate of potash (potassium chloride) for K and triple, double superphosphate and ammoniated phosphate (MAP, DAP) for P and N (see chapter 2), or as mixed NPK fertilizers.

Table 3-2 Annual input of fertilizer (kg/ha) in basic mineral equivalent of N, P and K over the last 5 years (S.Garcia pers comm, 2006)

	Fertilizer inputs (kg of nutrient/ ha/ yr) x season or crop cycle*											
Treatment	**Nitrogen N**				**Phosphorus P**				**Potassium K**			
	1	2	3	4	1	2	3	4	1	2	3	4
CFR	655	619	553	486	152	201	123	190	333	427	375	433
PI	591	673	509	494	97	74	72	72	233	168	164	164

NB: * the average inputs (years 1-3) were calculated from the 4 original replicates and on 2 replicates for year 4.

The need for irrigation was assessed from soil water availability measured to 160 cm soil depth by Diviner 2000 (Sentek PTY LTD, Australia), 3 times-a-week, combined with the daily weather data (rainfall; evaporation), crop needs and estimated evapo-transpiration rate.

3.10.3. Crop productivity

The intensive pasture systems (CFR and PI plots) have achieved variable yields during the 5 years of the forage production trial. Several species combinations (brassica, peas, clover and maize) were trialled (see Table 3.3) for the CFR plots during these years, and the different weather pattern may have contributed to these variations. Over all, high and sustained production was recorded for each of the intensive treatments averaging 41.2 t and 18.7 t DM /ha /yr for CFR and PI plots, respectively.

Table 3-3 Pasture yields for CFR and PI plots (kg DM /ha /yr)

	Average yield (t DM /ha /yr) x season or crop cycle			
Treatment	**1**	**2**	**3**	**4**
CFR	42.2	40.8	44.4	37.2
PI	17.3	18	16.7	22.8

CHAPTER 4: RESULTS

4.1. Changes in soil physical parameters

4.1.1. Bulk density

There was no effect (*P* >0.05) of treatment or treatment.period on BD, but there was an effect (*P* = 0.002) of period, with BD increasing from 1.35 to 1.38 and 1.42 g/cm^3 from years 0, 1 to 2, respectively (Table 4.1).

Table 4-1 Means and results of statistical analysis for bulk density (BD) (g/cm3), root penetration (R) (MPa), field capacity (FC) (cm3/cm3), permanent wilting point (PWP) (cm3/cm3) available water (AW) (cm3/cm3) and hydraulic conductivity (Ksat) (mm/h) in the topsoil (0-30 cm) for treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) and period (years 0, 1 and 2).

Items	Treatment (T) means			sed	Period (P) means			sed	Level of significance		
	CFR	PI	PE		Yr0	Yr1	Yr2		T	P	T.P
BD	1.39	1.40	1.39	0.08	1.35	1.38	1.42	0.02	ns	0.002	ns
R	0.93	1.03	1.50	0.22	-	-	-	-	ns	-	-
FC	0.41	0.40	0.41	0.05	0.41	0.43	0.39	0.01	ns	0.007	ns
PWP	0.23	0.23	0.23	0.01	0.22	0.22	0.24	0.01	ns	ns	ns
AW	0.18	0.10	0.18	0.03	0.18	0.20	0.15	0.02	ns	0.001	ns
Ksat	65	89	88	6.1	89	78	80	7	ns	ns	ns

There was also an block effect (*P* < 0.001) on BD with a mean ± se value of 1.47 ±0.02 and 1.29 ± 0.02 g/cm^3 for Replicates 1 and 2, respectively (see Figure 4.1).

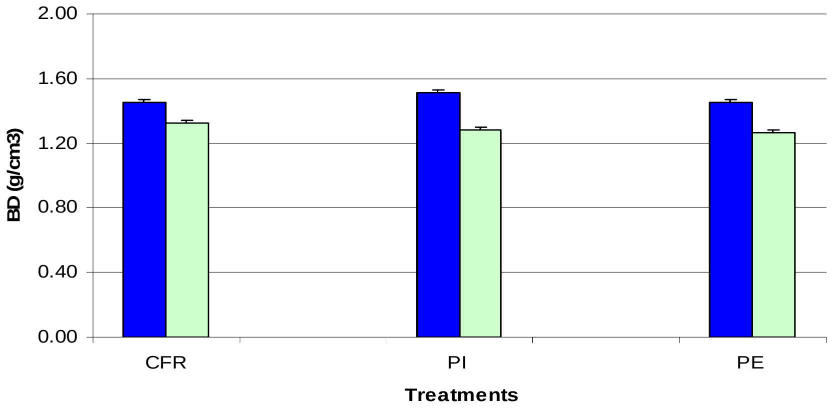


Figure 4-1 Soil bulk density (BD) (g/cm3) for samples taken from 0-30 cm soil depth for Replicates 1 (🟦) and 2 (🟩) for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments. Standard errors of the means are shown as vertical bars.

The BD of the topsoil (0-30 cm) increased in all treatments during the two years of the study, but the increase was gnificantly greater (*P* <0.001) in Replicate 2 (8.2%) than Replicate 1 (3.8%) (Table 4.2). Most of the increase in BD occurred during the second year (see Table 4.2) and primarily affected the 11-30 cm soil layer while the BD of the 0-10 cm layer actually fell (except in CFR2).

Table 4-2 Variation (%) (between year 0 and 2 or year 1 and 2) in soil bulk density (BD) for Replicates 1 and 2 for complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments, for 0-30 cm, 0-10 cm or 11-30 cm soil depth.

Treatment / replicate	Change in BD 0-30 cm (yr2-yr0)	Change in BD, 0-10 cm (yr2-yr1)	Change in BD, 11-30 cm (yr2-yr1)
CFR1	1.1	-10.5	6.3
CFR2	6.2	8.9	5.1
PI1	7.4	-7.0	14.2
PI2	7.4	-19.6	20.1
PE1	2.9	-10.8	9.6
PE2	10.5	-13.9	21.9

4.1.2. Resistance to root penetration

The comparison of soil resistance to root penetration (R) between plots was limited to one period in year 1 when soil moisture was similar on all plots and at an appropriate level to measure R. The mean R value ± se was greatest in the PE (1.50 ± 0.05 MPa), less in PI (1.04 ± 0.02 MPa) and least in the CFR (0.93 ± 0.02 MPa) plots (Table 4.1), but the means were not different ($P > 0.05$). The variability was also highest in the PE plots. There was no effect ($P > 0.05$) of block (mean ± se was 1.15 ± 0.20 MPa on average for Replicate 1 (brown chromosol) and 2 (black vertosol) on R (Table 4.3).

Table 4-3 Soil compaction properties: total soil porosity (%) and soil resistance to root penetration (R) (±se) (Mega Pascal (MPa)) (measured at 40% soil moisture content) in soil samples at 0-30 cm soil depth during year 1 for Replicates 1 and 2 for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments.

Treatment / Replicate	Total porosity (%)	R (mean ± se) (MPa)	
CFR1	45	0.914	(0.020)
CFR2	50	0.949	(0.020)
PI1	44	0.920	(0.026)
PI2	49	1.149	(0.013)
PE1	44	1.733	(0.072)
PE2	51	1.258	(0.033)

4.1.3. Field capacity

There was an effect ($P = 0.007$) of period, but not treatment or treatment.period on field capacity (FC), with FC falling from 0.43 cm^3/cm^3 in year 1 to 0.39 cm^3/cm^3 in year 2 (Table 4.1). There was a block effect ($P < 0.001$) with a mean ± se value of 0.46 ± 0.01 cm^3/cm^3 for Replicate 2 and 0.36 ± 0.02 cm^3/cm^3 for Replicate 1 (Figure 4.2), partly due to the difference in total soil porosity (see Table 4.3).

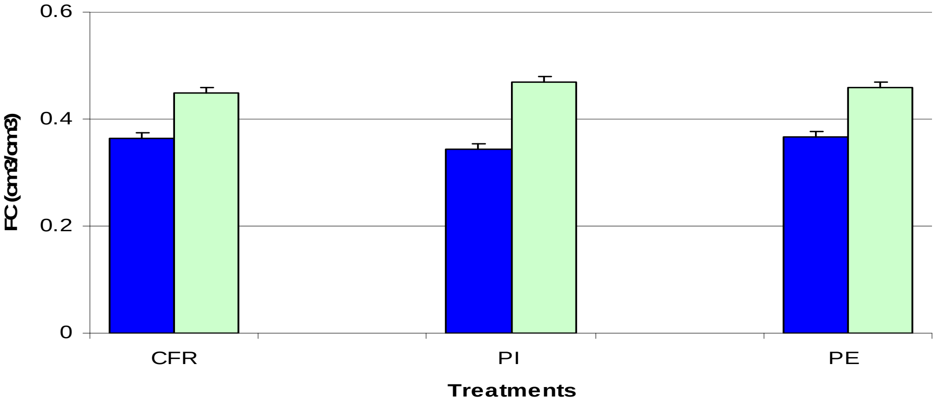


Figure 4-2 Soil field capacity (FC) (cm3/cm3) for samples taken from 0-30 cm soil depth for Replicates 1 (🟦) and 2 (🟩) for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments. Standard errors of the means are indicated as vertical bars.

4.1.4. Permanent wilting point

There was no effect ($P > 0.05$) of treatment, period or treatment.period on PWP (Table 4.1), but there was a block effect ($P < 0.001$), with a mean ± se value of 0.276 ±0.008 and 0.184 ± 0.002 cm^3/cm^3 for Replicates 1 and 2, respectively (see Figure 4.3).

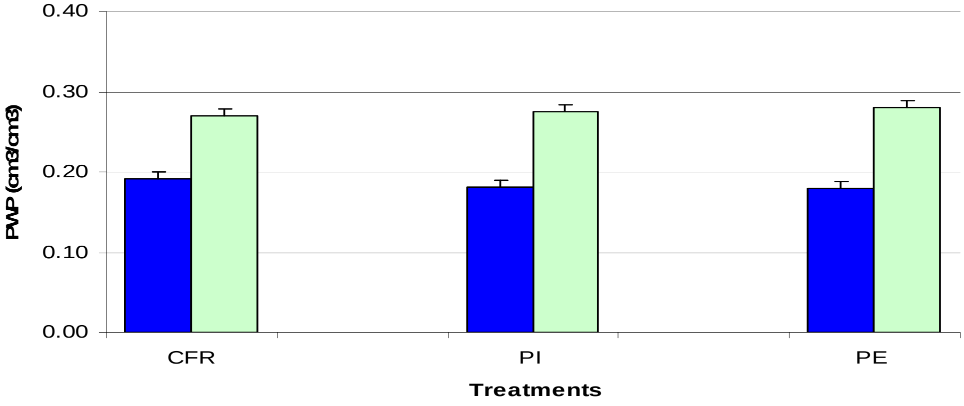


Figure 4-3 Figure 4.3. Soil permanent wilting point (PWP) (cm3/cm3) of samples taken from the 0-30 cm soil depth for Replicates 1 (🟦) and 2 (🟩) for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments. Standard errors of the means are indicated as vertical bars.

The PWP can influence the soil's capacity to supply water to plants. The PWP varied with time and ranged from 51 to 59% of total field capacity in year 0, 44 to 57% in year 1 and 60 to 74% in year 2.

4.1.5. Available water in the soil for plant use

The AW in the soil is directly related to the FC and PWP. There was no effect ($P > 0.05$) of treatment or treatment.period on AW. There was a difference ($P = 0.001$) in AW between years (0.184, 0.201 and 0.148 cm^3 / cm^3 for years 0, 1, and 2, respectively), and the block effect was not with a mean (± se) AW of 0.178 ± 0.011 cm^3/cm^3.

4.1.6. Saturated hydraulic conductivity

The soil saturated hydraulic conductivity (Ksat) measures the flux of water infiltrating the soil profile when the soil is saturated. There was no difference ($P > 0.05$) in Ksat between treatment, period or treatment.period, but there was a block effect ($P < .001$) with the mean ± se for Replicate 1 of 131.1 ± 8.0 mm/hr and Replicate 2, of 31.0 ± 1.3 mm/h (see Figure 4.4).

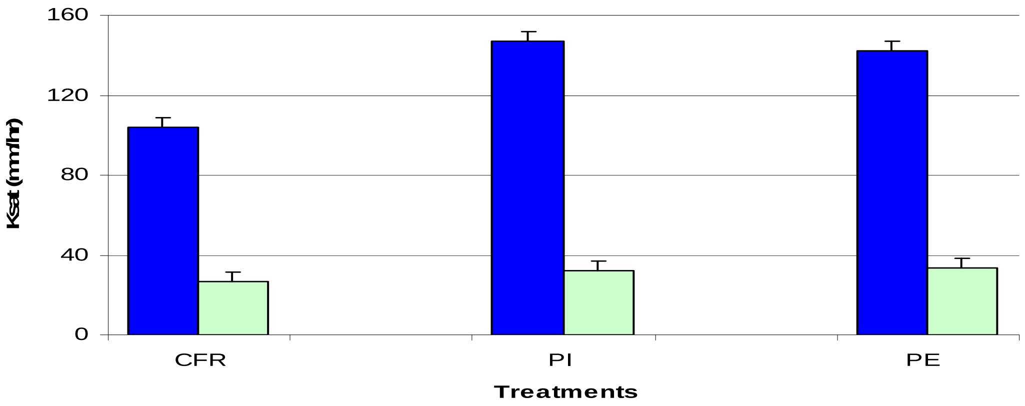


Figure 4-4 Soil hydraulic conductivity (Ksat) (mm/h) in samples taken from the 0-30 cm soil depth for Replicates 1 (🟦) and 2 (🟩) for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments. Standard errors of the mean are indicated as vertical bars.

4.1.7. Subsoil bulk density and soil hydraulic conductivity

There was no difference (*P* >0.05) in the BD or Ksat at the commencement of the monitoring period for any soil layer. There was no difference in the change in BD of the subsoil relative to the topsoil over the 2 years of the study in relation to treatment (1.39, 1.40 and 1.39 g/cm^3 for CFR, PI and PE, respectively) and blocks (1.47 and 1.29 g/cm^3 for Replicate 1 and 2, respectively) (see Table 4.4).

Table 4-4 Means and results of statistical analysis of subsoil bulk density (BD) (g/cm3), and deep hydraulic conductivity (Ksat) (cm3/cm3) in Replicates 1 and 2 for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatment for 30-70 cm (2) or 70-100 cm (3) soil depth.

Items	**Treatment (T) means**			**Level of significance**	
	CFR	**PI**	**PE**	**sed**	**T**
BD2	1.47	1.40	1.50	0.04	ns
BD3	1.53	1.55	1.55	0.06	ns
Ksat2	188	205	175	101	ns
Ksat3	705	151	212	360	ns

The variable in BD in subsoil relative to topsoil is shown in Table 4.5. There appears to be no clear change.

Table 4-5 Variation (%) in bulk density (BD) of subsoil (30-70 and 70-100 cm) relative to topsoil (0-30 cm) in years 0 and 2 for Replicates 1 and 2 for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments.

	Variation in BD (%) of subsoil-topsoil			
Treatments/ replicates	**Yr 0**		**Yr 2**	
	30-70 cm	**70-100 cm**	**30-70 cm**	**70-100 cm**
CFR1	8	11	10	14
CFR2	5	10	4	9
PI1	5	7	7	9
PI2	3	25	-6	14
PE1	15	16	13	14
PE2	14	20	5	11

4.1.8. Soil erosion

The mean ±se annual loss of soil through soil erosion was higher (P <0.001) on the CFR (664 kg/ha) than PI (75 kg/ha) or PE (80 kg/ha) treatments. The higher level of soil erosion recorded on the CFR treatments was probably due to the greater time of exposure of bare ground in the period between crops. The loss of soil was the same in year 2 (310 ± 135 kg/ha) than year 1 (235 ± 131 kg/ha). There was no significant difference (P > 0.05) between blocks in soil erosion with the mean ± se soil loss for Replicate 1 being 236 ± 99 kg/ha and Replicate 2, 306 ± 160 kg/ha soil (Table 4.6), despite the steeper sloping aspect of Replicate 1.

4.2. The water balance

Water input included rain, irrigation water, and to a negligible extent, dew and frost. A relatively large quantity of irrigation water was used during year 1 (drought) (with 59 and 66% of total water used for PI and CFR plots, respectively) to supplement the abnormally low rainfall of 464 mm (Figure 4.5).

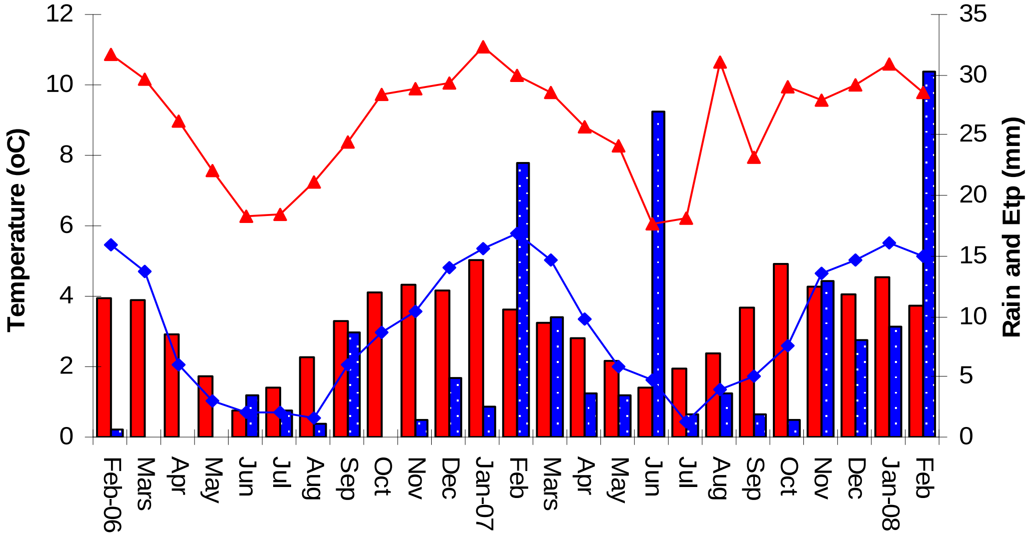


Figure 4-5 Mean monthly maximum (Δ) and minimum (◊) temperature (°C) and evapo-transpiration (🟥) and rainfall (🟦) over the 2 years at the study site.

This contrasts to year 2 when more than double the amount of rainfall (1030 mm) was received, leading to irrigation water contributing only 27 to 23% of total water required, for the PI and CFR treatments, respectively (Table 4.6). These extreme differences in rainfall between years 1 and 2 (Figure 4.5) allowed a most useful comparison of water dynamics to be investigated in contrasting situations.

There were no effect (*P* >0.05) of treatment or period on DD or soil moisture but there was a treatment.period effect (*P* < 0.001) (see Table 4.6). There was a effect (*P* < 0.001) of treatment, period and its interaction on runoff water. The runoff water from CFR was significantly more than PI which was greater than PE (Table 4.6).

Table 4-6 Means and results of statistical analysis for the water balance components (mm) in the topsoil for treatment (complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE)) and period (year 1 and 2).

Items	**Treatment (T) means**			**sed**	**Period (P) means**		**sed**	**Level of significance**		
	CFR	**PI**	**PE**		**Yr1**	**Yr2**		**T**	**P**	**T . P**
Deep Drainage	339	136	-117	282	89	149	79	ns	ns	<0.001
Irrigation	587	572	319	128	684	301	39	ns	<0.001	0.004
Soil moisture	-22	-33	-118	144	-83	-31	51	ns	ns	<0.001
Runoff	131	86	49	23	21	157	14	0.001	<0.001	0.003
Total water*	1334	1319	1066	128	1148	1331	39	ns	<0.001	0.004
Etp	843	1065	1017	22	956	993	18	<0.001	0.004	ns
WUE	30.3	15.3	4.3	1	17.2	16.1	0.4	<0.001	<0.001	<0.001

NB: * Total water = irrigation + rain

There was an effect of treatment (*P* <0.001) and period (*P* = 0.004) on Etp (see Table 4.6). The mean ± se Etp loss was highest on the PI plots (1065 ± 27 mm), closely followed by the PE plots (1017± 16 mm), while the CFR plots (843 ± 6 mm) had, on average, 19% less Etp than the pasture treatments, despite the similar water inputs (Table 4.6). The lower evaporative loss from the CFR plots was presumably because these plots had full canopy cover for a longer period than the grazed pasture plots. The effect of treatment, period and treatment.period on WUE was significant (*P* < 0.001) (mean ±se WUE for the CFR plots was 30.3 ± 1.5 kg DM/ mm water compared to 15.3 ± 1.2 kg DM/ mm water for PI plots) (see Table 4.6). Overall, Etp was driven by total water input, rain and irrigation, with correlation coefficients of 0.75, 0.6 and 0.52, respectively (Table 4.8).

Table 4-7 Water balance in the topsoil (0-30 cm); deep drainage (DD); Potential evapo-transpiration (Etp) and water use efficiency (WUE) (kg DM /mm total water) for Replicates 1 and 2 for complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments in years 1 and 2.

		WUE	**Irrigation**	**Rain**	**ΔSoil Moisture**	**Run off**	**Etp**	**DD**
Year	**Treatment / replicate**	**(Kg DM/ mm water)**	**Inputs**			**Outputs**		
1	**CFR1**	31.8	912	464	123	47	848	604
	CFR2	33.8	811	464	-90	14.8	827	345
	PI1	12.5	675	464	-47	51.6	1038	3
	PI2	16.6	837	464	74	1	1006	369
	PE1	3.9	613	464	-169	5.8	972	-69
	PE2	4.7	256	464	-392	2.8	1046	-719
2	**CFR1**	27.4	311	1030	-75	288	852	126
	CFR2	28.1	314	1030	-45	174	846	279
	PI1	14.3	396	1030	-146	176	1087	18
	PI2	17.9	378	1030	-12	116	1127	153
	PE1	3.1	326	1030	248	102	1024	477
	PE2	5.5	81	1030	-159	83	1024	-156

There was a difference (*P* =0.05) in WUE between blocks, with Replicate 1 having a mean of 15.6 ±4.9 kg DM/ mm of total water and Replicate 2, 17.8 ±4.8 kg DM/ mm of total water, due mainly to higher in runoff (111.8 ± 42.5 vs. 65.3 ± 29.1 mm /yr) and change in soil moisture (-10.9 ±66.8 vs. -103.8 ± 65.8 mm) for Replicate 1 than 2, respectively. The amount of runoff water was positively related to rainfall (r = 0.71) (Table 4.8) (varying from 1 to 52 mm in year 1, to 83 to 288 mm in year 2). But even in year 2, at 15% of rain input, runoff was still within the normal range recorded in Australia, for rainfed (1 to 20 %) (Cooper *et al.* 2005) and irrigated (10 to 20%) (Mundy *et al.* 2003), perennial ryegrass pastures.

Table 4-8 Correlation matrix between components of the water balance equation.

Water balance components	Soil moisture	DD	Etp	Irrigation	Runoff	Total water	Rain
Soil moisture	1						
DD	**0.71**	1					
Etp	-0.01	0.3	1				
Irrigation	0.18	**0.55**	**0.52**	1			
Runoff	0.16	0.36	0.3	-0.02	1		
Total water	0.22	**0.75**	**0.75**	**0.63**	**0.54**	1	
Rain	0.15	**0.57**	**0.6**	0.11	**0.71**	**0.84**	1

Note: Bold figures represented correlation > 0.5

4.3. Changes in soil organic matter and pH

4.3.1. Organic matter

Over the two years of the study, the mean ± se OM content was not different (*P* > 0.05) between treatments (CFR (5.5 ± 0.6 %), PI (6.0 ± 0.5 %) and PE (5.7 ± 0.5%)) (Table 4.9) despite the higher dung input (see Table 4.11) into the PI plots compared to the other treatments and the higher degree of cultivation in the CFR treatments.

Table 4-9 Means and results of statistical analysis of soil organic matter (OM) (%) and soil pH of the topsoil (0-30 cm) for treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments) and year (0, 1 and 2).

Items	Treatment (T) means				Period (P) means			Level of significance		
	CFR	PI	PE	sed	Yr 1.	Yr 2	sed	T	P	T. P
pH	6.11	6.57	6.26	0.31	6.13	6.64	0.11	ns	<0.001	0.003
OM	5.48	6.01	5.55	1.1	5.53	5.84	0.035	ns	ns	ns

The effect of period (years) was not significant (*P* > 0.05) (Table 4.9) however, the effect of season was (see Figure 4.6). The OM content increased during the first spring/ summer in all treatments, and this was related to periods of maximum accumulation of DM (above and below ground level) for pasture (spring growth) and crops (maize) there was but a decline over the subsequent autumn/ winter (Figure 4.6). The mean ± se OM content of Replicate 2 (6.2 ± 0.4 %) was at all times higher ($P < 0.001$) than Replicate 1 (4.1 ± 0.3 %) (Figure 4.6).

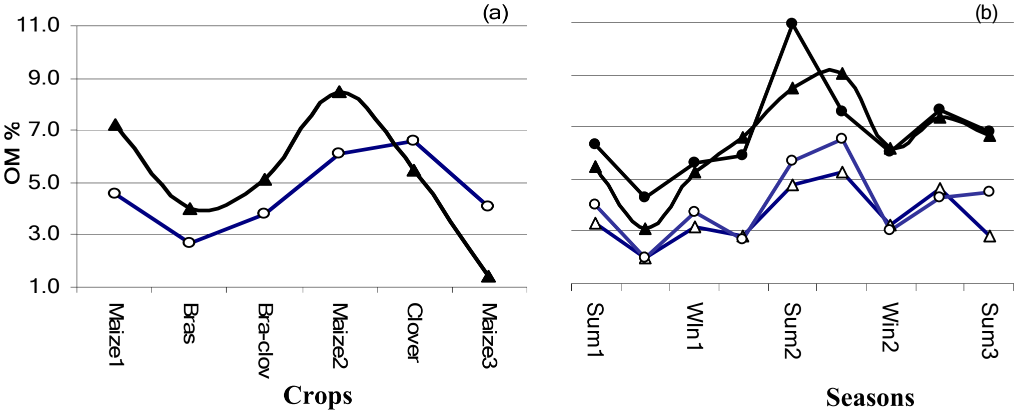


Figure 4-6 Soil organic matter (OM) (%) at end of each season or crop cycle (years 0, 1, or 2) for soil samples taken to 0-30 cm soil depth for complementary forage rotation (a) CFR1 (o) and CFR2 (▲), intensive pastures (b) PI1 (0), PI2 (●) and extensive pasture (b) PE1 (Δ) and PE2 (▲) treatments.

The greater loss of OM in the CFR plots was in the Maize1- Brassica and Maize 2-Maize 3 periods where the OM content dropped by 1.9 and 2.5 % units for CFR1, and 3.2 and 7.1 %, for CFR2, respectively (Figure 4.6). In the pasture plots, the periods of lowest OM accumulation were in Summer 1-Autumn 1 and Autumn 2- Winter 2. These fluctuations resulted in a net fall in OM content in the CFR plots, while the PI and PE2 plots recorded small gains (Figure 4.6). The change in OM in the 2 years was small (Table 4.10) and was not different between replicates ($P > 0.05$).

Table 4-10 Difference (%) in soil organic matter (OM) content for samples taken from 0-30 cm soil depth from commencement to completion of the 2 year monitoring period, and dung input (kg DM /ha) for Replicates 1 and 2 for complementary forage rotation (CFR), pasture intensive pasture (PI) and pasture extensive (PE) treatments.

Treatment / replicate	Total variation (%) unit (Yr2 - Yr0)	Input of dung (kg DM/ ha) (Yr1)	(Yr2)
CFR1	-0.5	1.54	0.55
CFR2	-5.8	1.14	0.46
PI1	0.52	5.23	7.79
PI2	0.53	4.38	4.68
PE1	-0.46	0.69	1.17
PE2	1.13	0.59	1.51

There was an improvement of soil C/N ratio (P <0.001) during the 2 years of study period which mean passed from 12.5 ± 0.2 in year 0 to 9.33 ± 0.4 in year 2.

4.3.2. Soil pH

At the start of the monitoring period (see Figure 4.8), the mean (± se) pH of the topsoil (5.97 ± 0.11 vs. 5.61 ± 0.07) and subsoil (7.42 ± 0.11 vs. 7.11 ± 0.09) was higher in Replicate 1 than Replicate 2, except for the PE treatments.

The effect of treatment on topsoil pH (0-30 cm) was not significant (P>0.05) (Table 4.9), but the effect was (*P* =0.04) for the 0 to 10 cm soil layer (Table 4.11). There was also a significant period effect (*P* <0.001) with pH rising in all plots in topsoil (0-30 cm) samples over the 2 years of the study (see Figure 4.8). There was significant block effect (*P* = 0.03), but only on the pH of the lower subsoil (from 30 to 70 cm) (7.09 for Replicate 1 and 6.75 for Replicate 2) but not the 30-70 cm layer (*P* > 0.05).

Table 4-11 Means and results of statistical analysis of pH of topsoil and subsoil (year 0) for treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) and period (years 0, 1 and 2).

Soil depth (cm)	Treatment (T) means			Level of significance			
	CFR	PI	PE	sed	T	P	T.P
0-10	6.36	6.93	6.4	0.25	0.04	<0.001	ns
11-30	5.78	5.65	5.51	0.20	ns	<0.001	ns
30-70	7.10	7.00	6.73	0.31	ns	ns	ns
70-100	7.83	7.78	7.51	0.14	0.03	<0.001	ns

The pH of the topsoil (0-30 cm) increased linearly for all treatments overall seasons and crop cycles (see Figure 4.7) with the greatest increase for PI2 plots (slope = 0.147 pH/ season; $r^2 = 0.99$) and the least for CFR2 (slope = 0.06 pH/ crop cycle, $r^2 = 0.33$).

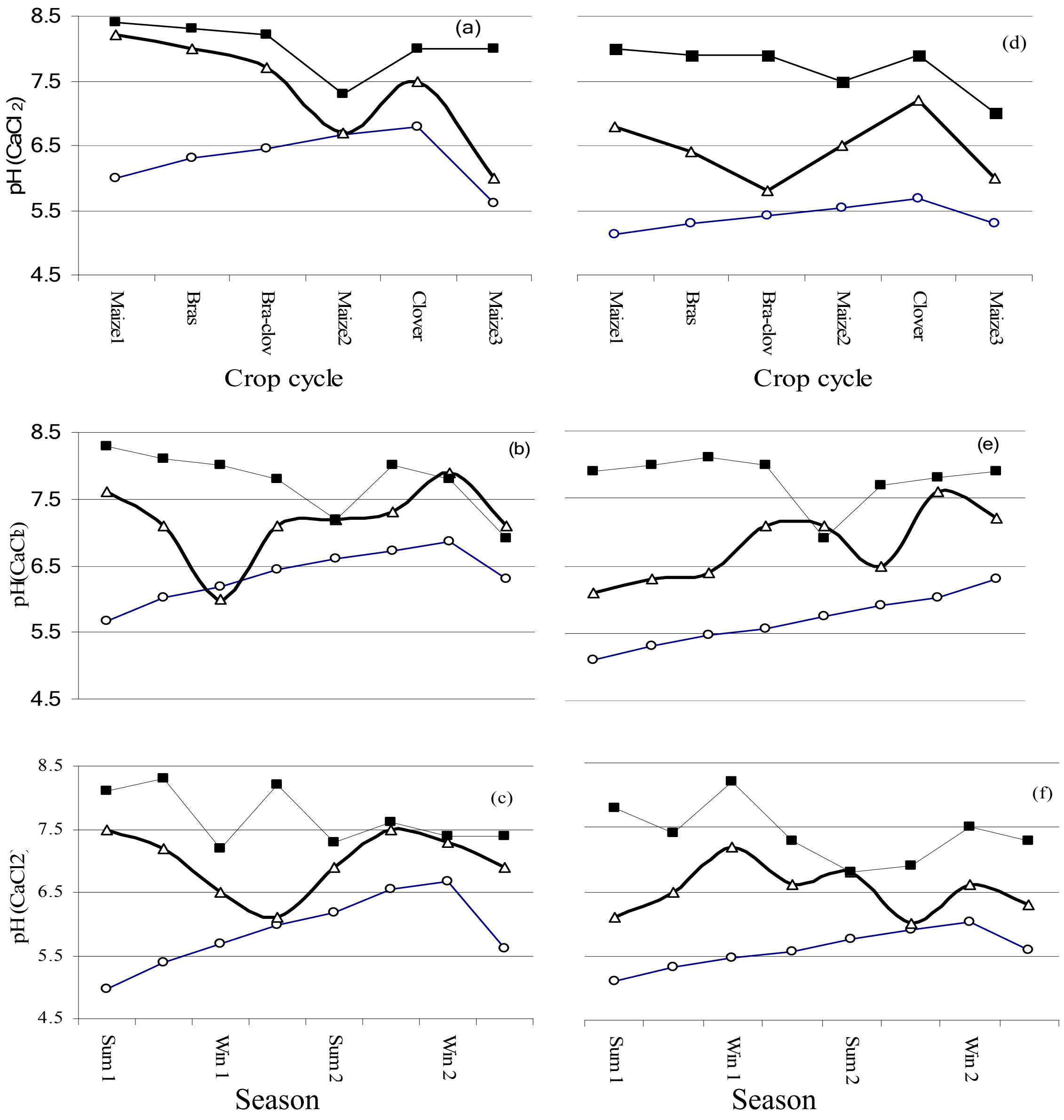


Figure 4-7 pH at end of each season or crop cycle (years 0, 1 and 2) for soil samples taken at 0-30 (o), 30-70 (Δ) and 70-100 (■) cm soil depth for Replicate 1 (CFR1 (a), PI1 (b) and PE1 (c)) and Replicate 2 (CFR2 (d), PI2 (e) and PE2 (f)).

There was a gradual fall in pH down the subsoil profile (30-70 and 70-100 cm soil depth increments) (see Figure 4.7), although, there was considerable variation, particularly between seasons. In both replicates, there appears to be an acidification of the 70-100 cm soil depth subsoil but the trend in the middle layer (30-70 cm) is not clear.

In fact, the decrease in pH for the CFR treatments (-0.11) over the study period was significantly smaller (and negative) than the pasture treatments (0.76), but this was due to a sudden fall in pH at the last sampling (see Figure 4.8).

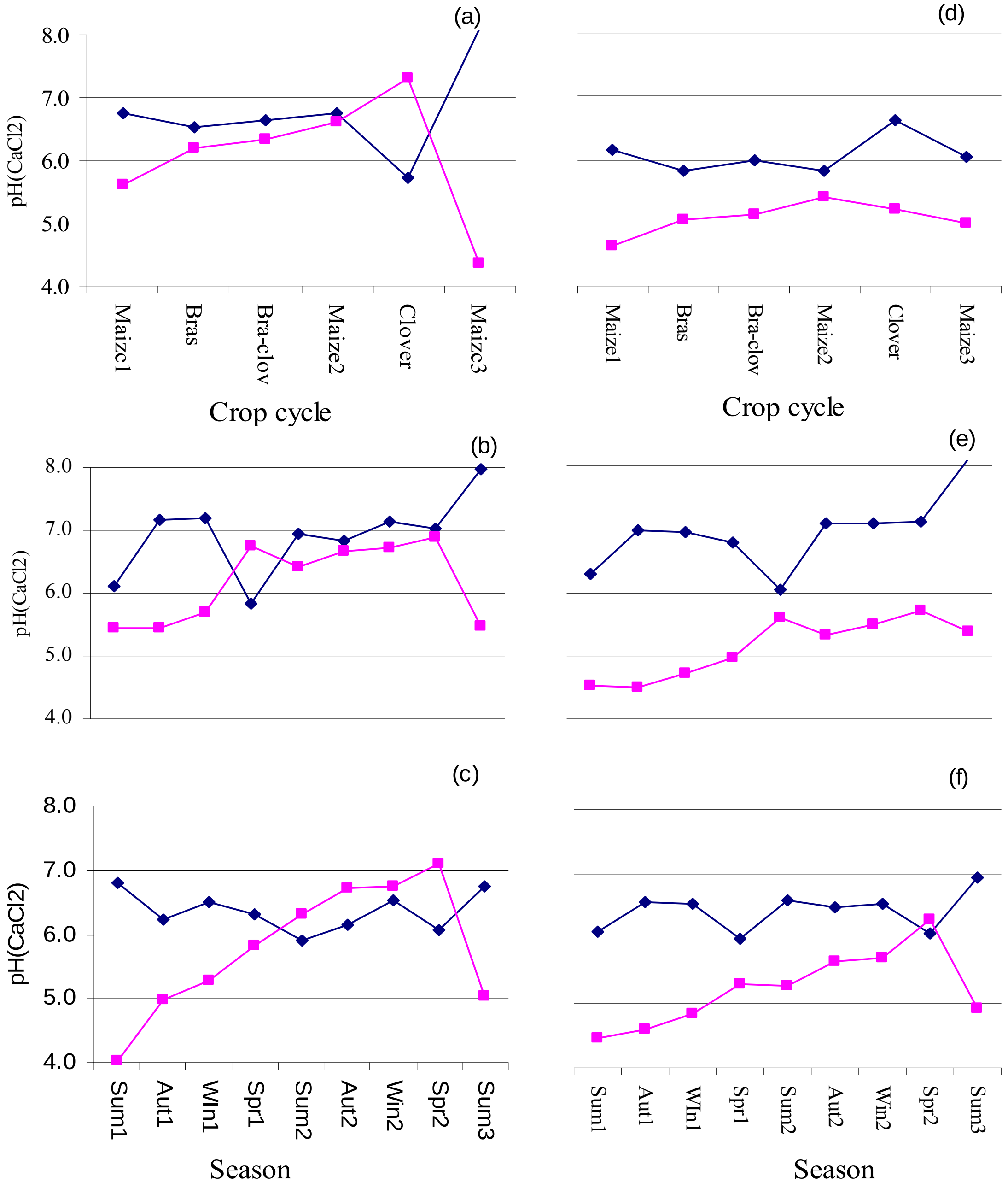


Figure 4-8 Soil pH at the end of each season or crop cycle (years 0, 1 and 2) for soil samples taken to 0-10(♦), 11-30cm (♦) soil depth for Replicate 1 (CFR1 (a), PI1 (b) and PE1 (c)) and Replicate 2 (CFR2 (d), PI2 (e) and PE2 (f)).

While the pH of sub-topsoil (11-30 cm) in Replicate 2 plots was substantial lower than the topsoil (0-10 cm). The difference in Replicate 1 was small but rose throughout the study period (Figure 4.8). The topsoil was then analyzed separately in increments of 5 cm from 0-30 cm soil depth and these revealed a different trend (Figure 4.9).

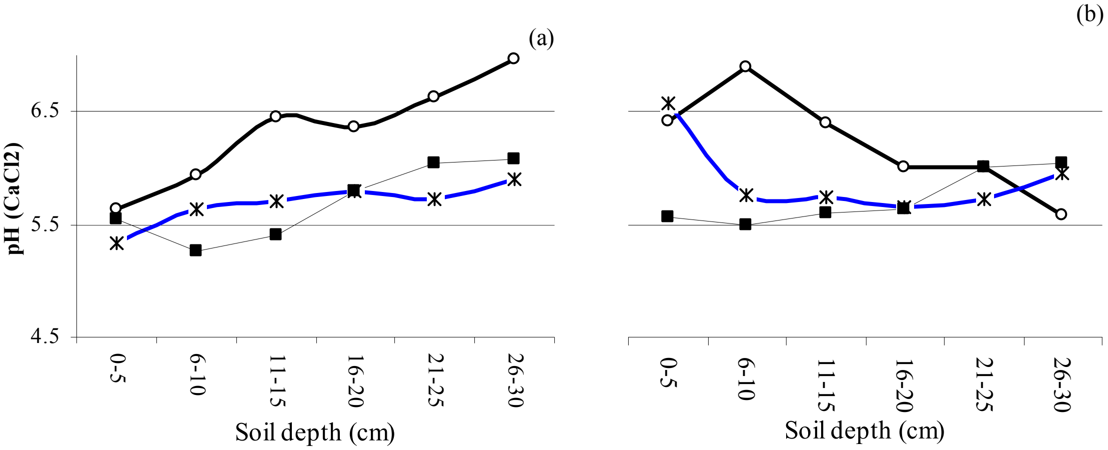


Figure 4-9 Soil pH and with soil depth (5 cm increments from 0 to 30 cm) over all seasons and crop cycles for Replicates 1 (a) and 2 (b) for complementary forage rotation (CFR) (o), pasture intensive pasture (PI) (*) and pasture extensive (PE) (■) treatments.

The mean ± se pH of the top soil (0-30 cm) for Replicate 1 (6.7 ± 0.1) and Replicate 2 (6.5 ± 0.1) was significantly higher ($P< 0.001$) at the end of the 2 years of monitoring compared to four years (1999 – 2003) previously when pH for Replicate 1 was 4.9 ± 0.1 and Replicate 2 was 5.0 ± 0.1. This reflects 4 cycles of CFR as well as the application of lime to the CFR plots

4.3.3. Soil pH buffering capacity

The soils titrated for buffering capacity were in the pH range from 4.5 to 7 and were therefore considered to be moderately acidic. Analyzing the titration results for the 0-30 cm soil depth indicated that the values for Replicate 1 (62.3 ± 12.2 kmol H^+/ ha/ pH) were lower ($P < 0.001$) than Replicate 2 (90.2 ± 6.1 kmol H^+/ ha/ pH) (Table 4.12).

Table 4-12 Regression equations for buffering capacity (pHBC) (kmol H+/ ha/pH) of soil and quantity of OH- added (0 to 1.11 meq) to 100g of soil samples taken from complementary forage rotation (CFR), pasture intensive pasture (PI) and pasture extensive (PE) treatments for Replicates 1 and 2 for soil increment of 0-30 cm.

Treatment	**OH (meq added/100g soil)**				**pHBC**	**Regression equation**	**se**	**r^2**
/replicate	0	0.37	0.74	1.11		**Y= buffer capacity**		
CFR1	6.02	6.31	6.47	6.67	74.9	0.209 X + 5.84	0.27	0.98
CFR2	5.12	5.30	5.43	5.56	100.3	0.146 X + 4.983	0.19	0.99
PI1	5.65	6.00	6.18	6.41	66.2	0.246 X + 5.445	0.32	0.98
PI2	5.12	5.32	5.47	5.59	90.7	0.156 X + 4.92	0.20	0.98
PE1	4.98	5.48	5.75	6.03	45.8	0.344 X + 4.697	0.45	0.97
PE2	5.02	5.25	5.37	5.51	85.6	0.159 X + 4.885	0.21	0.98

For the increments from 0-30 cm, the pHBC were in descending order, 100.3, 90.7, 85.6, 74.9, 66.2 and 45.8 kmol H^+ /ha /pH for treatments CFR2, PI2, PE2, CFR1, PI1 and PE1, respectively (Table 4.12). PI1 had a mean pHBC of 66.2 kmol H^+ /ha /pH despite an initially low pH, indicating a medium to high acidification effect in the top-soil. The large difference between replicates may be due to possible interaction between the soil type and the past crop practices (type pf pastures and soil amendments).

4.4. Changes in soil nutrients for plant growth

4.4.1. Quality of irrigation water

There were differences (*P* <0.001) between treatments, period and treatment.period on the amount of Cl, Mg and Na input by irrigation water onto plots but not on Ca input (see Table 4.13). The quality of irrigation water was markedly influenced by rainfall pattern with total salt dissolved (TDS) 72 % higher in the year 1 (drought year) (0.5 g/L) than year 2 (0.29 g /L).

Table 4-13 Means and results of statistical analysis for mineral input onto plots through irrigation water (calcium (Ca), chlorine (Cl), magnesium, and sodium (Na) (kg /ha /yr), electrical-conductivity (EC) (ds /m), sodium absorption ratio and pH of the irrigation water, on treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE)) and period (years 0, 1 and 2).

Items	Treatment (T) means			Sed	Period (P) means		Sed	Level of significance		
	CFR	PI	PE		Yr1	Yr2		T	P	P.T
Na	684	724	234	134	921	174	75.9	<0.001	<0.001	<0.001
Ca	49.5	64	52.7	10.7	55	43	6.87	ns	ns	ns
Mg	57.8	69.5	26.5	12.3	80	23	6.5	<0.001	<0.001	<0.001
Cl	538	610	273	119	657	290	43.6	0.011	<0.001	<0.001
EC	0.53	0.55	0.68	0.08	0.74	0.43	0.01	ns	<0.001	ns
SAR	23.6	22.6	26.6	4	28.5	20	3.3	ns	0.011	ns
pH	8.4	8.35	8.3	0.24	8.8	7.9	0.15	ns	<0.001	ns

The mean ± se input of NaCl in year 1 was 1578 ± 341 kg/ ha compared to only 464 ± 76 kg /ha in year 2. In this regard, the irrigation water used had a mean sodium absorption ratio (SAR) value of well over 20, and a pH above 8. Although different (*P* = 0.002) between the two years, the water was classified as saline, indicating a possible sodium hazard leading to sedimentation of Ca (Lindsay 2004).

Table 4-14 The input (kg/ha) of the four major minerals (sodium (Na), calcium (Ca), magnesium and Chloride (Cl)) onto plots from irrigation water for Replicates 1 and 2 of the complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments in years 1 and 2.

Year	Treatment / replicate	Na	Ca	Mg	Cl
		Mineral quantity (kg /ha)			
1	**CFR1**	1345	49	107	890
	CFR2	1033	60	76	639
	PI1	1216	52	110	859
	PI2	1295	72	118	963
	PE1	601	62	58	497
	PE2	37	34	10	93
2	**CFR1**	249	57	31	412
	CFR2	109	32	18	209
	PI1	221	55	28	361
	PI2	163	37	22	257
	PE1	233	52	28	377
	PE2	68	23	10	125

4.4.2. Loss of minerals through runoff

There were significant treatment effects (*P* <0.001) and the interaction (various *P* value) (see Table 4.15) for all the 4 minerals, while there was only a period effect (*P* =0.05) on Na loss. For the block effect, only Cl showed a different (*P* = 0.05).

Table 4-15 Means and results of statistical analysis for mineral loss from plots through runoff water (calcium (Ca), chlorine (Cl), magnesium, and sodium (Na) (kg /ha /yr), on treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE)) and period (years 0, 1 and 2).

Items	Treatment (T) means			sed	Period (P) means		sed	Level of significance		
	CFR	PI	PE		Yr1	Yr2		T	P	P.T
Ca	37.1	25	5	7	22	23	6	<0.001	ns	0.02
Cl	112	42	6	20	63	43	16	<0.001	ns	0.009
Mg	24.1	15	3	5	16	13	4	<0.001	ns	0.03
Na	100.2	26	8	19	61	29	16	<0.001	0.05	0.001

The loss of the major minerals through soil surface runoff is shown in Table 4.16 for the 2 years of study and surprisingly was greater in the dry year (year 1) than in the wetter year 2, presumably because more minerals were available to leach.

Table 4-16 The loss (kg/ ha) of the four major minerals (sodium (Na), calcium (Ca), magnesium, and chlorine (Cl)) (kg/ha), through runoff water for Replicates 1 and 2 for the complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments for years 1 and 2.

Year	Treatment / replicate	Mineral loss (kg/ha)			
		Na	Ca	Mg	Cl
1	CFR1	205.4	62.39	42.64	178.4
	CFR2	108.4	33.46	23.04	135.4
	PI1	37.7	30.45	22.83	59.7
	PI2	2.7	1.51	1.06	3.1
	PE1	8.2	3.51	3.39	3.2
	PE2	1.1	1.78	0.85	0.5
2	CFR1	36.5	24.32	16.29	40.8
	CFR2	50.3	28.33	14.54	92.9
	PI1	44.4	43.33	21.36	70.6
	PI2	20.7	24.79	15.32	32.6
	PE1	14.5	9.26	3.96	11.0
	PE2	8.5	5.56	3.72	7.2

There were treatment, period and period.treatment interaction effect for the net balance of Na, while there was only a treatment and interaction effect for Ca, Cl and Mg (*P* <0.001) (Table 4.17). There was no block effect (*P* >0.05) for the net balance of the 4 minerals (see Table 4.16).

Table 4-17 Means and results of statistical analysis for mineral net balance brought onto plots (calcium (Ca), chloride (Cl), magnesium, and sodium (Na) (kg /ha yr), on treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE)) and period (years 0, 1 and 2).

Item	Treatment (T) means			sed	Period (P) means		sed	Level of significance		
	CFR	PI	PE		Yr1	Yr2		T	P	P.T
Ca	53	153	67	21	87	90	17	<0.001	ns	0.02
Cl	437	623	278	132	617	275	50	<0.001	ns	0.009
Mg	50	102	34	13	87	37	10	<0.001	ns	0.03
Na	591	721	231	138	872	157	72	<0.001	0.05	0.001

Table 4-18 Net balance of the four major ions (kg/ha) accumulated during the two years for Replicates 1 and 2 for complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments.

Years	Treatment / replicate	Soil mineral balance (kg/ha)			
		Na	Ca	Mg	Cl
1	CFR1	1146	24	78	722
	CFR2	930	54	67	513
	PI1	1203	147	134	853
	PI2	1315	176	164	1013
	PE1	596	75	61	501
	PE2	39	47	15	100
2	CFR1	222	89	35	386
	CFR2	65	44	18	127
	PI1	207	165	69	356
	PI2	160	93	41	268
	PE1	224	84	39	377
	PE2	66	62	22	133

The greater accumulation of NaCl on the CFR plots was in the dry year (year 1) when on average 1655 kg/ha of NaCl was added to the plots. This fell to 400 kg /ha in year 2, which was similar to PI plots (Table 4.18) and simply reflects irrigation water input. In a wet year, the gain in NaCl in the PE plots was similar to the other treatments at 400 kg/ ha.

4.4.3. Effective cation exchange capacity (ECEC)

There was no effect ($P > 0.05$) of treatment or treatment.period interaction on Ca, K content of soil or on ECEC, but there was a ($P < 0.001$) treatment, period and treatment.period effect on both soil Na and Mg (Table 4.19). The soil content in sodium was highest, and Mg lowest, on CFR plots and the reverse was true for the PE control plots and reflects irrigation application rate. There was also a ($P < 0.001$) period effect on Na, Ca, K, Mg and ECEC (see Table 4.19) with the Na being highest in year 1 when irrigation input was at a maximum.

Table 4-19 Means and results of statistical analysis soil cations (calcium (Ca), potassium (K), magnesium, and sodium (Na)) content and effective cation exchange capacity (ECEC) (meq/100g soil)) on treatment (complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE)) and period (year 0 (yr0), 1 (yr1) and 2 (yr2)).

Items	Treatment (T)means			sed	Period (P) means			sed	Level of significance		
	CFR	PI	PE		Yr0	Yr1	Yr2		T	P	T.P
Ca	11.2	10.5	8.4	1.33	10.2	8	12	0.35	ns	<0.001	ns
K	5.2	5.4	4.8	1.34	4.4	4.4	6.6	0.33	ns	<0.001	ns
Mg	0.51	0.86	0.61	0.06	0.58	0.46	0.93	0.05	<0.001	<0.001	ns
Na	0.75	0.63	0.57	0.03	0.28	1.17	0.49	0.03	<0.001	<0.001	<0.001
ECEC	17.6	17.4	14.3	2.51	15.4	14	20	0.51	ns	<0.001	ns

The ECEC was significantly higher at the end of year 2 than year 1 or 0. The ECEC, (the sum of the major soil cations (Ca, K, Mg and Na)), decreased by the end of the first year (by less than 1% for PI1 to more than 14% for PI2), then increased over the subsequent year, relative to year 1, by 24% for PE2 to 55% for PE1.

The mean CEC in the soil from Replicate 2 (20.6 meq / 100 g soil) was significantly higher ($P < 0.001$) than Replicate 1 (12.3 meq/100g soil). In general, the variation in soil ECEC was driven by its Ca and K content, and to a lesser extent by Mg content (r values for the regression analysis between CEC and Ca, K and Mg in soil were 0.99, 0.92 and 0.59, respectively) (Table 4.20).

Table 4-20 Linear regression equation of K content (meq/100g soil) in the effective cation exchange capacity over the two years of the study from samples taken to 30 cm soil for Replicates 1 and 2 for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments.

Treatment/replicate	Linear equation	R^2
CFR1	1.3X + 2.5	0.83
CFR2	0.8X + 3.8	0.84
PI1	1.8X + 0.7	0.87
PI2	X + 4.5	0.33
PE1	0.7X + 1.3	0.86
PE2	1.2X +4.4	0.80

Over the two years of the study, the soil content of K increased the most (from 3 to 126 %). The slope of linear regression equation ranged from 0.8 to 1.82 with all R^2 over 0.8 except for PI2 treatment (r^2= 0.33), where the change was only different between periods (see Figure 4.10 and Table 20).

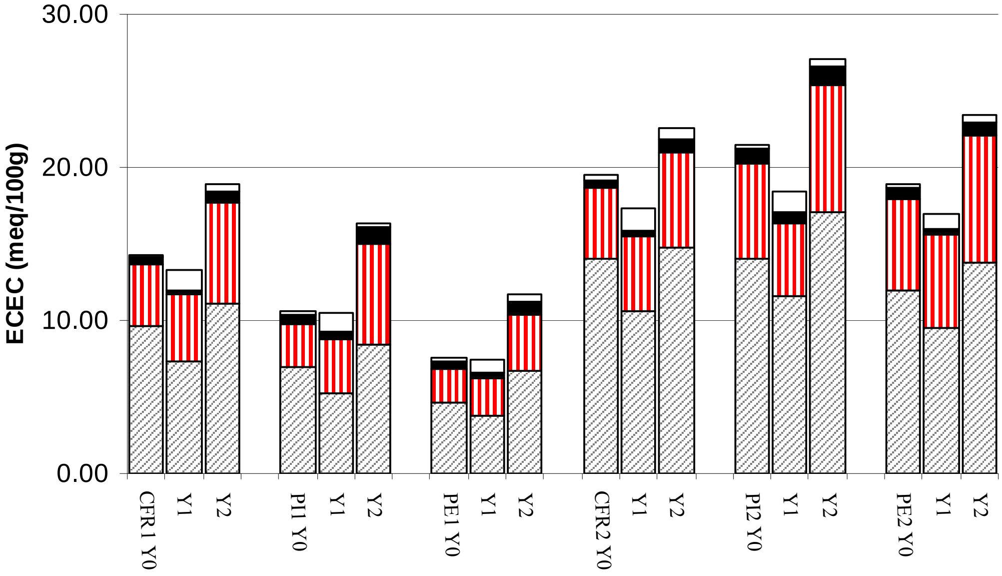


Figure 4-10 Soil effective cation exchange capacity (ECEC) (meq/100g soil) over the 2 years of the study from soil samples taken to 30 cm soil depth for Replicates 1 and 2 for the complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE) treatments. Values for calcium (▨), potassium (▥), magnesium (■) and sodium (□).

The rise in Mg content in the soil, over the study period, varied from 0.15 to 0.22 meq /year. The Mg content of soil was negatively correlated to the rate of application of irrigation water (r = -0.64) (see Table 4.21), being lowest in soil from the CFR plots (see Table 4.17) and, as expected with significant (*P* <0.001) seasonal variation. Sodium content in soil was strongly and positively related (r = 0.87), whereas Ca content was negatively (r = -0.28) correlated to irrigation application rate (Table 4.21). The proportion of the various cations was similar for each replicate/treatment (see Figure 4.11).

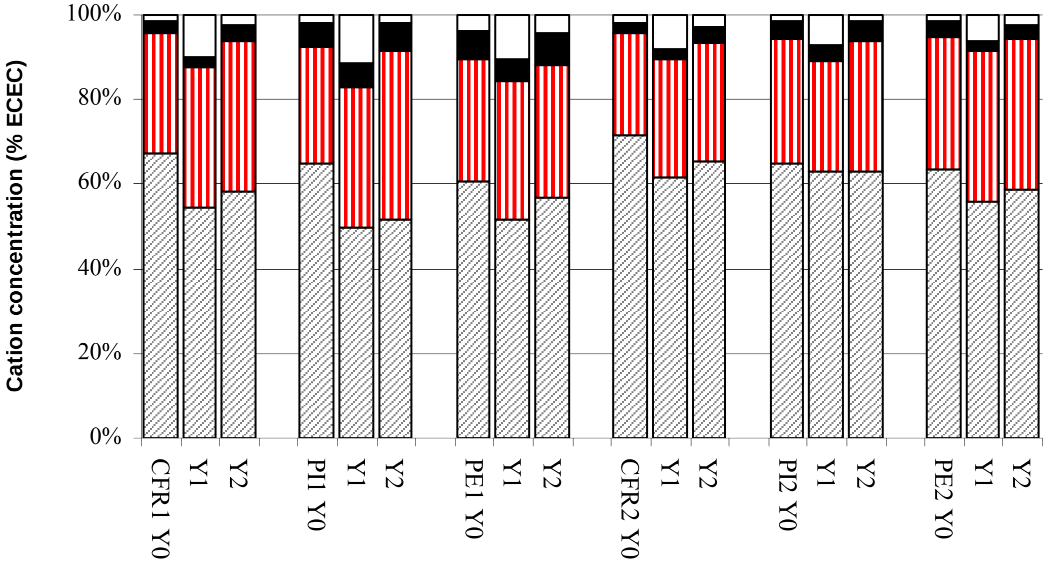


Figure 4-11 Change in the proportion of cations (%), value for (Ca (▨), K (▥), Mg (■) and Na (☐)) making up the soil ECEC over the 2 years (year 0 (y 0), year 1 (y 1) year 2 (y 2)) of the study for soil samples taken to 30 cm soil depth for Replicates 1 and 2 from the complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE)) treatments.

Table 4-21 Correlation matrix between the four major cations (Ca, K, Mg and Na) and ECEC in soil and amount of irrigation water applied (mm/ ha/ yr) to complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments.

	Ca	Irrigation	K	Mg	Na	Total ECEC
Ca	1					
Irrigation	-0.28	1				
K	**0.86**	-0.41	1			
Mg	0.56	**-0.64**	**0.61**	1		
Na	-0.28	**0.87**	-0.5	**-0.75**	1	
Total ECEC	**0.99**	-0.3	**0.92**	**0.59**	-0.33	1

Note: the bold figures represented correlation > 0.5

Calcium and K had by far the most influence on ECEC value (see Figure 4.11) with the proportion of K and Ca making from 83 to 96 % of ECEC (Table 4.21). In spite of the negligible influence of Na concentration on ECEC, the proportion of Na in ECEC was above the critical value of 5% by the end of the first year (Table 4.19), presumably due to the input of Na from irrigation water (mean ± se input of 657 ± 133 and 290 ± 46 kg Na /ha for years 1 and 2, respectively).

4.4.4. Soil salinity and electrical conductivity

There was an effect (*P* = 0.014) of treatment and period (*P* <0.001), but not the interaction, on the EC of topsoil. Thus, EC was greatest in the CFR plots and least in PE plots reflecting input of irrigation water and there was a reverse situation for the 70-100 cm soil depth samples (see Table 4.22). There was no effect (*P* >0.05) of treatment on EC of the 30-70 cm soil sample (see Table 4.22). Also there was a block effect (*P* = 0.008) for topsoil (0-30 cm) EC (0.128 ± 0.008 for block 1 and 0.147 ± 0.008 ds/m), but not for subsoil.

Table 4-22 Means and results of statistical analysis of electrical-conductivity (EC) (ds/cm) (0-30 cm) in topsoil (0-30 cm) and subsoil (30-70 cm and 70-100 cm) for treatment (complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE)) and period (year 1 and 2).

	Treatment (T) means				**Period (P) means**		**Level of significance**			
Soil sample	**CFR**	**PI**	**PE**	**sed**	**Yr1**	**Yr2**	**sed**	**T**	**P**	**T.P**
0-30 cm	0.16	0.15	0.11	0.02	0.16	0.12	0.01	0.014	< 0.001	ns
30-70 cm	0.22	0.21	0.26	0.04	0.23	0.23	0.04	ns	ns	ns
70-100 cm	0.23	0.27	0.43	0.07	0.36	0.27	0.06	0.013	ns	ns

The CFR plots were characterized by a stable EC value over the monitoring period over the whole soil profile (0-100 cm) (Figure 4.12a and d). In the pasture plots, there were large variations in soil EC between seasons in the subsoil profile (30-100 cm) but not in the top profile (0-30 cm).

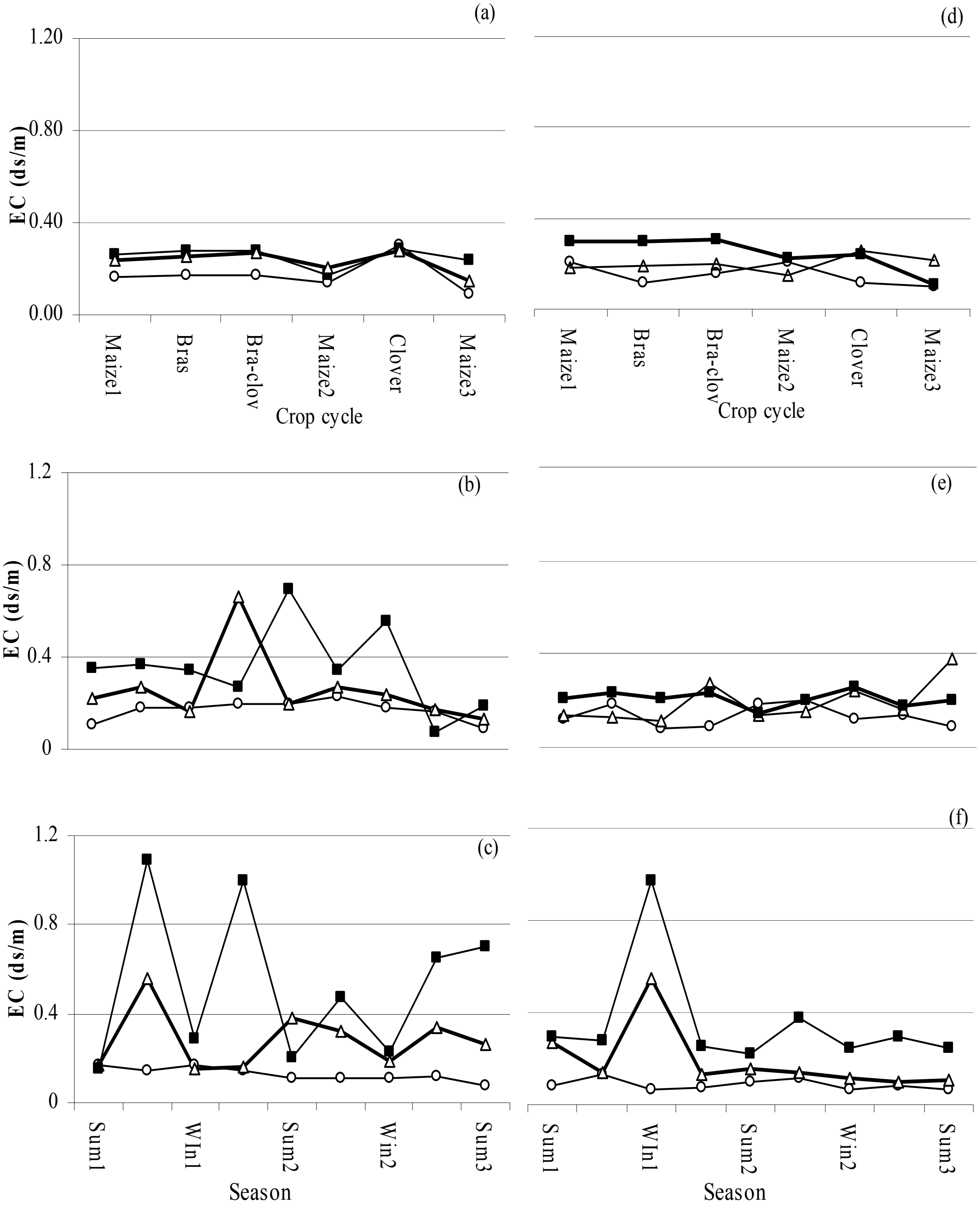


Figure 4-12 Soil EC (ds/m) at end of each season or crop cycle (years 0, 1, and 2) for soil samples taken at 0-30 (o), 30-70 (Δ) and 70-100 (■) cm soil depth for Replicates 1 (CFR1 (a), PI1 (b) and PE1 (c)) and Replicate 2 (CFR2 (d), PI2 (e) and PE2 (f)).

The absence or little irrigation in PE plots, combined with soil type and the status of subsoil salinity (see Table 3.1) could contribute to explain the subsoil salinity behaviour

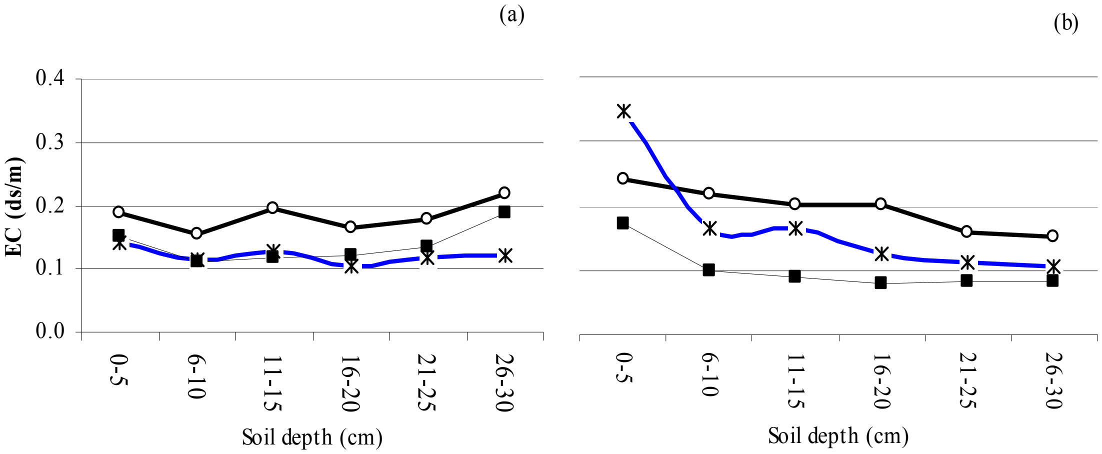


Figure 4-13 Soil electrical conductivity (EC) (ds/m) with soil depth (5 cm increments from 0 to 30 cm) over all seasons and crop cycles for Replicate 1 (a) and Replicate 2 (b) for complementary forage rotation (CFR) (o), pasture intensive pasture (PI) (*) and pasture extensive (PE) (■)treatments.

The topsoil was split into 5 cm soil depth increments from 0-30 cm and this showed a drop in EC in Replicate 2 (r^2 = 0.93, 0.69 and 0.56 for CFR2, PI2 and PE2, respectively, for regression analysis of EC on period) compared to a rise in the value of EC for Replicate 1 (PE1 and CFR1 but no change in PI1) and indicates a slight tendency to build up salinity in Replicate 1 (see Figure 4.13).

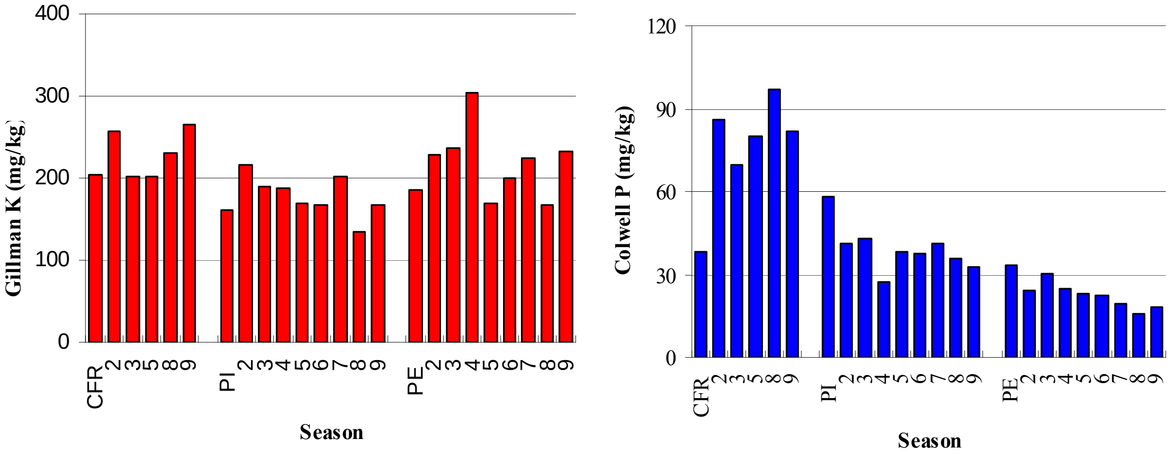
4.4.5. Change in available P and K in soil

There were effects (*P* <0.001) of treatment and treatment.period and for period (*P* = 0.003) and block (*P* <0.001) on soil Colwell P values. Gillman K content in the soil was effected (*P* = 0.04) by treatment (Table 4.23) and block effect (*P* = 0.01) only.

Table 4-23 Means and results of statistical analysis of soil Colwell P and Gillman K content (mg /kg) in topsoil (0-30 cm) for treatment (complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE)) and period (year 1 and 2).

	Treatment (T) means				Period (P) means			Level of significance		
Soil sample	CFR	PI	PE	sed	Yr1	Yr2	sed	T	P	T.P
Colwell P	77.4	41.3	24.6	11.8	45.7	50.0	1.4	< 0.001	0.03	< 0.001
Gillman K	224	176	214	21	209	200	12	0.04	ns	ns

Over the period of the study, the available P (Colwell) increased on the CFR plots but decreased on the PI and PE plots (Figure 4.14). As a result, Colwell P levels in the CFR soil were higher (*P* <0.001) than on the PI and PE plots. On the PE plots, Gillman K value was influenced by inputs of animal excreta and OM mineralization and varied more. The soil K content, was steady over time on all treatments but was higher (*P* =0.04) on the CFR plots than PI.



NB: Season 1(summer 1), season 2 (Autumn 1) …. Season 9 (summer 3)

Figure 4-14 Colwell P and Gillman K soil content (mg/ kg) for soil samples taken to 30 cm soil depth for the complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE)) treatments, seasonally/ crop cycle over the 2 years of the study.

4.5. Nutrient balance

4.5.1. Nutrient input and output

There was an effect (*P* <0.001) of treatment and period on input of N as excreta, with nearly 4 times more N onto PI plots than CFR plots, which reflects duration and stock rate of grazing (urine input) (Table 4.24).

Table 4-24 Means and results of statistical analysis of nitrogen input and output (kg N/ ha) for treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE)) and period (years 1 and 2).

Items	Treatment (T) means			sed	Period (P) means		sed	Level of significance		
	CFR	PI	PE		Yr1	Yr2		T	P	T.P
Excreta	43	122	29	7	57	72	2	<0.001	<0.001	<0.001
Fertilizer	486	494	0	662	343	310	54	<0.001	ns	ns
Irrigation	37	31	6	24	25	24	15	ns	ns	ns
Legume	107	159	87	37	113	122	21	ns	ns	0.012
O M	20	20	17	6	15	23	5	ns	ns	ns
Soil supply	68	1	26	54	-2	65	38	ns	ns	ns
Product	839	892	103	78	614	609	36	<0.001	ns	ns
Runoff	24	15	1	10	17	10	4	ns	ns	<0.001

NB: Soil supply was calculated from the difference between two soil tests

Most N input into the CFR and PI plots came from fertilizer (means = 65% of total input) but N fixed by the legume component also made a major contribution (mean = 18 % of the total input). Minor contributions came from OM breakdown (2.5%) and irrigation water (4.5%). There was no difference (*P* >0.05) between the intensive treatments on N removal as product or runoff.

There were treatment effects for all P inputs of excreta (*P* =0.002) fertilizer (*P* <0.001) and irrigation (*P* <0.001). As expected the P input from excreta was lowest in PE, significantly higher in CFR and highest in PI, and reflects excretion of dung during grazing (Table 4.25). Although P from irrigation was significantly different (*P* <0.001) between treatments, period and period-treatment interaction.

Table 4-25 Means and results of statistical analysis of phosphorus input and output (kg P/ ha) for treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE), and period (years 1 and 2).

Items	Treatment (T) means			sed	Period (P) means		sed	Level of significance		
	CFR	PI	PE		Yr1	Yr2		T	P	T. P
Excreta	20.4	32.6	7.2	7.0	12.3	27.9	5.9	0.002	0.008	ns
Fertilizer	190.4	72.0	0.0	6.6	81.5	67	19	<0.001	Ns	ns
Irrigation	1.2	0.8	0.3	0.2	1.4	0.2	0.1	<0.001	<0.001	<0.001
O M	10.7	9.0	7.3	2.8	3.3	12.2	2.3	ns	0.02	ns
Soil supply	-8.6	32	12.7	131	-33.4	12.4	19.2	ns	Ns	ns
Product	106	92.2	16.4	3.3	76.1	67	2.7	<0.001	<0.001	<0.001
Runoff	4.9	2.5	0.5	1.2	2.9	2.3	1.01	<0.001	Ns	ns

NB: Soil supply was calculated from the difference between two soil tests

The P removal in product and runoff were similar for the CFR and PI plots, but were greater (*P* <0.001) than the PE plots. The P input from excreta was greater (*P* =0.002) (nearly double) in year 2 than year 1 and this was due to the feed availability.

The input of K from excreta was over 4 times higher in PI than CFR plots and nearly 7 times higher than in PE plots (see Table 4.26). The input of K from irrigation water was virtually the same for CFR and PI but was lower (*P* <0.03) for PE and this is expected as the amounts of water applied to the intensive treatments was similar. Although, the K input from irrigation water was substantial, (18 % of total K input for CFR, 22 % for PI and for PE it was 31 %), by far the major K input for PE came from OM breakdown at 13 % of the total K input. The loss of K from runoff was not different between PI and CFR treatments but was significantly lower for PE. There was a period effect (*P* <0.001) with a reduction in K input from irrigation in year 2 and this was associated with a marked reduction in irrigation water use in year 2 and the lower mineral content of that irrigation water (see section of "quality of irrigation water").

Table 4-26 Means and results of statistical analysis of potassium input and output (kg K/ ha) for treatment (complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE)) and period (years 1 and 2).

Items	Treatment (T) means			sed	Period (P) means		sed	Level of significance		
	CFR	PI	PE		Yr1	Yr2		T	P	T.P
Excreta	25	108	15.3	19	60	39	16	<0.001	ns	ns
Fertilizer	433	164	0	10	180	218	9	<0.001	<0.001	<0.001
Irrigation	98	97	27	24	116	32	11	0.03	<0.001	0.002
O M	59	68	46	15	44	72	6	ns	<0.001	ns
Soil supply	-71	147	256	213	238	-17	174	ns	ns	ns
Product	700	799	144	31	565	510	25	<0.001	0.03	<0.001
Runoff	32	20	4.4	10	22	16	9	0.027	ns	ns

NB: Soil supply was calculated from the difference between two soil tests

4.5.2. Nutrient balances

Table 4.27 summarizes the inputs and outputs of N, P and K, then gives a balance for each treatment.

Table 4-27 Mean nutrient input (kg/ha) and soil supply (available) from fertilizer, irrigation water, animal excreta, OM mineralization, legume N fixation and output as product removal, runoff water, change in nutrients in the topsoil (0-30 cm) and nutrient balance (input-output) for complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments.

Balance components	Treatments (kg/ha/yr)								
	CFR			PI			PE		
	N	P	K	N	P	K	N	P	K
Fertilizer	486	190	433	494	72	164	0	0	0
Excreta	43	20	24	122	33	108	29	7	15
Irrigation	37	1	98	31	1	97	6	0	27
Mineralization	20	11	59	20	9	68	17	7	46
Legume	107	0	0	159	0	0	87	0	0
Soil supply	68	-9	-72	1	32	147	26	13	256
Total Inputs	**761**	**212**	**542**	**827**	**147**	**585**	**166**	**27**	**344**
runoff	24	5	32	15	3	20	1	0	4
Plant removal	839	106	700	892	92	799	103	16	114
Total outputs	**863**	**111**	**732**	**907**	**95**	**819**	**104**	**17**	**119**
Balance	**-102**	**101**	**-190**	**-80**	**52**	**-235**	**61**	**11**	**226**

If the “soil supply” of nutrients is positive, the soil has “released” the nutrient to make up the deficit between input (from other sources) and output. This means that the nutrient content in soil has declined. Thus, for the intensive treatments, the soil N has declined in the PI plots by 1 kg, CFR plots by 68 kg /ha and 26 kg/ ha for PE plots. In regards to K, the soil supply indicates K input as fertilizer could have been reduced in CFR, but probably needed to be substantially increased for the PI treatments. For P, CFR were in balance but the PI plots used 32 kg/ ha over the 2 years and PE used less at 13 kg P/ ha which could be a critical issue of nutrient loss through runoff. In this regard, the loss of N was extremely low (3.2% for CFR, 2% for PI and 0.6% for PE. The loss of P through runoff was also negligible and K (2.2% for CFR, 2% for PI and 0% for PE) was also low (5.3% for CFR, 3.4% for PI and 1.2% for PE).

The balance at the bottom of Table 4.28 reflects the difference between estimated input and output including changes in soil nutrient content. This balance should be nil but may not be due to losses of nutrients into the subsoil (soil’ “supply” measured changes in the topsoil (0-30 cm soil layer only) and errors in measurements and calculations. Thus, where the balance is positive, it is possible that nutrients may have been lost into the subsoil and from N volatilization and, to answer this, Table 4.29 presents at nutrient changes in the subsoil.

Table 4-28 Mean change in nutrients (kg/ ha/ yr) in the subsoil layers from 30-70 cm and 70-100 cm for complementary forage rotation (CFR) intensive pasture (PI) and extensive pasture (PE) treatments.

Soil depth (cm)	Treatments (kg/ha/yr)								
	CFR			PI			PE		
	N	P	K	N	P	K	N	P	K
30-70	8.8	-20.9	70.0	-74.8	-6.2	0.8	-12.3	-0.1	71.6
70-100	1.4	-4.6	22.8	-14.8	-1.6	-1.8	-5.4	-12.5	-26.3

A little nutrients movement (mainly released) from the soil during year 1 and substantial amount were fixed in year 2 excepted for K as indicated Table 4-29

Table 4-29 Mean change in nutrients (kg/ ha) in the subsoil layers from 30-70 cm and 70-100 cm for periods 1 and 2.

Soil depth (cm)	Periods (kg/ha/replicate)					
	Year 1			Year 2		
	N	P	K	N	P	K
30-70	8.0	6.4	89.6	-60.2	-24.5	5.4
70-100	-3.3	-2.7	-66.7	-9.3	-9.7	63.1

The changes in P in the subsoil layer for CFR and PI (25.5 and 7.8 kg /ha, for 30-70 and 100 cm, respectively) only accounted for about 5 and 12% of the decline in P from the topsoil. In fact, the changes for all nutrients are so small as to be insignificant except perhaps for P in the CFR treatment (22% of balance). Therefore the nutrient balance away from nil in Table 4.27 must have due to errors in assumptions and calculation, invariably at the input level, as the outputs (product and runoff) were measured reasonably accurately without any estimates or assumption being made. If this is the case, the errors are low for N, but high for P (discrepancy balance and total input for P = 26%) and for N and K the subsoil has also gained.

The nutrient balances in relation to year are shown in Table 4.30.

Table 4-30 Mean nutrient input (kg /ha) from fertilizer, irrigation water, animal excreta, OM mineralization, legume N fixation and changes in soil supply (available) and output as product removal and in runoff water and nutrient balance for years 1 and 2 in the in the topsoil (0-30 cm).

Balance components	Years (kg/ha)					
	1			2		
	N	P	K	N	P	K
Fertilizer	358	85	180	258	90	218
Excreta	57	12	60	72	28	39
Irrigation	25	1	116	24	0	32
Mineralization	15	6	44	23	12	72
Legume	113	0	0	122	0	0
Soil supply	-2	-30	237	65	22	-17
Total Inputs	**566**	**75**	**637**	**565**	**152**	**344**
Total outputs	614	76	565	609	67	497
Plant removal	16	3	22	10	2	16
Runoff	**630**	**79**	**587**	**619**	**69**	**513**
Balance	**-64**	**-4**	**50**	**-54**	**82**	**-169**

There were substantial differences between the 2 years in changes in soil nutrient content with a large loss of K from soil (237 kg /ha) in year 1, but a slight gain in year 2 (-17 kg /ha) while P was the reverse with a small gain in year 1 (-30 kg/ ha) and loss (22 kg/ ha) in year 2. This is reflected in available soil P and K shown in Figure 4.14.

The nutrient balance in relation to blocks is shown in Table 4.31.

Table 4-31 Mean nutrient input (kg/ha) from fertilizer, irrigation water, animal excreta, OM mineralization, legume N fixation and output as product removal and in runoff water for replicates and in the topsoil (0-30 cm).

Balance components	Replicate (kg/ha)					
	1			2		
	N	P	K	N	P	K
Fertilizer	305	88	202	319	87	196
Excreta	66	26	46	63	14	53
Irrigation	24	1	83	25	1	65
Mineralization	17	8	49	20	10	66
Legume	99	0	0	136	0	0
Soil supply	11	-1	-14	52	-7	235
Total Inputs	**523**	**121**	**366**	**615**	**106**	**615**
runoff	28	12	35	3	13	32
Plant removal	584	68	565	609	67	510
Total outputs	**612**	**68**	**524**	**638**	**75**	**552**
Balance	**-89**	**53**	**-158**	**-23**	**31**	**63**

In general, there was a larger loss of P from Replicate 1 than 2, and at 43% and 30% respectively, the loss is significant

4.5.3. Nutrient use efficiency

Table 4.32 shows the means and statistical analysis for apparent use efficiency of N, P and K for the 3 treatments.

Table 4-32 Means and statistical analysis of nutrient use efficiency (kg DM/ kg nutrient/ yr) for complementary forage rotation (CFR), intensive pasture (PI) and extensive pasture (PE).

	Treatment (T) means				Level of significance		
	CFR	**PI**	**PE**	**sed**	**T**	**P**	**T.P**
N	51.45	26.03	28.3	3.54	<0.001	Ns	0.027
P	178	315.1	138.2	157.3	ns	Ns	ns
K	67.5	33.57	42.83	9	0.006	<0.001	<0.001

The data clearly show nearly double the efficiency of use of N for the CFR plots than in the PI plots with the efficiency of use of PI and PE being about the same. There was no difference (*P* >0.05) in NUE for P, but the NUE of K was also greater (*P* =0.006) for the CFR plots than the other 2 treatments.

There was no difference (*P* >0.05) in the mean ± se NUE between replicates (Replicate 1; N = 36 ± 5, P = 148 ± 18 and K = 46 ± 8 kg DM /kg nutrient, and Replicate 2, N = 35 ± 5, P = 273 ± 126 and K = 50 ± 13 kg DM /kg nutrient) nor between years (year 1; NUE for N = 35 ± 6, P = 285 ± 124 and K = 36 ± 13 kg DM /kg nutrient and year 2; N = 35.1 ± 5.4, P = 135.8 ± 15.1 and K = 60.0 ± 5.0 kg DM /kg nutrient).

CHAPTER 5: Discussion

In this study, the major change observed in the soil status over the past 2 years of monitoring a CFR and a high input pasture system control has been the accumulation of salts, but these have been due to input from irrigation water and relate to the difference between output from runoff and input from irrigation, with both depending on rainfall.

As expected, there also appeared to be some acidification of the topsoil at the end of the 2 years, but this can be easily ameliorated by application of lime. The changes are complicated by the application of 4 t limestone /ha just prior to beginning of this study. The effects of liming seem to have moved from the 0-10 cm topsoil into the 11-30 cm layer during the following 2 yr (Figure 4-8). Based on the current buffering capacity assessment for the two soil types (Table 4-12), the primary lime application would have increased (in theory) soil pH by 0.5 to 1.2 pH units, respectively for CFR and PI plots (0-30 cm) (commercial calcium). The recent decline of soil pH during the last sampling season may indicate the necessity of re-applying lime to all plots. There were changes in soil OM and various physical properties of soil but these were related to season and soil type rather to than treatment.

The BD of the topsoil (0-30 cm) (table 4-1) not different between treatments, but did increase slightly over the two years, from 1.35 to 1.42 g/ cm^3. However, this increase in BD over time was due to a fairly substantial increase in BD of the 11-30 cm soil layer, and there was an actual decrease in BD in the 0-10 cm soil layer. Previous studies by Franzliebbers (2002) and Greenwood and McKenzie (2001) have also reported compaction in the lower topsoil layer and an improvement in the top (0-15 cm) layer under both cropping and grazed pasture situations. This is understandable, under CFR system the topsoil layer is subject to ground preparation when a seed bed for maize is prepared, loosening the topsoil and even under grazing the topsoil layer can be disturbed by pugging (hoof indentation), compacting the lower topsoil layer.

The accumulation of OM in the topsoil layer (0-10 cm) (crop residues and dung) may also have been responsible for improving the BD (Franzliebbers 2002). Interestingly, the R value, soil resistance to root penetration, was actually reduced in the intensive treatments (CFR and PI), further evidence to support the role of accumulation of OM in the topsoil (Table 4-3). More specifically the greater root penetration of the intensive treatments would be expected to leave macro-spores on decay and thus facilitate water movement down the profile as proposed by Devitt and Smith (2002).

In the present study, the soil (replicates) differences had a much greater influence on BD and R than year, with a higher BD and greater increase in BD of 8.2% in Replicate 1 (yellow duplex soil) compared to 3.2% for Replicate 2 (dark clay soil) and this was reflected in a lower FC and PWP for Replicate 1 (Figures 4-3 and 4-4). For Replicate 1, the hydraulic conductivity (Ksat) and water infiltration rate was 3 to 4 times greater than in Replicate 2, presumably due to the high clay content of the latter (Rengasamy and Mehanni 1988) as the BD was greater, (Austin and Prendergast 1997; Ross and Bridge 1984) and to less extent this induced an increase in Ksat near the root zone as reported by Frensch and Steudle (1989). The moisture and salinity status of the soil can also decrease infiltration rate, especially when saline water is used for irrigation (Rengasamy and Mehanni 1988).

In view of the large seasonal variations in OM content of the soil, it could be expected that there would be some uncertainty in relating changes in soil status from yearly measurements (Ratliff *et al.* 1983). Walker *et al.* (1992) noticed similar seasonal variations in PWP and Tchiadje (2007) suggested that could be due to the increasing soil salinity.

The only major adverse impact on the physical status of the CFR on the soil was an increase in soil loss through soil erosion, but at 0.6 t/ha /yr, it is still well below the average value for cropping land (4.7 t /ha /yr) and pasture (1.3 t /ha /yr) (Laughlan *et al.* 2004; Magid and Nielsen 1991; Mc Farlane *et al.* 1992). These losses were negligible for all the plots and representing 0.016% and 0.002% of the total topsoil, respectively CFR and pasture plots (PI and PE). The higher loss of soil from CFR plots was probably associated with the time and the soil was bare when being prepared for sowing of the maize crop and this could be substantially reduced by direct drilling the maize. Direct drilling can give similar yields as in a fully prepared seed bed if appropriate equipment is used. Thus, apart from the greater loss of soil from CFR plots than the PI and PE plots, there does not appear to be any adverse effects of the CFR on the physical status of the soil and its water holding capacity.

The large difference in rainfall between the 2 years provided an interesting comparison in both water balance and nutrient movement within the system (Table 4-7). These changes induced great period.treatment interaction effect ($P = 0.004$) on total water inputs and irrigation (Tables 4-6). Thus, the amount of runoff in year 2 was at all times greater than in year 1 and deep drainage was nearly double. Both of these factors led to a slight decrease in WUE in year 2 compared to year 1 (from 17.2 to 16.1 kg DM/ mm water/ yr) but the difference was minimized by the higher yields, particularly of the PI. Overall, the impact of irrigation water change, combined with the soil and crops type have induced large period.treatment interaction effects on deep drainage ($P < 0.001$), soil moisture content ($P = 0.003$) and WUE ($P < 0.001$) (Table 4-6). This also meant a larger proportion of salts (NaCl) were lost from the system in year 2 than 1. For example, only 6.6% of Na input from irrigation water was lost as runoff in year 1, but this rose to 16.6% in year 2 (Table 4-16). As a result, more exchangeable accumulated (Na, Ca, Mg and K) in year 1 (1663 kg/ ha) than in year 2 (559 kg /ha). For treatments, cation accumulation it was higher respectively on PI (1599 kg/ ha) and CFR (1131 kg/ ha) than PE (610 kg/ ha) (Table 4-18). This difference between the intensive treatments and PE obviously was due to input of minerals from irrigation water, and between the intensive treatments was probably associated with the greater runoff from CFR (131 mm/ ha) compared to PI (86 mm/ ha) plots. Overall, soil moisture (correlated at 0.71) was the main factor influencing the quantity of runoff water (Table 4.8) (Cooper *et al.* 2005), followed by total water received by plots (correlated at 0.54).

Although the lower Etp explains some of the higher WUE of CFR compared to PI (30.3 ± 1.5 vs. 15.3 ± 1.2 kg DM / mm water), by much the greater influence would have been the doubling in yields of the CFR compared to PI (40.5 ± 1.8 t DM/ ha 20.4 ± 2.3 t DM/ ha, respectively) (Table 4-6). An additional factor would have been the ability of the deep rooting crops to source water from lower in the soil profile that would otherwise be lost during the few floods during the dry seasons, particularly in the Autumn-spring ryegrass phase (Dawson and Pate 1996). In turn, the surface runoff from the CFR was increased by growing the crops on raised beds (6 m wide with furrows about 0-30 cm deep).

The soil OM is one of the most important soil fertility indexes (Tchiadje 2007), not only does it influence soil physical structure but it is also critical in providing continual release of plant nutrients by mineralization and also improves ECEC (Condron *et al.* 2000; F.A.O. 1995; Foth and Ellis 1997). Despite no difference between treatments in OM content of soil (see Table 4-9), there were substantial seasonal and replicate variations, with OM content of Replicate 2 always being 2 units above Replicate 1. The mean OM content of about 5% is good and is in range of recommended for crops (about 5-7.5%) and pasture (about 2.5 to 5%) (Baldock and Skjemstad 1999), as these recommended values are for the 0-10 cm soil layer which is invariably higher in OM than the 0-30 cm layer on which present measurements are based. The periods of maximum forage growth in Winter/Spring for pastures and summer for crops tended to be associated with higher rates of OM accumulation due to root development. The change in the C/N ratio, over the 2 years of the study indicates an excess of cover N mineralization during the study (Rosco *et al.* 2001).

The only significant treatment effect on soil pH was in the topsoil (0-10 cm) where PI plots (6.93) were higher than in the CFR (6.36) or PE (6.4) plots (Table 4-11). There was an increase in pH over time ($P < 0.001$) in the 0-30 cm layer but the pH in the 0-10 cm soil layer was actually steady whereas in the 11-30 cm soil layer, pH increased substantially. This probably reflects the movement of lime down the soil profile from application of 4 t /ha in 2004 before the start of the present study. In addition, the accumulation of OM could have impacted positively on soil pH (Drinkwater *et al.* 1995; Reganold 1988). According to Conyers *et al.*(1997) a deficit water balance (year 1) in a calcareous soil could explain the pH variations especially from the residual lime on the topsoil (previous liming). This could induce to the greater period.treatment interaction effect ($P = 0.003$) on the topsoil pH (Haynes 1983) (Table 4-9). In addition, irrigation with alkaline (55% samples above pH = 8) water would have increased soil pH. Yadav *et al.* (2002) reported similar results when alkaline tertiary-treated sewage water was used to irrigate. Lastly, some of the variation in soil pH may have been attributable to weathering of parental material, such phenomenon has been reported by Sollip (1998) in tropical lowland rain forest. The climatic condition of the site (high summer temperature and rainfall in year 2) matched these conditions.

The initial soil pH of the intensive pastures prior to this investigation was similar (4.9 ± 0.4) to this of the beginning the CFR trial. At the commencement of the monitoring period, pH in the topsoil (0-10 cm) was above 6, and remained relatively stable over the 2 years of the study. However, in the lower topsoil layer (11-30 cm) the pH increased to about 5.6 ± in CFR and PI, but PE1 stayed at 4.0 with the Replicate 2 block means at 4.6. This, plus the gradual increase in pH of the 11-30 cm layer probably indicates a movement of lime from the topsoil to the lower layers.

The pH changes over time in the lower topsoil could be due to the lime effect and the root dynamism, mixing the two layers of the topsoil (Figure 4.8). Also Ca diffusion in the soil is low, trapped below the root system due to the low Ca diffusion down the soil profile in the PI plots (Tang *et al.* 2000) whereas cultivation for corn sowing would have mixed the Ca through the surface profile (Figure 4.8).

The mean input of NaCl from irrigation water in year 2 was about 25% of year 1 (1578 ± 341 vs. ±464 ± 76 kg NaCl/ ha) and this was a consequence of 2 factors:

1- Only 44% of irrigation water was used in year 2 compared to year 1.
2- The quality of the irrigation water with the total dissolvable salts being 72% higher in the drought year (0.50g /L) than in year 2 (0.29g / L).

Although, the loss of NaCl through runoff was greater in year 1 (124 ± 64 kg/ ha) compared to year 2 (71.6 ± 20.5 kg/ ha), as a proportion of total input it was much less, at 6 and 17%, respectively. As a result, 1800 kg NaCl / ha accumulated during year 1 on the intensive plots (CFR and PI) and a further 445 kg NaCl / ha in year 2. The use of highly saline irrigation water is known to limit productivity (Peverill *et al.* 1999) by its adverse effect on soil structure (soil dispersion) (Bernstein 1975; Hall 2008), leading to decreased porosity and infiltration of water down the soil profile. The Tables 4-15 and 4-17 show a similar level of significance for the 4 major ions (Ca, Mg, Na and Cl) which indicated that the ions flows (in and out) were proportional. The greater treatment.period effects for these ions indicated that substantial amount mineral introduced by irrigation water can be easily removed through runoff when climatic conditions become favourable.

The ECEC of the soil really relates to the proportion of Ca and K in the soil. The ECEC of Replicate 2 was greater than Replicate 1 presumably due to the higher clay content in soil of Replicate 2 (Peinemann *et al.* 2000). Potassium as a proportion of total ECEC rose most during the study period with input primarily from fertilizer but also from mineralization of OM (Foth and Ellis 1997; Manrique 1991).

There was a negative correlation between irrigation and Mg (r = 0.64) that is explained by the replacement of Mg by Na from the irrigation water. The massive Na input from irrigation water would have also replaced some of the Ca ions in the soil, thereby reducing the impact of saline water on ECEC (Feigenbaum and Meiri 1988) (Table 4-19). But this will lead to problems especially on heavy soils and the subsoil that is close to the surface on the slopes, and tunnels. Lastly, the greater variability of Na inputs introduced through irrigation water during the study period may also affect proportionally its content in ECEC (treatment, period and interaction effects; $P < 0.001$) (Table 4-19).

The EC recorded in the topsoil ranged from 0.19 to 0.45 ds /m (with 20 to 40% clay) which is regarded as an acceptable level of salinity for most crops (Shaw 1999). The EC was lower in the PE plots (0.11 ds/m) than in the intensive plots (0.16 and 0.15 ds/m, for CFR and PI, respectively) and probably relates to input of irrigation water and fertilizer on the latter plots.

The results of the studies indicate that the major problem with build up of salinity comes from irrigating with relatively saline water for all intensive pasture plots (Table 4-19 and 4-13), caused mainly by Na, Mg and Cl and could explain the greater interaction treatment.period (Table 4-13). The rise of soil salinity reduced available water for plants and could explain the increase soil PWP (Tchiadje 2007) recorded in Section 4.1.4. The rising salinity in the subsoil (Figure 4.22) could limit the roots capacity to explore a deeper soil volume, conditions recorded by Mehanni and Repsys (1986). However, this increase in salinity was not related to treatments and did not affect forage yields in the same sites where this study was conducted, and where CFR and PI treatments were compared for 4 consecutive years (Garcia *et al.* 2008). However, the long-term use of saline water for irrigation is a risk due to the effect on water-table and spreading land salinity (Bethune and Wang 2004). Strict control of water quality will be necessary to sustainable maintain productivity (Peverill *et al.* 1999).

Another major goal of this study was to quantify losses of nutrients as runoff in surface water and deep drainage, in view of the possible impacts on the environment. The estimated runoff of N from the CFR was 24 kg/ ha/ yr, or 3.1% of total estimated input of N compared to 1.8 % for PI and 0.6% for PE, with the latter being virtually zero (Table 4-26). The combination of rainfall and plant grow potential (contribution of legume N input) could have been responsible for the high period.treatment effects on legume N input (P =0.012) and indirectly on excreta N input (P< 0.001) through frequent grazing, and therefore on total N loss ($P < 0.001$) (Table 4-24). Thus, although the loss of N from the CFR was higher than either pasture treatments, the total N lost was still very low. There was a net loss of N from the soil pool of 68 kg/ ha/ yr for CFR whilst the PI plots were neutral due to N movement down the soil profile in CFR plots (Table 4.30). This was probably due to greater exposure of bare ground on the CFR plots (drainage) and water aggressiveness (rainfall and irrigation) generating more runoff events (Gentrya *et al.* 1998).

The balance of N represented about -102 and -80 kg/ ha more N used than applied respectively for CFR and PI and probably reflects an underestimation in the calculated inputs (legume N, OM or excreta, probably through microbial immobilization) (Table 4-29). The subsoil layer played an important role in storing and later releasing the surplus N from the topsoil layer (30-100 cm) in the CFR plots, where 10.2 kg N/ha /yr or 1.3% of the total N input, was likely to be leached, perhaps due to the soil preparation (tillage), as reported by Stenberga *et al.* (1999). Overall the results indicate an adequate input of N in relation to output and this is expected as only N is less storable nutrient in the soil compared to P and K. There was low contribution from OM breakdown both in absolute values 20 kg/ ha and relative to total N input (2.6%). The use of slow N fertilizer with low leaching potential such as urea nitrate, ammonium nitrate (ONCE), or isobutylidine diurea (IBDU) could reduce N the leaching (Swift 1995) in the CFR.

Seasonal soil analysis indicated a decline in plant available P for the PI and PE treatments but an increase in the CFR plots and suggests an increase in P fertilizer application may be needed in the PI plots (Figure 4.14) in relation with potential P cycle (soil release, microbial contribution and crop needs) (Nelson and Janke 2007). The greater treatment.period effect ($P < 0.001$) on P irrigation was due to the quality of irrigation water and the amount of water applied during the study period. Also, the reduction of number of crops (3 to 2 in year 2) may have changed the crop P demand and therefore may induce the great treatment.period effect ($P < 0.001$) on P removal (Table 4-25) and overall soil P available (Table 4-23). The decline P in PI would be expected as with adequate fertilizer application; the soil is being mined (retained by soil). These results are in line with changes in soil P supply where there was a gain of 9 kg/ha in the CFR plots and losses in the PI and PE (Table 4-28).

The loss of P from runoff follows the same trend as with N in the CFR plots 4.9 kg/ ha/ yr or 2.4% of the total estimated input of P, for PI, the figures were 3 kg/ ha/ yr or 2% of input and for PE the loss was zero as the faith of P is linked to uptake of N (Nelson and Janke 2007). These losses are very low, in contrast with some studies, for example (Dougherty *et al.* 2008; Williams and Haynes 1991). However, in another study, the major loss of P was mostly soluble P and organic P constituted a minor part of the loss (Tate 1984). Nash *et al.* (2007) found a correlation between decrease of P sorption and the increase of water extractable P and P sorption saturation. The movement of particulates with irrigation in the present study would have been negligible particularly in Replicate 2 with a flat aspect (slope <0.5%) and set sprinklers applying at a rate to coincide with infiltration rate. In addition the major P input was with pre-maize sowing when most was incorporated into the soil. It is possible that the movement of P in dung during intensive rainfall events, especially in year 2, could have been significant and hence increased P loss. This is likely as the unexplained P loss was large high for CFR and PI plots.

The trends in available K for all plots over time indicate an adequate supply of K. The significant period.treatment effects (Table 4-26) were recorded for fertilizer, irrigation and crop removal indicated high variability of nutrients inputs which depended on crop type (plant growth potential) weather; and amount of inorganic fertilizer input (depending on crop needs and soil release). There was a build up of K in the soil of the CFR plots (72 kg/ ha/ yr) but the substantial losses in the PI (147 kg/ ha/ yr) and PE (256 kg/ ha/ yr). There were probably due to high K fertilizer input in CFR plots, especially as the vertisol soil of Replicate 2 while has a strong K buffering capacity and can release substantial K (Marta *et al.* 2004) from non-exchangeable sources (see Table 4.32). The loss of K from runoff is again small and relatively similar to P and N losses 32 kg/ ha/ yr. or 5.3% of total estimated K input, for PI it was 20 kg/ ha/ yr or 3.4% of input and for PE it was 4 kg/ ha /yr or negligible.

The study by Meiri *et al.* (1984) indicated that K leaching increased with increasing Ca and Na content of irrigation water. In year 1, when 2.3 times more irrigation water was used at 5.3 times the Na content, the unexplained loss ‘balance’ was 50 kg/ ha whilst in year 2 169 kg/ ha were gained by the system. Also, Kolahchia and Jalali (2006) highlighted a possible displacement interaction between these cations (Ca^{2+} and Na^{+}) and K^{+} in the soil (ECEC) exposing K more to losses. That may be true as ECEC Ca was near 2 fold in Replicate 2, compared with Replicate 1. The potential subsoil (30-100 cm of soil layer) K leaching was higher in CFR plots; 92.8 kg K / ha/ yr. or 15.5% of the total input, for PE it was 45.3kg K/ ha/ yr. and negligible for PI plots. The leaching is due to the soil potentiality to release K (in relation with soil type), fertilizer inputs, crop needs and water mobility (Johnston and Goulding 1992).

Movements of the most mobile nutrients (N and K) were directly influenced by water balance, which related to crop productivity. As a consequence, the CFR plots recorded 2 fold greater NUE for N and K compared to PI plots, while P use efficiency showed an inverse trend. This was due to high P inorganic fertilizer (190 kg/ ha/ yr for CFR against 72 kg P/ ha/ yr.) in regards to low plant P uptake (99 kg P/ ha/ yr). In fact, the soil has released substantial P during the 2 years of the study corresponding to 112 kg P/ha/ yr for CFR and PI plots compared to PE with 78 kg P/ha/ yr which could explain the significance effect on available soil P recorded in Table 4-24. Nitrogen and potassium were limiting production nutrients and where the input varied during the study period, which were mainly replenished through fertilizer could have induced treatment.period effect on N and K use efficiency (Table 4-32). These data illustrate the necessity of understanding the mechanisms of soil nutrient release in order to optimize fertilizer inputs.

CHAPTER 6: Conclusions

The comparison between 2 intensive systems (CFR and PI) and an extensive pasture system (PE) control indicated no adverse effects on soil physical and chemical properties. Differences between the pasture and CFR systems were due more to different management interventions which saw rotational grazing for the pasture systems and a mixture of periods of cultivation and crop growth and timed grazing during the brassica and clover stages in the CFR system. In the absence of eventual soil physical changes recorded during the two years of the investigation, it can be concluded that at an experimental scale at least, carefully managed CFR can be implemented for several consecutive cycles with minimal effects on soil properties and nutrient balance, despite its potential to double the yield of well managed pastures. In addition the CFR combines very different fodder types some of which may complement cows' diet in much the same way as concentrates (e.g. forage rape with its high ME), and there may be other management benefits from the combination of grazed (forage rape and clover) and harvested options (maize).

Provided that there are no significant scaling up issues, from the perspective of sustainability of local soil and nutrient systems it would seem that the CFR approach is a viable option for dairy farmers to significantly intensify forage production on their farm. The results of this study also suggest that CFR systems could succeed in a range of soil types.

The achievements of the CFR under trial at EMAI since 2004 represent a milestone for the dairy industry facing rapidly increasing pressures on availability and costs of quality agricultural land, declining access to irrigation water, the raising cost of fertilizer, concentrate and hay. A CFR may allow dairy farmers to reduce the area of their farm allocated to forage production while securing quality forage in a sustainable manner. Some dairy farmers may face a situation where they have little choice but to intensify production and reduce expenditure on bought in feeds, and depending on their resources, a CFR may enable them to do this and remain in business.

Overall, this study has demonstrated that greater yields are achieved through CFR systems without adversely affecting soil physical and chemical properties compared to typical pasture production systems. With consistent yields achieved over the four years that the FutureDairy CFR trials have been running at EMAI, the CFR is fast emerging as a useful option for forage production with the potential to allow farmers to produce significantly more DM from a given area of land and with similar inputs of fertilizers and water for irrigation as required for high yielding pastures. Of course, results at experimental plot scale need to be verified at a commercial scale and to this end, trials to characterise the potential and constraints around CFR on real dairy farms. These studies include detailed studies of crop production in addition to examining the labour and lifestyle impacts and economic outcomes for farmers. In addition, whole farm systems research commenced in 2007 which is examining the CFR as one element of a pasture-based dairy farm system and the undergoing research at the University of Sydney's dairy at Corsterphine (Camden NSW) could find answers to these questions.

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