A review of the nature of beef cattle industry in the Solomon Islands with emphasis on Soil Fertility factors influencing pasture production on selected farms

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ABSTRACT

A general review of primary production in the Solomon Islands indicated that cattle grazing is mainly an activity involving smallholder farmers for cash income and consumption for their extended families. The review and a farm survey indicated that the productive capacity of pasture soils and many agricultural soils in Solomon Islands, continues to decline because poor, near-subsistence, farmers are unable, for economic reasons and lack of training, to provide land management strategies for crops and grazed pastures that maintain or improve soil fertility.

This thesis reports on three investigations undertaken to assess the fertility levels of some pasture soils in Solomon Islands. This knowledge is required to develop soil fertility management strategies to assist in sustaining the productivity of grazed pasture and the beef cattle industry in the country. The review indicated that most soils are developed from volcanic materials and a few from corals. Most land considered suitable for agricultural use has not been characterised and recorded. Increasingly, the soils require additional sources of nutrients as they only obtain nutrients from decomposed organic matter and weathering soil minerals.

Four farms (ASI, ILA, NAC, and STJT) were selected and surveyed focussing on examining their general background information, identification of pasture species, and evaluating the efficiency of record keeping practices. The pasture grass/legume species identified on the farms are T-grass, Carpet grass, Paragrass, White clover, Puero, Centro and Mimosa. Attempts to maintain soil fertility were based on traditional methods of using local waste materials as organic manures. The survey indicated that farmers are lacking in knowledge and did not value the importance of farm record keeping. Therefore, farm records were not available to provide sufficient information to construct a nutrient budget for each farm.

Soils and herbage samples were collected in different places within the study areas. Soils were collected at 0-7.5 cm and 7.5-15 cm depths. These samples were chemically analysed and used in a glasshouse trial to test the growth response of white clover *(T.Repens)* to phosphate (P) and potassium (K) and sulphur (S) fertilizer additions. Low soil P test values were common, however analysis of the field sampled herbage did not confirm P deficiency. In the glasshouse trial, however legume growth was highly responsive to soil type, initial soil P status and added P fertiliser. Legume growth was non-responsive to application of K and S.

Recommendations relating to farm record keeping, soils and herbage tests results, and alternative strategies to improve/maintain the soil fertility are discussed. Future research directions that should be taken to boost the production of pasture and beef cattle industry are also discussed.

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The Almighty God for His endless love and provision.

DEDICATION

This piece of work is dedicated to my brothers (Jeffrey, Moses and Junior), sister (Selina) and grandfather (Jeffrey Silas Fokao), particularly, my mother (Nathalyn) and father (Roland) who believed in me and dedicated their time for my education.

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All my struggling extended family members and distant relatives who believe in their own efforts.

Tagio baita asia na uria liothaua kamolu fuaku. Foa la oe bia angi la oe, Arai lo e lua na i tara'ina. Nia kai adomi kolu ana si kade tala e ni u kainao ani kolu.

Tangoa God! Tangoa God! Tangoa God!

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CHAPTER 1 INTRODUCTION TO THE RESEARCH

This Chapter provides a brief introduction to the research topic and outlines the structure of the review (Chapters 2 and 3) and research sections (Chapters 4, 5 and 6) of this thesis.

1.0 Background to the establishment of grazed pastures in the Solomon Islands

The Solomon Islands (see Figure 1) consists of a group of islands located in the South Pacific region. It was discovered in 1568 during a Spanish expedition to the Pacific, captained by Alvaro de Mendana de Neira. He gave the name, "The Islands of Solomon" to the islands in the belief that he had found the lost riches of King Solomon (Bennett, 1987). The expedition was aimed at establishing new colonies for Spain, hunt for treasures, and to convert people from paganism to Christianity. However, no treasures were found and consequently the Solomon Islands (SI) were not colonised. After the discovery, the Solomon Islands had no regular contacts with other countries for a period of two hundred years until the arrival of whalers and traders from Europe. During the 1800s, whaling was a major economic activity in the Solomon Islands' waters, which consequently resulted in the exploitation of the country's natural resources. Traders who intermarried and/or exchanged items for land settled in various parts in the Solomon Islands. They established coconut plantations under the Levers Pacific Plantation Limited (LPPL) on most islands in the Solomon Islands (Hinton, 1969).

Later in the mid-19th century, christian missionaries arrived and introduced cattle and goats into the country chiefly for milk and thereafter, expanded cattle production as an industry. Cattle farming has been regarded as suitable for the Solomon Islands in terms of locally available pastures according to past research (Osborne, 1979). The development of the beef cattle industry was initiated by the Solomon Islands' government from 1970s-1980s through support from institutional services such as the Livestock Development Authority (LDA), and the Development Bank of Solomon Islands (DBSI). Although the Sixth National Development Plan had aimed to raise 80,000 head of cattle by 1981-1983 (Waroka, 1997), this target was not achieved due to several socio-economic factors which hampered the country's development. A similar situation had also occurred between 1996 and 2009 where the industry target being set were not met due to political upheavals. A cattle herd of 400 was recently (October, 2011) imported from Vanuatu to revitalise the industry (Ministry of Agriculture and Livestock Development, 2011). The expansion of the beef/cattle industry was due to two main contributing factors: (i) the development of coconut plantations and the increase in demand for imports from overseas, and (ii) the need to promote import substitution in beef. At the time, the major importers of cattle for beef production and control of undergrowth on coconut plantations were the LPPL and Government, and cattle were sourced from Australia, New Zealand, New Caledonia, Vanuatu, and Papua New Guinea (Reece, et al., 1988; Wahananiu, et al., 1993).

Initially, the cattle industry made good progress however, at a later stage, it experienced some fluctuations and slowly declined as result of (i) World War II in the South Pacific region, (ii) poor management practices, and (iii) outbreak of diseases (Wahananiu et al., 1993). Up until the present time, the political instability experienced by the Solomon Islands Government has had a significant negative impact on the productivity of existing farms and has delayed the implementation of strategies targeted at revitalising the beef cattle industry. The success or otherwise of other major primary industries in the Solomon Islands also has a bearing on commercial activity whether or not there is interest in cattle farming and a demand for meat products. Apart from the above factors, the fact that there is little information on both soil fertility and pasture species of existing grasslands may have also affected the ability of key players involved to manage and sustain a productive beef cattle industry. Research (Gutteridge, 1978; Gutteridge & Whiteman, 1978a; Litscher & Whiteman, 1982; Watson & Whiteman, 1981) has shown low yields in terms of weight gain in the animals and poor performances in pastures grown, which are subject to poor pasture management and limited amount of essential nutrients present in the soils. This thesis includes firstly, a review of the developments in the primary industry in the Solomon Islands and secondly, a detailed survey of the soil fertility and pasture species of selected farms in Solomon Islands.

The productivity of pasture-based enterprises largely relies on the climate, moisture regime, and fertility status of soils. Generally, in Solomon Islands, soils have low fertility and there is no widespread use of fertilizer. This is confirmed by Gutteridge and Whiteman (1978a) who noted that there is low fertility in pasture soils in the Solomon Islands. This often results in low yields thus affecting the income of individual farmers and other key players in the agriculture industry. The low pasture yields obtained further contribute to poor growth rates (weight gain) in cattle. To date, research on soil fertility in pasture soils of the Solomon Islands has not been considered a priority in many agriculture development projects. In addition, other studies (Gutteridge, 1978; Litscher & Whiteman, 1982; Watson & Whiteman, 1981) conducted in the Solomon Islands did not consider climatic conditions, soil fertility, and appropriateness of pasture species as important. Furthermore, no study has been conducted to establish the optimum nutrient requirements to maximise and sustain animal production from pastures.

1.1 Overall Research Study Hypothesis and Research Objectives

Hypothesis

The hypothesis for the study is:

A detailed survey of grazing management on a small number of cattle farms plus a study of the presence and nutrient status of indigenous pasture species and soils on thesis farms will: (a) identify soil fertility factors limiting the growth of productive pasture species; and (b) provide evidence-based information on how to manage the provision of essential nutrients to grazed pasture in the future, in a sustainable manner.

Aim

The aims of this study are to: (i) undertake a review of the role of cattle grazing in Solomon Islands Primary production, and (ii) conduct a pilot survey on 4 selected farms.

Objectives

The main objectives of the project are:

i. To provide a general overview of Solomon Islands, development in the agricultural sector, including cattle production from grazed pastures.

ii. To identify four farms suitable for a survey of cattle production from grazed pastures.

iii. To design and undertake a survey on cattle production, pasture type, grazing management, and soil fertility in order to construct a nutrient budget of farming activities specific to each location.

iv. To sample and chemically analyse soils and pasture species of four farms on Malaita and Guadalcanal to determine their soil fertility and acidity statuses, as well as to identify the dominant pasture species grown in these sites.

v. To evaluate the pasture soils by conducting a subtractive nutrient glass house trial to assess the response (growth/yields) of white clover to different fertilizer treatments.

vi. After understanding the fertility of the soils under study, propose alternative farm soil fertility management strategies to assist in sustaining the grazed pasture production in the Solomon Islands.

1.2 Scope and Limitations

The scope of this study involves the collection, analysis and presentation of information from the selected farms to be used as a model for other beef cattle farms in the country. As revitalisation of the cattle industry is one of the Solomon Islands government's development priorities, this study is timely as it coincides with the stage of pasture establishment or improvement at the farms identified under the National Cattle Development Project. The outcome of this research will provide a strategy and future reference for the evaluation and development of pasture systems in the Solomon Islands. In terms of limitations, the research carried out on soils in Solomon Islands country is limited. The time available in this research for the field trial was also limited. These may therefore have implications on the results of the study.

1.3 Organisation of the Thesis

There are seven chapters in this Thesis. Chapter One provides an introduction to the thesis, which includes the aims and objectives of the research. Chapter Two explores the overview of background information of Solomon Islands, developments in the agricultural sector, and related information. Chapter Three provides a literature review on the importance and sources of soil fertility, chemical indicators of soil fertility, importance and sources of soil acidity and alkalinity, factors affecting soil fertility, factors affecting the performance of pastures, important soil tests to evaluate soil fertility and acidity status, and limitations to productivity of fertile soils. Chapter Four describes the methodologies used in field survey, collection and disposal of samples, soils and herbage chemical analysis, glasshouse trial, and report writing. Chapters Five and Six involves description and discussion of the results obtained. Chapter Seven outlines the conclusions and recommendations.

CHAPTER 2 SOLOMON ISLANDS

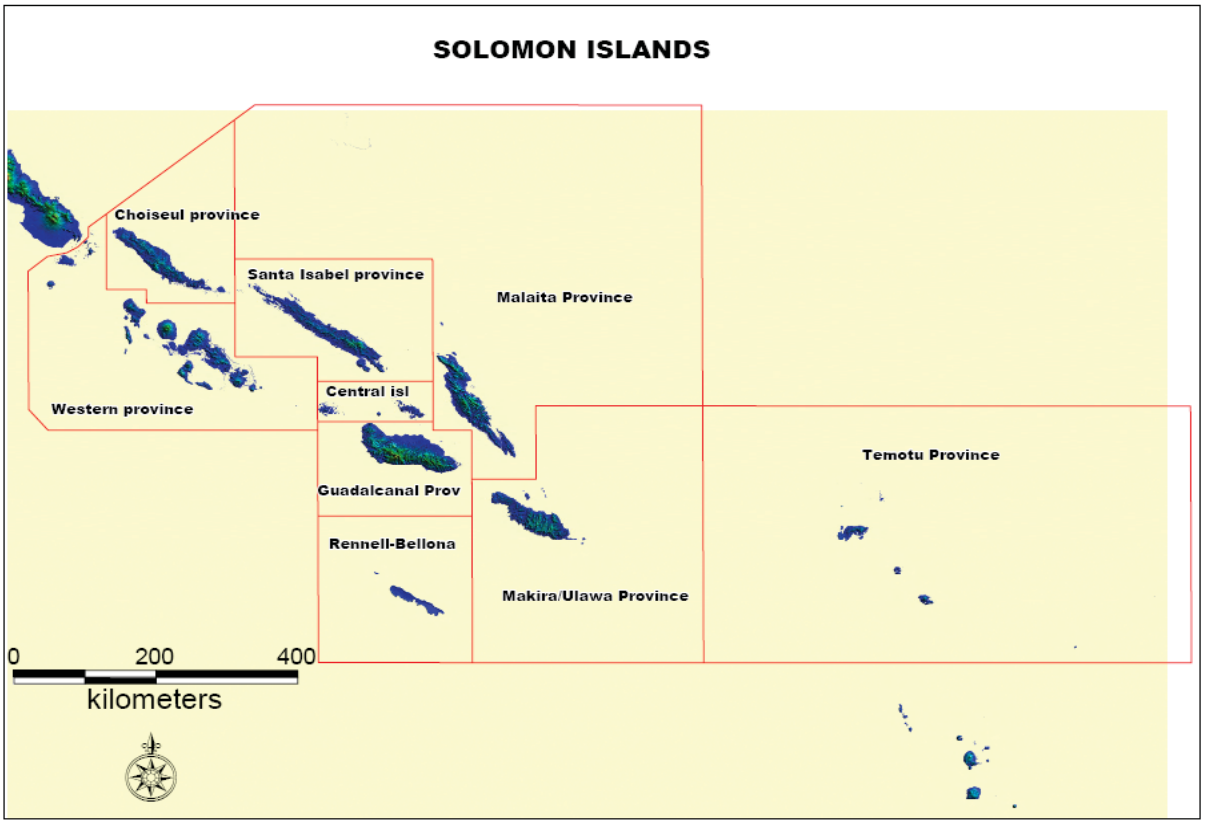
2.0 Chapter Overview

The purpose of this chapter is to provide an overview on the general background of the Solomon Islands, its history, and current agricultural development in the country. Section 2.1-2.6 describes the geography of Solomon Islands, government, population, its vegetation, climate and humidity and temperature. Section 2.7 describes the specific location of the study, which includes location and soils. Primary industries, which are tuna fishing, tourism, forestry, minerals, crops and plantation agriculture, and livestock production, are described in section 2.8. Section 2.9 concludes the chapter.

2.1 Geography

Solomon Islands is located between the latitudes of 5˚ and 12˚ South of the equator, and between the longitudes of 154˚ and 162˚ East. It consists of a scattered double chain of islands in the South Pacific that stretches across the Bismarck Archipelago, about 1,000 km from Bougainville in Papua New Guinea. Solomon Islands' closest neighbouring countries are Vanuatu and Papua New Guinea. The country is made up of six large islands (Guadalcanal, Malaita, New Georgia, Santa Isabel, Makira and Choiseul) and more than 900 odd small islands, atolls, and clays. Solomon Islands' total land area is about 30,000 km^2 where one third is under agricultural activities (Hansell & Walls, 1974), and the land use patterns differ from one island to another (Hviding, 1996; Hviding & Bayliss-Smith, 2000). The capital of Solomon Islands is Honiara, which is located on the north-western coast of Guadalcanal, the largest island (5,650 km^2) (Berdach & Llegu, 2007).

Figure 1 Map of Solomon Islands



Source: Solomon Islands National Statistics Office (2011)

2.2 Government

The Solomon Islands gained its independence in 1978 after being a British protectorate since the 1890s. The framework for the national government system has been predominantly influenced by the British Westminster system, which was adopted under British rule. National elections are held every four years to elect members of parliament who represent their constituencies (Crocombe, 1989). After the national election, a government is formed either by the party with the majority of the 50 seats in the parliament, or by confederacy between several parties. The Prime Minister is voted by the 50 members of parliament and is often a member of the party that has the majority in the parliament.

2.3 Population

Nationally the estimated population of Solomon Islands is 515,870 people, with 2.3% average annual growth rate. The population of Malaita province in 2009 was estimated around 137,596 and growing at an average annual growth of 1.2% while for Guadalcanal, it was estimated to be 93,613 people (Solomon Islands National Statistics Office, 2011).

2.4 Vegetation

The majority of the country's land area is clothed in tropical rain forest except for small areas of probably anthropogenous grasslands and heaths, which occur in regions with a seasonal climate. The main features of the vegetation are described and related to the exceptionally wet climate of the archipelago. The extensive areas that carry thickets of small trees and climber tangles instead of high forest are due to the combined influence of man, earthquakes, landslips, and cyclones. Many species are shown to have wide ecological amplitudes (Whitmore, 1969).

2.5 Climate

The country's climate is primarily determined by the equatorial conditions, modified by the surrounding oceans, with high humidity and high rainfall all year round. It is one of the wettest regions of the world. Average annual rainfall is mostly within the range of 3000 to 5000mm with the majority of monthly rainfall amounts in excess of 200 mm (Hansell & Walls, 1974; Solomon Islands National Statistics Office, 2002). Heavier seasonal rains are normally experienced from December to April when the equatorial trough migrates across the islands (Solomon Islands Meteorological Service, 2010). According to the Köppen Climate Classification System, the climate of the Solomon Islands can be classified as **Af** climate, a hot, humid tropical climate with all months above 18°C.

2.6 Humidity and Temperature

The main feature of temperature in Solomon Islands is its uniformity, with seasonal variations extremely small, and little variation with latitude is evident. It is between 22-31ºC throughout the day and between 19-21ºC at night. The land and sea breezes cause the lower night temperatures. The South easterly winds can alter the weather conditions during the dry months from June to October. From December to May, tropical cyclones occasionally occur, often causing extensive damage to the country's flora and also impacting negatively on national infrastructure and economic development.

2.7 Specific location of study

2.7.1 Location

This study was conducted in two locations, namely Malaita Province and Guadalcanal Province (see Figure 1). The two provinces were selected because of their easy access to road and sea transport, and both contribute in terms of beef production towards the local market.

2.7.1.1 Malaita Province

The Island of Malaita (see Figure 1) is located (9°02'48.71" S 161°08'05.88" E) at the southern end of the northern group of Solomon Islands. It has a total land area of 4,200 km^2, which is made up of three islands: namely Maraupaina (Big Malaita), Maramasike (Small Malaita), and Malaita Outer Islands. The Malaita Outer Islands are made up of coralline atolls. They are Lord Howe, Ontong Java, Sikaiana and Ndai. Ndai Island is approximately 40 kilometres off the north of Big Malaita with an area of 17 km^2. On the southern end of Malaita province are Ugi and Ulawa islands, of Makira Province (Hansell & Walls, 1974).

The coastal shorelines of Malaita province consist of coral reefs and were formed by volcanic activities. The intended coastal shores provide good seaport inlets for boats during bad weather. These coralline inlets along the shores of Big Malaita have formed some sea water lagoons, referred to as Lau lagoon, Ara'Are lagoon, and Langa Langa lagoon (Hansell & Walls, 1974). The land formations in certain regions of the province were formed from low flat coral and calcareous soils have developed. In the central and mountainous areas, the soils are red clay (silty clay loam) and brown in colour and they are derived from strongly weathered volcanic materials (Hansell & Walls, 1976).

2.7.1.2 Guadalcanal Province

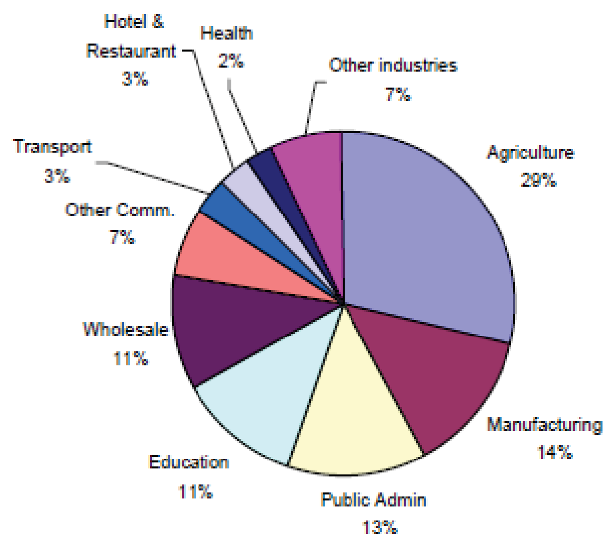
The Guadalcanal province (see Figure 1) is regarded as the largest of the main islands in Solomon Islands with a total land area of 5,310 km^2. The province is located (9°35'14.30" S 160°14'16.17" E) in the Central Southern part of the country where the capital city (Honiara) is situated and most decentralization has taken place. On the North-West and South-East of Guadalcanal there are rugged mountains whilst coastal plains known as the 'Guadalcanal Plains,' which have high potential for agriculture use are also located within the North-West region. The two highest mountains of the province are Popomanaseu (2,330 metres) and Makaranakomburu (2,450 metres) (Hansell & Walls, 1976).

The soils in Guadalcanal province are Andisols ("dark soils") mainly derived from volcanic material, and basaltic or andesitic ash with a high content of allophane (an amorphous clay mineral). The weathering process of the high mountainous regions and the deposition of sediments from the sedimentary rocks had contributed to the formation of the soils in the low-lying areas. The soils formed on Guadalcanal have common characteristics such as free drainage and are brownish loams and clays. On the Guadalcanal Plains, the soils are less susceptible to flooding risks and are generally covered with grass, deep dark and carbon-rich, and drier than soils in the upper regions. The plains have six land systems where about 337 km^2 out of 450 km^2 have been estimated to be available for agricultural production. The Guadalcanal plains are located between the Nggurambusu and Kombito rivers, and extend for about 11 km in-land to the Metapona River (Hansell & Walls, 1976; Rapaport, 1999).

2.8 Primary Industries

The economy of the Solomon Islands is dominated by a number of key players in the primary industry, which operate locally and play an important role in the country's development. These industries are agriculture and livestock, fishing, forestry, and minerals from which 75% of the export earnings are derived from (Solomon Islands National Statistics Office, 1995). Each of these primary industries contribute significantly towards the majority of the people in the Solomon Islands in terms the provision of employment, cash income, shelter, food consumption, and other means of support for their livelihood and well-being. However, the most important industries, which have a comparatively huge impact on the people, are agriculture and the livestock industry. This is because the majority of the people in the Solomon islands follow a subsistence lifestyle involving minor and major farming activities such as crop and livestock production (Douglas, 2004). A large proportion of the population is involved in the primary industries (see Figure 2) which contributes towards the export of commodities such as copra, cocoa, palm oil, fish and timber (Asian Development Bank, 2010; Rarawa, 2010). Most of the export earnings however, come from the agricultural sector (including timbers and fisheries) (Solomon Islands National Statistics Office, 2008).

Figure 2 Industry Contributions to National Provident Fund



Source: Rarawa (2010)

2.8.1 Tuna fishing industry

Solomon Islands (SI) domestic tuna fishery began in 1972 with the establishment of Solomon Taiyo Limited (STL). In July 2000, the company ceased its operation and withdrew its shares as a result of a two-year social unrest in the country. The company is now 100% owned by the SI Government Investment Corporation (SIGIC) and has been renamed as Soltai Fishing and Processing Limited. The fishery operated under STL and then Soltai, and it has grown to become one of the major foreign exchange earners and the largest employer (see Table 1) in the country (Oreihaka, 2001). Tuna fishing has been the second highest source of foreign revenue earner to the country from the export of frozen and other processed tuna products to overseas markets (Diake, 2005).

Table 1 Employment by Sectors

The agriculture sector generally has the highest employment throughout the years compared to other primary industries (forestry, fishing, and mining) or sectors.

Employment by sectors	Year			
	1995	1996	1997	1998
Agriculture	4157	4093	3809	3356
Forestry	4040	3313	2709	2658
Fishing	2623	2844	2579	1412
Mining & Exploration	32	38	62	1412
Manufacturing	1471	1612	1665	4348
Electricity & Water	631	703	650	387
Construction	1474	1925	1638	1187
Retatil & Wholesale	3921	4066	3844	4641
Transport & Telecom	1427	1972	1777	1878
Finance	1291	1422	1602	1183
Public Administration	6244	6198	1016	4261
Other	4080	8567	5057	8750
Total	**31536**	**36846**	**26408**	**34061**

Source: Houenipuela (2000)

The methods of fishing used inside the country's territorial waters are pole-and-line, purse seine, and long lining. Fishing vessels from Japan, Taiwan and Korea are allowed to fish within the territory under bi-lateral arrangements whilst US purse seiners have access to the restricted zone of the Exclusive Economic Zone (EEZ) under the Multi-lateral Treaty arrangement (Oreihaka, 2001). The foreign-based tuna fisheries companies have operated in the country for a number of years.

The Solomon Islands' ocean is about 1.3 million km^2, which has been rated as the seventh largest fishery zone in the south Pacific region (Argue & Kearney, 1982). Skipjack (*Katsuwonus pelamis*) and small yellowfin (*Thunnus albacares*) are the main tuna species caught for processing and exportation. The main fishing company currently operating and/or based at Noro in the Western province is Soltai Fishing and Processing Limited. It is owned by SIGIC and is a joint-venture with foreign companies to fish within the territory (Makasi, 2010; Oreihaka, 2001).

2.8.2 Tourism industry

The tourism industry in the Solomon Islands began in 1900s long after contacts between natives and foreigners (whalers, traders and Christian missionaries) had formed in the 1800s. During those days, efforts to attract a regular flow of Europeans were unsuccessful. Whether prompted by a sense of curiosity or inquisitiveness, these efforts were futile because of very little information about the country appeared in the international media (Douglas, 2004). However, over the years, the tourism industry has slowly expanded. In 2009, the industry continued to expand total visitor arrivals increasing to 19,440 visitors during the year, up by 11% compared with the same period in the previous year. Of this total, 18,260 were air arrivals and 1,180 sea arrivals. Most of the visitors were from Australia (49%) and New Zealand (8%) and stayed on average for about 15 days in the country. Tourism development in the country has been boosted by a number of key factors such as an increase and/or improvement of airline and hotelier services, and an increase in competition in international routes complemented by reduced travelling price (Rarawa, 2010). The remnants of World War II, diversity of cultures, traditional artefacts, lifestyle, wild life, and so forth are some of the major tourist attractions, which Solomon Islands currently have. The tourism sector has the potential to contribute more towards overall economic development if adequately supported and carefully developed (Douglas, 2004; Keqa, 2010).

2.8.3 Forestry industry

About 85% of the total land area of Solomon Islands is covered by approximately 2.4 million hectares of forest. Eighty seven percent of the total land area is under customary land tenure system where land-use is decided by a tribe or community. Less than 20% of the natural forest is suitable for commercial log harvesting (Duncan, 1994).

Forestry has been the largest foreign exchange earner in the Solomon Islands' economy (Duncan, 1994); however, logging activity was weak in 2009, with a decline in exports (Rarawa, 2010). This is because of the low demand from external markets, in particular, the weakness experienced in the Asian housing markets. Log export volumes dropped by 31% to 1,044,854 cubic metres, following the 5% growth reported in 2008. Log export applications totalled 1.488 million cubic metres, with approved applications totalling over 1.3 million cubic metres, valued at USD 105 million (SBD 821 million).

The Ministry of Forestry has introduced two new policies, to promote an increase in domestic income from logs and to create a more sustainable industry. The policies involve the enforcement of downstream processing by all logging companies to increase production of sawn timber and final timber products, and a reforestation program targeted at replanting of one third of logged areas (Rarawa, 2010).

2.8.4 Minerals

The Solomon Islands is located on a so called, 'rim of fire' where the Pacific Plate is forced below the Australian Plate (Crocombe, 1989). This 'rim of fire' is well known for vast areas of mineral deposits that runs passing across Indonesia, the Pacific, to Australia. The discovery of phosphate, gold, copper, oil, and other minor minerals in the Solomon Islands has been the result of numerous explorations in search for mineral deposits in the 1980s-1990s.

In the past, gold exports have come from alluvial gold deposits found by local people. In 1998, gold mining operation was first opened and operated in Solomon Islands by a company named Ross Mining at Gold Ridge in Guadalcanal Province. Its production made a first time contribution to the Solomon Islands' production and export base during the quarter when the first export consignment was made in August 1998. However, the net benefit was small because of (i) the small size of the operations, (ii) the low gold prices in the international markets, and (iii) the high level of external costs (Central Bank of Solomon Islands, 1998). In 2000, Delta Gold Limited took over the operations and ownership of the Gold Ridge Mining Limited (GRML), but in June of that same year the company was forced to abandon the mine because of the civil unrest on Guadalcanal. Through an international bidding process, the Australian Solomons Gold Limited (ASG) took control of the Gold Ridge Project in 2005.

Despite unresolved issues on (i) land acquisition, (ii) resettlement scheme, (iii) the tailings dam, (iv) landowners' demands, and (v) continued delays from political risks, the re-development of the Gold Ridge Mine on Guadalcanal has always been a priority of successive governments (Houenipuela, 2008). The successful takeover of this project in late 2009 by Allied Gold Limited was a major step forward in the redevelopment of Gold Ridge, as the company brought with it a large amount of secured equity finance. The mining operations were expected to begin in the second quarter of 2011 and had already started when this report was written. Annual production was estimated at 136,000 ounces of gold in the first three years and 124,000 ounces thereafter over the seven-year life of the mine (Rarawa, 2010). There are prospecting activities on nickel that are continuing on Isabel and Choiseul provinces where high occurrences of nickel ore has been confirmed (Rarawa, 2010).

2.8.5 Crops and plantation agriculture

Minor cash crops grown in the Solomon islands are chilli (*Capsicum annuum*), ginger (*Zingiber officinale*), pineapple (*Ananas comosus*), peanuts (*Arachis hypogaea*), and tomato (*Solanum lycopersicum*), which are cultivated by farmers on a semi-intensive level. In agriculture, cash crops are those crops that are grown for profit. They are produced predominantly for home consumption and the surpluses are sold at local markets for income. The majority of minor cash crops are sold at the urban centres to meet the consumption needs of the country's working population. According to Varuia (1993), on average a farmer would spent half of his or her time cultivating food crops and vegetables. The rest of his/her time is spent on the maintenance of buildings and fulfilling other commitments to the family and community. The major food crops (staple crops) that are grown from regular to a seasonal basis and sold at the local markets are: potato (*Impomoea batatas*), cassava (*Manihot esculenta*), yams (*Discorea alata*), pana (*Dioscorea esculenta*), and taro (*Colocasia esculenta*) (Solomon Islands National Statistics Office, 1995). These are grown on semi-intensive farming systems. The importation of other food crops for domestic consumption needs has been substituted by self-sufficient domestic food crops and vegetable production. The Solomon Islands' economy partially relies on agricultural exports where most cash crops are produced under semi-intensive and commercial systems/farming.

The chief commercial cash crops in the country are oil palm (*Elaeis guineensis*), cocoa (*Theobroma cacao*), and coconut (*Cocos nucifera*), which are generally processed before exportation. Oil palm is processed into palm oil and palm kernel, coconut into copra and coconut oil, and cocoa into dried beans. Both coconut and cocoa products have enjoyed strong growth in volume and are standout successes in terms of sustainable export earnings (Roughan & Wara, 2010). Cocoa production grew 5% to 4,553 tons in 2009, following a 0.4% increase in 2008 to 4,326 tons. Due to the weakness in the performance of the Commodities Export Marketing Authority (CEMA) (the agency tasked with overseeing the country's commodity exports), copra production was affected. In 2009, CEMA was constrained by financial and budget limitations however, this did not preclude the increase in the volumes of coconut oil produced at the end of 2009 by 16% (to 634 tonnes from the previous year's tonnage of 546 tons) (Rarawa, 2010).

Overall production of oil palm derivatives, with the exception of palm kernel oil (PKO), also experienced a significant growth. Crude palm oil (CPO) rose by 14% to 25,123 tons, indicative of an increase in the extraction rate of 21%. Similarly, palm kernel increased by 15% to 7,083 tons. Palm kernel oil was processed with a total of 3,098 tons, 187 tons below 2008 levels. Palm kernel expeller (meal) grew 21% to 3,632 tons from 2,993 tons reported in the previous year. The positive output resulted from the improved yield of fresh fruit bunches, which rose by 15% to 119,377 tons (Rarawa, 2010). In a novel situation for the Solomon Islands, the Guadalcanal Plains Palm Oil Limited (GPPOL) is currently processing palm oil for export from plantations managed by both independent out growers and the company itself (Roughan & Wara, 2010). GPPOL is a Papua New Guinea (PNG) based company, which took over the operation of the former Solomon Islands Plantations Limited (SIPL) on the Guadalcanal plains in May 2005 (Houenipuela, 2006). Vangunu Oil Palm project is another palm oil producing company, which began in 1992 on a 10,000 hectares crown owned land on Vangunu Island (Houenipuela, 2005), and currently operates at a small scale, producing oil with a capacity of 5 tons per hour (Houenipuela, 2006). In March 2009, the Auluta Oil Palm Project marked its establishment phase in the Auluta basin on Malaita (Rarawa, 2009). Other export products in 2009 included kava (*Piper methysticum*) whilst commodities such as honey, vanilla, coffee, and rice, which are slowly expanding have been identified for future exportation, excluding rice (Rarawa, 2010).

2.8.6 Livestock production

The livestock production in the Solomon Islands comprises of poultry, goats, ducks, pigs, and cattle (see Table 2), which are generally raised for meat consumption to improve the protein intake of individuals in the local community (Jansen, et al., 2009; Keqa, 2010). The Solomon Islands is self-sufficient in pork and poultry production at rural community level. About 80% of the population raises pigs and poultry, either by traditional or commercial methods whereas cattle farms are mostly owned by (i) small holders (communities or individuals), (ii) private companies, and (iii) Christian mission schools (Wahananiu et al., 1993). Due to problems associated with erratic and costly supplies, transport costs, lack of electricity for processing and storage, and marketing difficulties, most of the livestock commercial activities are concentrated around Honiara while very little activities take place in the Provincial centres (Wate, 1995). The suburbs in Honiara and the provincial centres receive adequate and a consistent supply of pork and chicken, while beef supply is scarce therefore resulting in the high level of imports of beef products.

Table 2 Species and breeds of livestock in the Solomon Islands

Cattle	Pigs	Goats	Horses	Chickens	Ducks	Bees	Potential Breeds
Brahmans	Large White	Angora	Origin unknown	Austrolop	Muscovy	Apis mellifera	Temotu Wild Fowl
Hereford	Landrace	Sanaans		Rhode Island Red	Peking		Megapode Birds
Shorthorn	Berkshires	Anglo Nubian		Anacona	Indian Runner		
Jerseys	Tamworth			Malayan Game	Khaki Campbell		
Friesians	Saddleback			Hampshires			
Ayrshires	Wild pig			Broiler breeds			
Santa Gertrudis	Local crosses			Layer Breeds			
Limousines				Village Crosses			
Simmental				Santa Cruz Wild Fowl			
Solomon Island Red							

(Source: Nonga and Keqa (2004)

2.8.6.1 Poultry industry

The poultry industry has experienced a rapid development over the past years. It consists of traditional smallholder farmers who are raising village chickens (local species) for income, as well as for their personal protein needs, and commercial farmers who are raising layers for eggs and broilers for meat. The traditional smallholders operate independently from the commercial layer and broiler industry and they produce about 210,000 birds per year, selling eggs and live birds in local markets as one of their major sources of income. It is estimated that 21,000 families (about 40% of the rural population) are currently involved in the production of eggs and live birds (Glatz, 2009). Birds are fed from household food scraps and other locally available feedstuffs, and a family consumes only about one bird per month on average. For commercial birds, fertile eggs are imported from New Zealand and Australia by two local hatcheries, which hatch day-old chicks (DOC) which are then sold to farmers. The cost of meat and eggs from the commercial birds are high compared to village birds and this is mainly due to the high costs of imported feed from New Zealand, Australia, and Papua New Guinea (Jansen et al., 2009).

2.8.6.2 Pig industry

The pig industry in the Solomon Islands consists of exotic, cross and local breeds. They are Large White, Berkshire, Duroc, Landrace, cross breeds between exotic and local breeds, and native breeds. In terms of production systems, pigs are raised mostly under traditional methods. Commercial production systems aimed at meeting the high demand for pork at local markets are not common in the country in fact only one exists, operated by a project under the Taiwan Technical Mission in Honiara, which was established in 2005 as a breeding unit. This unit is also intended to be a pilot model for other farmers to replicate. The unit supplies information, semen and/or improved breeds to local farmers throughout the Solomon Islands. Under this intensive system, pigs are permanently confined in built houses with concrete floor pens, and either cheap local bush materials or imported building materials. In addition, pigs are raised on semi-permanent enclosures where they are kept in partial confinement, with access to pasture in fenced paddocks and good clean water. Housing for pigs is made from local or imported materials. As one of the development projects in the livestock industry, the Malaita Provincial Administration in cooperation with the Department of Livestock and Veterinary Services is currently implementing a 300-sow unit for commercial operation at Dala in Malaita, which is aimed at supplying domestic demand for quality pork and breeding stock to farmers (Keqa, 2010).

Under the traditional system, the rearing methods used in rural areas throughout the country are free range and earth yard. Tethering and palisade are practiced on some islands; however, the most common traditional method used nowadays is slatted floor system where pigs meant for fattening are kept individually in pens made of large timbers or planks. Rearing of pigs is essential throughout the Solomon Islands as an alternative source of protein, food security, and income. Pig farming operations are concentrated in areas around Honiara, boarding vocational and high schools, and provincial centres throughout the Solomon Islands. Feed availability for animals in the country has been an issue, as the production and quality of feed provided by a recently established local feed mill is considered to be of low standard. Also, import costs are high and subject to erratic shipping schedules. This contrasts with free-range systems, where farm owners do not have issues of feed shortage because pigs are allowed to roam around to fetch their own food and water. Food scraps and kitchen leftovers are normally given from time to time as a source of food for animals. This rearing system is only common in the rural areas. Generally, at the local markets, the cost of purchasing one live weight pig at different age levels is independent of the rearing system used (Ajuyah, 2002; Wate, 1995)

2.8.6.3 Cattle industry

Unlike pigs and chickens, there is no history of cattle production among the indigenous people of the Solomon Islands. Cattle were introduced into the islands in the late 1800s to keep the grass understory of coconut plantations under control (Jansen et al., 2006). After the establishment of high-quality pastures for beef cattle production, research on pasture evaluation and cattle production continued beyond the Solomon Islands independence (7^{th} July 1978) until mid-1980s. The cattle industry is targeted mainly at beef production, and the animals at different age levels are reared together under different grazing systems. These include cut-and-carry, tethering and paddock grazing (pasture under coconuts grazed by free-ranging cattle in fenced paddocks and open, improved pastures grazed by free-ranging cattle in fenced paddocks). In the country, three production systems are recognised to have been practiced in beef production (Kama, 1999), and these are (i) small holder sub-sector, (ii) intermediate communal sub-sector, and (iii) large-scale commercial/government sub-sector.

The overall pasture resources for ruminant livestock production in the Solomon Islands can be categorized as open pastures, pasture under coconuts, and pasture under trees. In all cattle production systems, the common improved grass and legume pasture species are koronivia grass (*Brachiaria humdicola*), signal grass (*B. Decumbens*), para grass (*B. Mutica*), batiki grass (*Ischaemum aristatum* var. *indicum*), Pueraria phaseoloides (*Puero*), and Centrosema pubescens (*Centro*). Other less common improved grass and legume varieties are green panic grass (*Panicum maximum* var. *trichoglume* cv. *Petrie*), Nadi blue (*Dichanthium caricosum*), Stylo (*Stylosanthes guianensis* cv. *Endeavour*), Vigna (*Vigna luteola*), silverleaf (*Desomodium uncinatum*), hetero (*D. Heterophyllum*), siratro (*Macroptilium atropurpureum* cv. *Siratro*), and glycine (*Neonotonia wightii* cv. *Tinaroo*). Most of these pasture species have been introduced into the Solomon Islands when the Solomon Islands Government and other non-government organisations (Development Bank of the Solomon Islands and Livestock Development Authority) made a decision to expand the beef cattle industry through assistance from the Asian Development Bank (Macfarlane, 1996; Wahananiu et al., 1993).

Production systems

Under the smallholder sub-sector, the number of cattle owned is often 10 or less per household, which is managed or looked after by surplus family labour and the system is extremely labour intensive. As the system is aimed at utilizing unsuitable lands for other uses, the animals are tethered around backyards or around the villages to graze. The land holding of the system comprises mainly small farms of 5-50 hectares and is oriented towards subsistence and cash income. At the intermediate communal sub-sector, herds of cattle often consist of 10-25 cattle and the holder employs surplus community or tribal labour for looking after herds. The system utilizes community or tribal land that is unsuitable for other uses.

The land holding of the communal sub-sector comprises small farms of 50-200 hectares, and is made up of commercial enterprises and administered by established communal groups. Under this system, the animals are usually paddock-grazed

The large-scale commercial sub-sector has been a leading sector in the cattle industry in the Solomon Islands; however, this was disrupted by the social unrest between Malaita and Guadalcanal communities from 1999 to 2003. Under this sector, farms are owned by companies and the government, skilled labour are involved, and the cattle herd number is greater than 75 in a herd. The animals are raised under coconut plantations on 3000-4000 hectares in Central Province and open pasture on Guadalcanal. On Guadalcanal, the holdings have been returned to the original landowners for them to manage. The meat produced under these beef production systems are sold only at the local markets. They provide a source of income for farm owners and protein in their diet, and also help to meet other social obligations and ceremonial activities in the communities. To supplement locally produced beef, fresh packed meat is imported from Vanuatu and Australia while canned beef is usually imported from other countries (Kama, 1999). There is only one small dairy herd of 26 cows in the Solomon Islands owned by the Betikama Adventist Secondary School. All milk and milk by-products are imported from either New Zealand or Australia (Wate, 1995).

Potential of the beef cattle industry

Given an annual off-take of 15-20%, the current herd has the potential to supply 750 animals, or 60-75 tonnes/year of boneless beef to the local market each year. This represents approximately one-quarter of Honiara's current demand. Despite past developments within the industry, the local beef cattle industry has the potential to play an important role in the future of the Solomon Islands' livestock sector, for the following reasons: (i) the demand for beef is strong and prices are less volatile compared with other agricultural commodities; (ii) the Solomon Islands have high-quality pastures and concentrate feeds that could support high levels of beef production; (iii) cattle play a dual role by keeping the understorey of coconut plantations free from weedy growth; (iv) cattle suits the life style of Melanesians; and (v) it requires minimal daily attention (Jansen et al., 2006).

Breeding management

Breeding management of small herds poses difficulties for those in the industry, because it is not viable or practical for all farmers to own a bull. There is no local system of artificial insemination nor is it viable to establish one. The use of bulls owned by missions and other medium–scale operations is the most efficient way to address this issue. Owners of cows have to pay a small service fee for the use of the mission's bulls. This practice has encouraged the formation of satellite herds within the vicinity of the missions and helps improve the delivery of technical information and other services to those in the industry. Bull exchange among larger herds could be carried out on a two-or-three-yearly basis, and new genetics could be introduced from Guadalcanal or Russell Island Plantation Estates Limited (RIPEL) every five years. In all cases, bulls need to be rope-trained from a young age and undergo stringent checks during selection for their temperament. These are activities that have previously been done by the staff of the Department of Agriculture and Livestock (DAL) (Jansen et al., 2006).

2.9 Conclusion

The agriculture sector in the Solomon Islands comprises of different plantations and food crop industries with smallholders comprising most of the livestock production. A total of 1170 km^2 of land is considered suitable for agriculture, in terms of permanent pastures and crops (Berdach & Llegu, 2007; Osborne, 1979). There are three distinctive farming systems operating within the agriculture sector of the Solomon Islands: (i) subsistence, (ii) semi-intensive and (iii) commercial farming. In the past, about 10,000 km^2 under commercial farming system are occupied by the agricultural production sector (Hansell & Walls, 1976). At the present, the size of land used for agricultural purposes may have increased however; it has not been recorded and documented.

A large percentage (85%) of Solomon Islanders relies on subsistence agriculture for their own food production, consumption, and income while the remaining 15% are employed by other industries. Four-fifths of the farming population cultivates the land, under the customary tenure system where patterns of land utilization are largely determined by a tribe or clan other than the individual.

Approximately 85% of total land area (28,785 km^2) of the Solomon Islands is under customary ownership, with a very small percentage of (~ 5% of total land) being customary registered land. Only ~ 15% of the land area is either privately held or classified as Crown land. The customary land ownership system is transferred from one generation to the next and the land cannot be sold without the communal members' agreement. However, there have been constant threats to land ownership from land developers because of increasing demand for land for commercial activities. In terms of agricultural land use, 590 km^2 are utilised for permanent crops, 400 km^2 for permanent pasture, and 180 km^2 is arable. There are other lands under customary ownership which are not recorded, but which have been cultivated by the local communities for sustainable food production. Most suitable lands for agricultural use have been converted to settlements, urban centres and so forth because of the need for easy access to public services such as land and sea transport.

The locations of the areas of study and their land and soil formation have been described in Section 2.7. All livestock and Agricultural operations and production systems discussed in this Chapter (2) are also similar as those in and around the study areas. The next Chapter (3) provides a general review, which generally look into chemical aspects of soils, how they are measured, and some studies that were carried out on soils and pastures in the Solomon Islands. This provides an understanding of the role of soil in the nutrition of crops, trees, and pastures.

CHAPTER 3 General Review of Soil Fertility Principles

3.0 Introduction

Acquiring knowledge and information on the status of soil fertility and acidity of a particular soil is vital for gauging the potential productivity of any agricultural development setting or project. Apart from the biological and physical aspects of soils, there are various aspects of soil chemistry, which have also contributed to interactions between the soil and plants and thus indicate the relative productivity of a particular soil. Hence, prior to getting involved in any agriculture development, particularly involving the growing of plants, it is crucial to consider and understand some chemical characteristics of the soil and determine whether they are self-sustaining or require active management to avoid diminishing productivity or causing any adverse impacts on the environment.

3.1 Chapter Overview

This chapter contains nine main sections. Section 3.2 discusses soil fertility and its importance to agricultural development. Section 3.3 describes the different sources of essential elements in soil. The chemical indicators of soil fertility are described in Section 3.4. Section 3.5 explains soil acidity and alkalinity, and its importance. Section 3.6 outlines the sources of soil acidity and alkalinity. Processes and/or factors of chemical degradation in soil are outlined in Section 3.7. Section 3.8 describes soils and soil fertility maintenance in Solomon Islands. It outlines traditional methods used to improve/maintain soil fertility. Section 3.9 outlines fertilizer use. Section 3.10 describes previous research on pastures in Solomon Islands. It includes pasture under light/heavily shaded conditions; light transmission, stocking rates and weed control; soil nutrient content of some pasture soils; determination of components of yield in 'pasture /coconut system;' and pasture management practices. Section 3.11 concludes the chapter.

3.2 Soil fertility and its importance

Soil fertility refers to the capacity of the soil to provide an adequate and balanced supply of nutrients for plant growth (Ahern, et al., 1994). The essential nutrients mostly dissolved ions, are taken up by plant roots from the soil solution. These are replenished from the surfaces of soil particles and organic matter. Water held in a soil (soil solution) contains a range of dissolved ions and organic substances that have detached from the surfaces of soil particles and organic matter or that have been added to the soil via fertilisers and decaying animal or plant material. However, nutrients in the soil solution may be removed (fixed) into insoluble forms not readily available to plants. A fertile soil is not necessarily a productive soil because poor drainage, weeds, insects, disease, drought, and other factors may limit production even when fertility is adequate (Price, 2006). Hence, to make a fertile soil a productive soil, it is important to know about other factors that may support, or limit productivity, and how these factors can be changed to ensure that the soil is in a good condition to be productive.

In agricultural development, soil fertility is important as human societies depend on soil for different agricultural uses (cropland, grazing land, forestry and so forth) that require different soil management (Plaster, 2009). Soil productivity is the capacity of a soil to produce a certain yield of agronomic crops, or other plants, with optimum management (Foth & Ellis, 1997). For this research project, it is important to understand factors, which contribute to making the soils productive. All productive soils are fertile for the crops being grown, however, many fertile soils become unproductive because of unsatisfactory management practices. Therefore, maintaining soil fertility is the basis of productivity and all forms of sustainable land use, that is, land use that remains productive in the long term. If fertility has fallen below a critical level through long-term agricultural use without replacement of nutrients or as a result of erosion, or if it is naturally very low, the replenishment of nutrients may be a precondition for productive agriculture (Schroth & Sinclair, 2003).

Deficiencies in vital nutrients for example resulting from unsustainable land use practices or inadequate application of fertiliser can cause side effects to plants, or impact negatively on the expected output of agricultural production. Not only will yields begin to decline, but also the lower emergence of weaker seedlings will occur. The plants will not be able to root as deeply and therefore will become increasingly susceptible to drought conditions. In addition, plants' resistance to diseases and insects will be compromised and total plant health will decline, overall resulting in poor quality yields (Gates, 2009).

3.3 Sources of soil fertility

Current soil fertility can be explained by understanding the chemical aspects of soil formation, climate, current and historic vegetation, erosion, and human activities. The formation of soil involves various processes such as: development of soil from minerals and parent materials that have been derived from weathered rocks; and decomposition of organic materials (Lavalle & Spain, 2001; Troeh & Thompson, 1993). These processes occur under the influence of climate, topography, parent material, time, and soil organism activities. Therefore, the makeup of the fertility of soils can originate from soil organic materials, minerals, atmospheric chemical reactions, and human activities.

3.3.1 Soil Organic Matter (SOM)

Soil organic matter refers to dead materials, which consist of plant, animal, and microbial residues in various stages of decay. These materials can be from weeds, residues of crops, animal or human wastes and so forth. SOM contains about 5% nitrogen, so it serves as a storehouse or reserve for nitrogen (N). In organic matter, N is present as organic compounds and is not readily available for plant uptake because the process of decomposition usually occurs quite slowly. Although a particular soil may contain large amounts of organic matter, fertilizer nitrogen is usually needed to provide non-legume crops and grasses with an adequate supply of this important element. Plant and animal residues contain variable amounts of other plant nutrients such as P, magnesium (Mg), calcium (Ca), S and micro-nutrients and as they decompose, these nutrients become available for plant uptake (Price, 2006).

3.3.1.1 Decomposition of organic matter

In organic matter, decomposition refers to the sequence of its transformation, which involves two simultaneous but complementary processes (mineralisation and humification). Mineralisation is the catabolic process through which the elements contained in organic form within biological tissues are converted to inorganic forms such as nitrate, phosphate, and sulphate ions. In contrast, humification is the anabolic process through which organic molecules are condensed into degradation-resistant organic polymers, which may persist little altered for decades or centuries. Both processes occur simultaneously and are important aspects of soil fertility. Mineralisation determines the fluxes of plant and micro-organism-available nutrients and their distributions in time and space; humification regulates the accumulation of stabilised organic matter within the soil.

The decomposition of organic matter releases plant nutrients although some, particularly N and S, may be temporarily tied up during the process because the microbes involved require N to build protein in their bodies. If the organic matter being decomposed has a high carbon nitrogen ratio, meaning that it has low N, the organisms will use any available soil and fertilizer N. In tropical regions, most soils are inherently low in organic matter because the high temperature and rainfall speed up the decomposition process. However, good management practices can increase levels of organic matter in these soils. In cooler climates, decomposition of organic matter takes places more slowly and soil organic matter can be raised to quite high levels (Lavalle & Spain, 2001; Price, 2006).

In terms of cultivation, it speeds up decomposition process of organic matter and decreases its content in the soil. A product of this decline results in the release of large amounts of plant nutrients, particularly N. However, more frequent or continuous cropping, less frequent tillage, the production of high yields and the return of crop residues will help to maintain soil organic matter at a satisfactory level (McLaren & Cameron, 1996).

3.3.1.2 Role of organic matter in soil function

There are three ways which organic matter contributes to soil fertility. Firstly, cementation of soil occurs within aggregates. It refers to part of the soil organic matter that occurs in colloidal forms and cements soil particles together to create solid structural units known as aggregates. These are surrounded by inter-connected pore spaces that permit the movement of water, solutes, and gases through the soil matrix, which contribute substantially to erosion resistance. The second contribution of organic matter is retention of cations. As a material possessing a pH-dependent, net negative electrostatic charge at soil pH values, and soil organic matter aids the retention of positively-charged cations, especially in the acid pH range where soil minerals may retain lesser amounts. The above first and second properties are common to SOM and clay minerals, although some differences exist. For example, in soils more acid than pH 4.2, soil minerals retain few cations whereas humic molecules still retain an appreciable cation exchange capacity down to pH 2.5 (Bonneau & Souchier, 1982). Conservation of nutrients in organic forms is the third contribution of organic matter to soil fertility. Organic matter conserves both nutrients and energy in forms that are neither readily assimilated by microorganisms nor susceptible to leaching. Low concentrations of nutrients frequently limit growth processes in soil and their conservation in organic forms is a key feature of decomposition. In addition, the synchronisation of nutrient release through decomposition with demand is of paramount importance in avoiding nutrient losses (Swift, 1984; van Noordwijk & de Willigen, 1986). Therefore, organic matter is one of the sources, which supplies nutrient elements to the soil solution and determine its fertility status.

3.3.2 Minerals

Minerals are natural inorganic compounds with definite physical and chemical properties that are so conspicuous in many granitic rocks. They are one of the components that make up a soil. Minerals are broadly grouped into primary and secondary minerals. *Primary minerals* are those that have not been altered chemically since their crystallization from molten lava. Disintegration of rocks composed of primary minerals (by physical and chemical weathering) releases the individual mineral particles. Many of these primary minerals particles become sand and silt particles in parent materials and soils. Primary minerals weather chemically (decompose) and release their elements to the soil solution. Some of the elements released in weathering react to form *secondary minerals*. Secondary mineral results from the precipitation of the decomposition products of minerals. Secondary minerals originate when a few atoms react and precipitate from solution to form a very small crystal that increases in size over time. Because of the generally small particle size of secondary minerals, they dominate the clay fraction of soils (Carrow, et al., 2001; Foth, 1990).

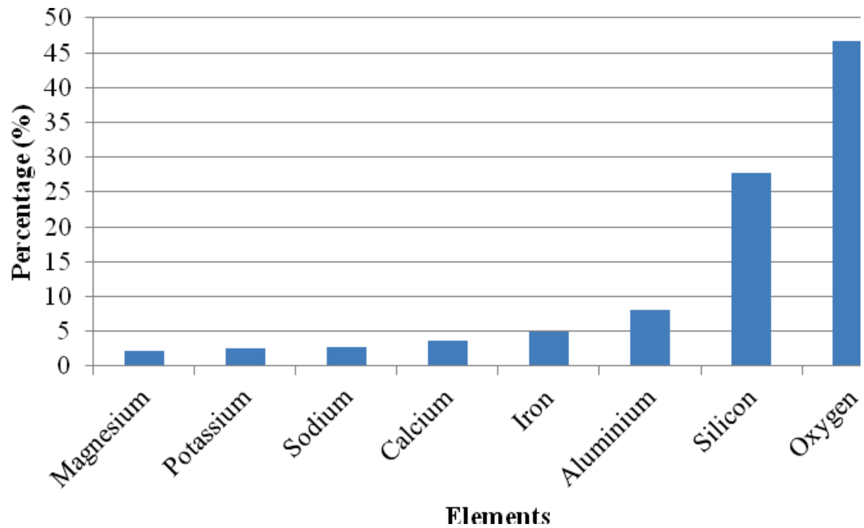
Consideration of the characteristics of minerals found in soils, and their transformation from one form to another, is essential to understanding both the nature of the soils' chemical properties and the origin of its fertility. Since soils develop from parent material composed of rocks and minerals from the earth's crust, attention is directed first to the chemical and mineralogical composition of the earth's crust (Foth, 1990).

3.3.2.1 Chemical and mineralogical composition of the earth's crust

About 100 chemical elements are known to exist in the earth's crust. Considering the possible combinations of such a large number of elements, it is not surprising that some 2,000 minerals have been recognized. Relatively few elements and minerals, however, are of great importance in soils (Foth, 1990).

Approximately 98% of the mass of the earth's crust is composed of eight chemical elements (see Figure 3). In fact, two elements, oxygen, and silicon, comprise 75% of it. Many of the elements that are important in the growth of plants and animals occur in very small quantities. Obviously, these elements and their compounds are not evenly distributed throughout the earth's surface. In some places, for instance, phosphorus minerals (apatite) are so concentrated that they are mined; however, in other areas, there is a deficiency of phosphorus available for plant growth.

Figure 3 The eight elements in the earth's crust



Sources: Clarke (1924) and Foth(1990)

The origin and mineralogical composition of igneous rocks, and the sedimentary rocks, shale and sandstone, are given in Table 3. Limestone is also an important sedimentary rock, which is composed of calcium and magnesium carbonates, with varying amounts of other minerals as impurities. The dominant minerals in these rocks are feldspars, amphiboles, pyroxenes, quartz, mica, apatite, clay, iron oxides (goethite), and carbonate minerals.

Table 3 Average Mineral Composition of Igneous and Sedimentary Rocks

Mineral Constituent	Origin	Igneous Rock, %	Shale, %	Sandstone, %
Feldspars	Primary	59.5	30.0	11.5
Amphiboles and Pyroxenes	Primary	16.8	-	a
Quartz	Primary	12.0	22.3	66.8
Micas	Primary	3.8	-	a
Titanium minerals	Primary	1.5	-	a
Apatite	Primary or secondary	0.6	-	a
Clays	Secondary	-	25.0	6.6
Iron oxides	Secondary	-	5.6	1.8
Carbonates	Secondary	-	5.7	11.1
Other minerals	-	5.8	11.4	2.2

Sources: Clarke (1924) and Foth (1990)

3.3.2.2 Contribution of minerals to soil fertility

As minerals have a great chemical diversity, their dissolution contributes essential elements. For example, under acid soil environment, weathering of minerals release some elements into the soil solution to be available for plant growth. For example, the reaction of feldspar (albite) with water (hydrolysis) and hydrogen ion (H^+) is as follows:

$$2NaAlSi_3O_8 + 9H_4SiO_4 + 2H^+ = H_4Al_2Si_2O_9 + 4H_4SiO_4 + 2Na^+ \qquad \text{Equation 3.1}$$

(albite) (kaolinite)

In the reaction a primary mineral, albite is converted to kaolinite, which gradually increases in size with attachments from ions and become resistant to weathering. Sodium is released as an ion into soil solution (Foth, 1990).

Minerals also contribute to soil structure and the ability of soils to hold nutrient ions in a plant available form. For example, the mineral structure may permit some elements to partly substitute for each other in proportions that are determined by the environment. For instance, during the crystallization of mica from magma, some aluminium ion (Al^{3+}) substitute for some of the silicon ion (Si^{4+}) in the tetrahedrons (under conditions of high temperature and pressure) (Foth, 1990) or Mg^{2+} for Al^{3+}. These substitutions leave the minerals net negatively charged which attracts positively charged cationic nutrient from soil solution. This cation exchange capacity (CEC) resides almost entirely within the smallest soil particles called colloids (layered silicate clays, iron and aluminium hydrous oxides, amorphous-like materials and organic colloids), which are smaller than 2 micrometers (µm, micron) in diameter (Carrow et al., 2001). Because of their size, they have very high surface area per unit mass, which along with their chemical structure, causes them to be highly active chemically. Additionally, iron and aluminium hydrous oxides on colloids may carry some positive charges. These charges attract some anionic elements e.g. phosphate $H_2PO_4^-$.

Hence, the fertility of soils is also determined by minerals and processes that they are involved in.

3.3.3 Atmospheric chemical reactions

Some important nutrient elements found in soils originate from the atmosphere and these do exist in the atmosphere in gas form. They are nitrogen (N_2), oxygen (O_2), argon (Ar), carbon (CO_2), neon (Ne), helium (He), hydrogen (H_2), krypton (Kr), xenon (Xe) and iodine (I_2). However, not all elements are involved in atmospheric reactions with the soil or directly supplied into the soil to be available and taken up by plants. Nitrogen is one good example. About 98% of the world's N exists in the lithosphere (see Table 4). The second largest N reservoir is the atmosphere, which contains about 2% of the total, and is generally considered the most important for plants and animals. It exists in the air as N_2 and, as such, is unavailable to higher plants and most soil microbes. There are some species of bacteria (nitrogen fixers) that absorb N_2 gas from the air and convert the N into ammonia that they and the host plant can use. This process is known as nitrogen fixation and is an important symbiotic relationship exploited by pasture legumes. The bacteria obtain food from the host plant and the host plant benefits from the nitrogen fixed. The bacteria then respond to and invade the roots of the host plant, and the host responds by forming a nodule that surrounds the bacteria, and in which nitrogen is fixed (see Table 4 and Figure 5).

Therefore, the fertility status of soils is also determined by conversion of some elements from the atmosphere to soil through some atmospheric reactions (Foth, 1990; Foth & Ellis, 1997).

3.3.4 Human activities

Human activity can accelerate the addition or removal of nutrient from soils, or change the soil condition. The use of mineral fertilizers and animal manures is a good example, which maintains the availability of plant nutrients (Schjonning, et al.,2004). Fertilizer may be applied before, during, or after the planting of a crop (Troeh & Thompson, 1993). The decision in this matter depends partly on the amount of fertilizer needed and whether the nutrient is mobile or immobile in soil. For example in humid regions, K is removed by leaching (Foth & Ellis, 1997). Large applications of K can be made by the plough-down method, where fertilizer is applied before planting. This practice places most of the fertilizer in a zone a few inches below the surface and is superior to broadcasting and disking in the fertilizer. Plant roots grow downward and soon encounter the fertilizer that has been ploughed down. Permanent cover crops such as pastures fertilisers are normally top-dressed seasonally allowing natural leaching and soil organism activity to incorporate the fertiliser-borne nutrients into the soil. Fertilizer application is one of the activities by humans, which maintains the fertility status of soils, and the removal of crops or animal products without fertiliser or manure use will reduce the nutrient status of the soil.

3.4 Chemical indicators of soil fertility

The fertility of soils can be measured by chemical indicators, which are important when assessing their status or quality. The chemical aspect of the soils has to be considered because it can make a significant contribution to the fertility of soils. The output and/or the productivity of agricultural inputs are majorly influenced by the type of environment, which the farms have been established on. The chemical status of soils is also one of the important environmental factors that need to be taken into account. Some of the chemical indicators are soil pH, cation exchange capacity, phosphorus concentrations, and others (Blakemore, et al., 1987; The United States Department of Agriculture, 1996).

3.4.1 Soil pH

One of the most important properties involved in plant growth that affects soil fertility is the pH of a soil. Chemically, the soil pH is defined as the negative logarithm of the hydrogen ion activity (pH = - log (H^+) where its scale goes from 0-14.

$$pH = \log + \frac{1}{[H+]} \text{ or } pH = -\log [H^+] \qquad \text{Equation 3.2}$$

However, for most soils the common range is pH 4.0 to 10.2. H^+ ion is an indicator of soil acidity and basicity, (H^+). Hydrogen ions hydrate similarly to other cations in the soil solution. It is called active acidity and is in equilibrium with H^+ ions on CEC sites or associated with other constituents. A soil reaction of 7.0 is neutral where H^+ activity equals OH^- activity. Below pH 7.0 is the acid range with greater acidity as pH gets lower in number, while above 7.0 is the alkaline range, where alkalinity increases as pH increases. Within the acid range, acidic cations (H^+, Al^+) dominate the soil's cation exchange surfaces, while above pH 7.0 basic cations (Ca^{+2}, Mg^{+2}, K^+ and sodium (Na^+)) predominate and OH^- activity exceeds H^+ activity (Carrow et al., 2001; Foth, 1990; Foth & Ellis, 1997).

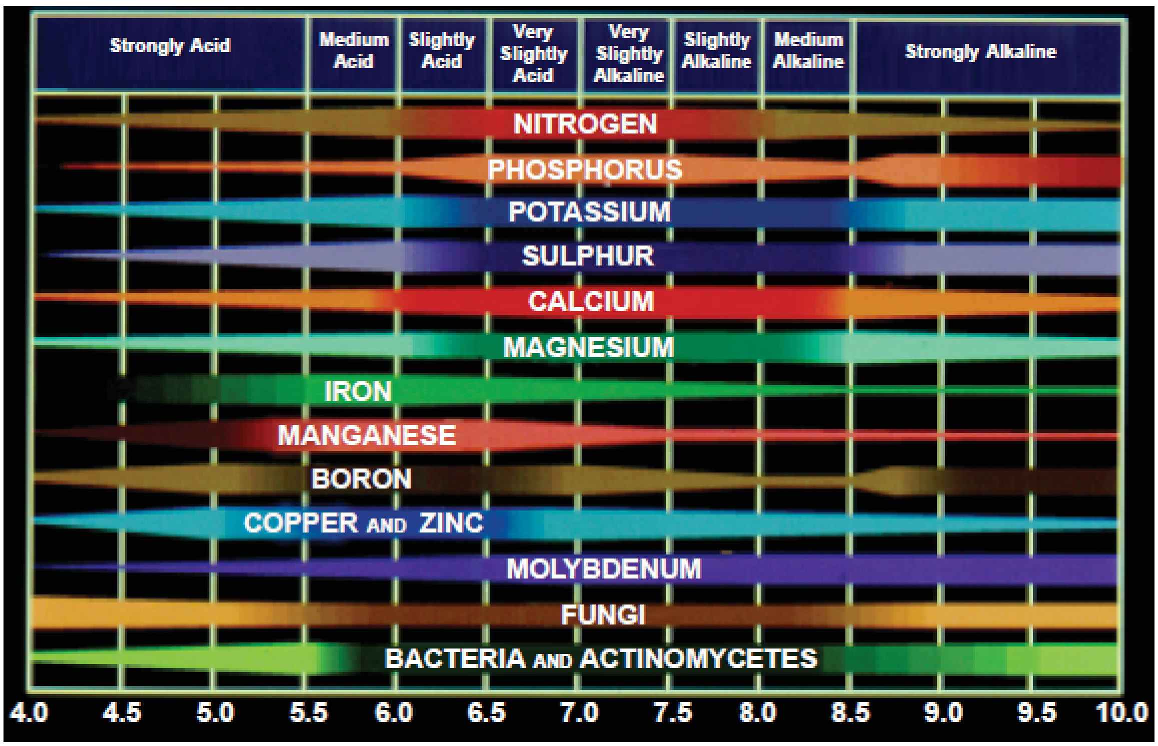
3.4.1.1 Importance of soil pH

Soil pH can influence plant growth through a variety of mechanisms (Delhaize & Ryan, 1995; Foy, 1992). They are nutrient availability and losses, toxicities and acid soil complex, lime and sulphur requirements, influences on CEC, soil microorganisms and microbial transformations, and plant community composition.

Nutrient Availability and Losses

Soil pH has a profound influence on the availability of nutrients. A change in soil reaction modifies the balance of cations on CEC sites, influences chemical forms, and alters microbial activity associated with certain nutrients, such as N and S, transformations. Nutrient availability is generally most favourable at pH 6.0 to 7.0 on mineral soils. Under increasing acidic conditions, nutrients such as N, P, K, Mg, and S are most likely to be deficient. Calcium levels will decline but unless a salinity stress is present, Ca deficiency is very unlikely. Under increasingly alkaline condition, iron (Fe), manganese (Mn), P, and boron (B) are nutrients that may become deficient. Primary reasons for potential deficiencies under acid and alkaline conditions are listed in Table 3.2. Soil pH can influence N losses by volatilization and denitrification. Under alkaline pH, N volatilization from applied N is more likely than under acid conditions, especially for urea. Also, gaseous loss of N under poor aeration is greater at alkaline than acid pH. (Foth, 1990).

Figure 4 Influence of soil pH on nutrient availability



Source: The United States Department of Agriculture (1996)

Table 4 Primary reasons for soil pH reduced nutrient availability of individual nutrients

Nutrient	Soil pH	Reason for Potential Nutrient Deficiency[a]
N	Acid	Bacteria populations involved in nitrification (conversion of NH_4^+ to NO_3^- in the soil) decline so NH_4^+ accumulates but NO_3^- level is low. Less microbial N fixation.
P	Acid	Phosphate ions form insoluble chemical compounds with Fe, Mn, Al.
Ca, Mg, K	Acid	Fewer basic cations are present. They are replaced by H^+ and Al^{+3} on the cation exchange sites.
S	Acid	SO_4^{-2} ion may bind with Al and/or Fe oxides and kaolinite.
Mo (Molybdenium)	Acid	Relatively unavailable Mo compounds form at pH <5.0.
B	Acid	Relatively soluble at low pH but can be easily leached in acid sands.
P	Alkaline	Phosphate can form relatively insoluble compounds with Ca.
Fe, Mn, Cu, Zn	Alkaline	Form less soluble hydroxide and oxide forms.
B	Alkaline	Increasing amounts bound in clay colloids at higher pH.

[a] Strongly acid or alkaline conditions are more serious than less acidity or alkalinity pH levels (Source: (Carrow et al., 2001)).

Toxicities and Acid Soil Complex

Under very acidic (pH<4.8) soil conditions, chemicals such as aluminium (Al) and Mn become much more soluble and can be sufficiently high in soil solution to cause direct plant root toxicity. They are found in subsoils (and sometimes surface zones) of many cool, humid temperature soils, and humid subtropical and tropical soils. Often Al and/or Mn toxicities are in conjunction with other stresses namely, deficiencies of Mg, K, Ca or high P, and high soil strength of nonexpanding kaolinite clays and Fe/Al oxides. This complex toxicities/deficiencies/high soil strength is called the 'acid soil complex.' While high H^+ can be directly toxic to plant roots, Al and Mn toxicities normally occur before soil pH is sufficiently low to develop H^+ toxicity (pH<4.0), except in acid sulphate soils. However, high H^+ concentration may adversely affect soil microorganisms. Iron toxicity is also possible under acidic, poorly drained situations. (Foth, 1990).

Lime and Sulphur Requirements

Soil pH is an important factor in establishing how much lime or elemental sulphur will be needed to adjust initial pH to the 6.5 to 7.0 range. It will require more lime to adjust pH from 4.5 to 6.5 than from 5.5 to 6.5. (Foth, 1990).

Influence on CEC

Many soils have a CEC component that does not vary as pH changes (pH independent CEC) and a component that is altered as pH changes (pH dependent CEC). Soils with the most pH dependent CEC contain Fe or Al hydrous oxides, allophane, kaolinite, or humus. Increasing pH of these soils from pH 4.0 to 5.0 up to pH 6.5 to 7.0, result in significant increase in CEC. Conversely, acidification of soils containing pH dependent CEC, results in a significant reduction in CEC. Therefore, excessively acidic soils containing these colloids cannot retain as many nutrients. However, excessively acidic soils with 2:1 clay types do not exhibit loss of CEC since their CEC is pH independent. (Foth & Ellis, 1997).

Soil Microorganisms and Microbial Transformations

Population levels of specific soil microorganisms, whether beneficial or pathogens are influenced by soil reaction, pH is a primary factor. There are some examples. Generally, total fungal populations remain relatively constant over a very wide pH range, but specific fungi species are favoured by narrow ranges. The total populations of bacteria and actinomycete steadily decline at pH<5.5. Chemical transformation of organically bound N into simple inorganic forms (NO_3^-, NH_4^+) that are available to plants is called *mineralization*. In the first stage, *ammonification*, soil microorganisms transform organic bound N into NH_4^+. *Nitrification* involves transforming NH_4^+ (ammonium ion) into NO_3^- (nitrate-N) by the following reactions:

$$2NH_4^+ + 3O_2 \rightarrow 4NO_2^- + 4H^+ + 2H_2O \qquad \text{Equation 3.3}$$

$$2NO_2- + O_2 \rightarrow 2NO_3^- \qquad \text{Equation 3.4}$$

Both ammonification and nitrification are suppressed as pH decreases below 5.5 with nitrification being the most sensitive to pH reduction. Suppression of this reduction is due to reduced populations of the specific bacteria species involved. Phosphorus held in organic matter can be mineralized by microorganisms into inorganic forms that are available to plants. This process is somewhat inhibited at low pH because of suppression of the microorganisms responsible for the process. *Thiobacillus* spp. bacteria can transform reduced S forms into an oxidized form (sulphate, SO_4^{-2}) that plants can use. Also, microbial decomposition of organic matter can release organic S, which, upon mineralization, is a major source of plant available S. As pH declines, some *Thiobacillus* species involved in these processes decrease in number, while other species increase in number. Therefore, soil reactions and/or pH has some effects on soil organisms. (Foth & Ellis, 1997).

Plant Community Composition

The preference of acid and alkaline soil reaction varies with plant species and the niche to which they have adapted. This is due to reasons such as intolerance to high Al or Mn levels; requirements for a high level of a particular nutrient; nutrient balances and levels of nutrients at a particular pH range favourable to the plant; nutrient deficiencies induced by pH; and pH influence on mycorrhizae relations with a plant. For instance, the optimum pH range for white clover and ryegrass is 5.6 to 7. Other plants that prefer a pH of 5 or less include jack pine, black spruce, and cranberry (Foth, 1990). Because plants have specific soil pH requirements, there is a need to alter or manage soil pH for their successful growth. Hence, all plants have different preferences for growth in acidic and alkaline soils.

Measures of Soil pH

Practically, there are methods developed for assessing the Soil pH status of soils (Blakemore et al., 1987). A calibrated test such as the pH in H_2O will be used to assess soil pH status in this study (see Section 4.5.1 in Chapter 4).

3.4.2 Cation exchange capacity

Cation exchange capacity is another important chemical characteristic, which influences the fertility of soils. By definition, it is a quantitative expression of soil components to hold exchangeable cations (Foth & Ellis, 1997; McLaren & Cameron, 1996). In other words, it is the sum of positive (+) charges of the adsorbed cations that a soil can adsorb at a specific pH (Foth, 1990). Each adsorbed K^+ contributes one + charge, and adsorbed Ca^{2+} contributes two + charges to the CEC. The CEC is the sum of the + charges of all of the adsorbed cations. (Conversely, the CEC is equivalent to the sum of the - charges of the cation exchange sites). The CEC is commonly expressed as centimoles of positive charge per kilogram [cmol (+) kg^{-1}], also written as cmol kg^{-1}, of oven dry soil. A mole of positive charge (+) is equal to 6.02 x 10^{23} charges. For each cmol of CEC per kg there are 6.02 x 10^{21} + charges on the adsorbed cations (Foth, 1990).

3.4.2.1 Components supporting CEC

Some of the soil components that are involved in CEC are silicate clay minerals, allophane, and humus (see Table 5). Each of these materials has negative charges that attract cations. The cations are can be also called exchangeable if they can be replaced with other cations dissolved in water surrounding the particles. Such replacement is possible if the bonding is not too strong and if the sites are accessible to the soil solution (Troeh & Thompson, 1993).

Table 5 Cation Exchange Capacities of Soil Clays and Humus

	Cation-exchange capacities (me100g^{-1})	
	Representative	**Usual range**
Humus	200	100 – 300
Vermiculite	150	100 – 200
Allophane	100	50 – 200
Montmorillonite	80	60 – 100
Illite	30	20 – 40
Chlorite	30	20 – 40
Peat	20	10 – 30
Kaolinite	8	3 – 15

Source: Troeh and Thompson (1993)

3.4.2.2 Negative charges and CEC

Soil component negative charges, responsible for cation exchange capacities, arise in three ways. First, cation substitutions within mineral layers, the substitute +2 cations fit into the mineral structure with no change in external form. For instance, cation substitutions occur within the layers of all 2:1 layer silicates. One negative charge from the surrounding O-ions is left over wherever a Mg^{2+} or an Fe^{2+} ion replaces an Al^{3+} ion in an octahedral sheet or an Al^{3+} replaces a Si^{4+} ion in a tetrahedral sheet. These negative charges are balanced by cations held between or outside the layers. Charges arising from cation substitutions are part of the cation-exchange capacity if the cations are held at the outer surfaces of the particle. Cations held between layers are exchangeable if the lattice expands (as montmorillonite and vermiculite). Cations inside the nonexpanding lattices are nonexchangeable due to inaccessibility. However, weathering processes, gradually open lattices and release the previously nonexchangeable cations. Second, broken-edge bonds occur in all minerals because mineral lattices are held together by continuous sequences of ionic bonds. There is no place to terminate the structure without leaving some ions with unsatisfied negative or positive charges at the edges. Broken-edge bonds are only important in clay particles. The amount of charge attributable to broken-edge bonds increase with decreasing particle size. For instance, in allophane, this reaches maximum. The disorganised nature of allophane results in large numbers of broken-edge bonds. Third, the ionizing of H^+ from carboxylic and phenolic functional groups of organic materials results in attraction of cations onto the negative sites of the organic particle (Troeh & Thompson, 1993). Hence, CEC is a chemical indicator with negative charges that occurs within and around soil clays and humus, and it influences the soil's fertility.

3.4.2.3 Importance of CEC in soil management

In soil management, CEC indicates the nutrient-holding capacity of a soil; partially determines how often and how much lime must be applied; and determines at what rate and frequency cationic nutrients other than lime can be applied. On very low CEC soils, K may need to be side-dressed during the growing season, but on high and medium CEC soils, it can be broadcasted before planting; and on high CEC soils.

Measures of CEC

Practically, CEC is measured using ammonium as a cation ion in a leaching or batch extraction (see Section 4.5.1 in Chapter 4).

3.4.3 Phosphorus concentrations

Phosphorus is another major nutrient element required by all forms of life (Lavalle & Spain, 2001) where its concentrations are one of the chemical indicators of soil fertility. Phosphorus concentrations are amounts of P, which exists in the soil as inorganic/orthophosphate (phosphate; HPO_4^{2-} and $H_2PO_4^-$) and organic forms. Plants obtain HPO_4^{2-} and $H_2PO_4^-$ from the soil solution where they depend on the soil pH (Havlin, et al., 2005). When there is a high H^+ concentration, $H_2PO_4^-$ is the dominant ion in soils (i.e. the pH is below 7.0), while above 7.0 the HPO_4^{2-} ion is the main form present (McLaren & Cameron, 1996).

The total P in surface soils ranges from 0.005 to 0.15% P, depending on the parent material from which the soil has developed, and the extent to which weathering and leaching have taken place (Havlin et al., 2005). P is less abundant in soils than N and K and commonly it limits plant growth (Foth, 1990).

3.4.3.1 Sources and amounts of P

There are different sources, which P originates from. First, the native P in soils, inherited from parent materials, originates mainly from primary P minerals known as apatites in igneous rocks (see Table 6), in which P is present especially as tricalcium phosphate, $Ca_3(PO_4)_2$. The mineral contains Ca, as well as other elements such as fluorine (F) and chlorine (Cl). When the apatite breaks down and releases P into the soil, several compounds including the two orthophosphates ions taken up by plants, are formed. These orthophosphate ions are present in small amounts in the soil solution.

Table 6 Examples of apatite minerals

Mineral	Formula
Fluorapatite	$3Ca_3(PO_4)_2.CaF_2$
Hydroxyapatite	$3Ca_3(PO_4)_2.Ca(OH)_2$
Carbonate apatite	$3Ca_3(PO_4)_2.CaCO_3$
Chlorapatite	$3Ca_3(PO_4)_2.CaCl_2$

Source: McLaren and Cameron (1996)

SOM is an important source of P for plant uptake, although it must be converted to mineral forms for plants to be able to do so. SOM contains about 1-3% P and phosphorus in organic matter may represent about 50% of the total phosphorus in soils (Price, 2006). As with N, organic phosphorus is mineralized by microorganisms and is again released into the soil solution as $H_2PO_4^-$. The P ions react quickly with other ions in the soil solution, resulting in precipitation and adsorption to mineral colloids that convert the phosphorus to an unavailable or fixed form. As a consequence, most of the P ions from mineralization of organic P, or mineral weathering, may be converted to an unavailable form before plants have an opportunity to absorb the phosphorus and before loss by leaching can occur. The kinds of ions in the soil solution that render phosphate insoluble are related to soil pH (Foth, 1990).

Measures of available P

A number of soil extractants have been developed for assessing the P status of soils (Hedley, 2008). These extractants are designed to remove weakly adsorbed P and readily mineralisable P from soils. This is normally a small fraction 5-6% of the total inorganic and organic P content of soils. It is important that the P extracted by such tests has been calibrated to plant growth response to P availability. This requires extensive field trial work such as that completed for grazed pastures in New Zealand (Saggar et al., 1999; Sinclair, et al., 1997). A calibrated test such as the Olsen P will be used to assess soil P status in this study (see Section 4.5.1 in Chapter 4).

3.4.3.2 P movements and losses

Phosphorus moves very little in most soils. Generally, it stays very close to where it is placed. Except for deep, sandy soils, very little P is lost by leaching, because it moves freely in sandy than in clay soils. Surface soil erosion (run-off) can remove soil particles, and since the surface is where much of the applied (fertilizer) phosphorus resides, erosion of surface soil can lead to significant loss of P. In fact, erosion and crop removal are the most significant ways that P is lost from the soil (Price, 2006).

Therefore, phosphorus concentrations are soil indicators of soil fertility where they are limited in amounts in soil solution, quickly react with other ions, precipitated and become fixed or unavailable for plant uptake. Less amounts of P are lost through leaching and run-off.

3.4.4 Others

The other chemical indicators of soil fertility are measurements of salinity, organic matter, and concentration of elements that may be potential contaminants (heavy metals, radioactive compounds, etc.) or those that are needed for plant growth and development (Blakemore et al., 1987; The United States Department of Agriculture, 1996).

3.5 Importance of acidity and alkalinity in soil management

As stated earlier, the acidity in soils refer to the amount of H^+ and Al^{3+} in soil solution while alkalinity or basicity refers to amount of OH^- and/or other basic cations (Mg^{2+}, Ca^{2+}, K^+) in soil solution. Both can be measured by pH and their importance has already been stated in section 3.4.1.1.

3.6 Sources of soil acidity and alkalinity

3.6.1 Sources of soil acidity

The acidity of soil depends on the concentration of H^+ ions in the soil. The generation of H^+ ions in soils results mainly from oxidation reactions in the carbon, N or S cycles. The generation of OH^- ions results from reducing reactions in the carbon, N or S cycles. If oxidation reactions occur and the oxidised product is lost from the soil before reduction can take place, then reserve acidity accumulates in soils. Examples of this are the oxidation of $NH_4{}^+$ to NO_3^- by nitrification followed by NO_3^- leaching before plant uptake of NO_3^- and assimilation (reduction) into plant protein (Sustainable nutrient management in New Zealand agriculture, 2010). The rate and extend of soil acidification depends on the vigour of plant growth and nutrient cycling and the buffer power of soil minerals (McLaren & Cameron, 1996).

3.6.1.1 Leaching of bases

The removal of basic cations such as Ca^{2+}, Mg^{2+}, and K^+ from the soil by leaching lowers the base saturation of the soil and is a consequence of acid being generated by the C, N and S cycles. Exchangeable bases leached from the soil are replaced on cation exchange sites by acidic cations H^+ and Al^{3+}, which is derived from a number of processes as described below. (McLaren & Cameron, 1996).

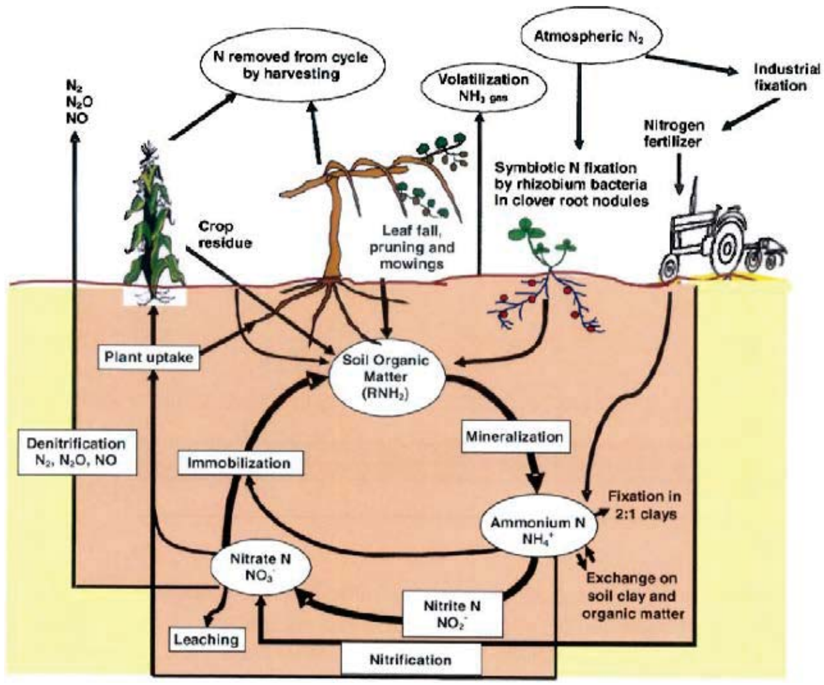
3.6.1.2 Formation of soluble acids in the carbon and nitrogen cycle

Soluble acids for example organic and carbonic acids are produced by incomplete oxidation and respiration of microorganisms and plant roots. When they react with water the dissociation of the acid releases H^+ ions into the soil solution (see Equation 3.5).

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \qquad \text{Equation 3.5}$$

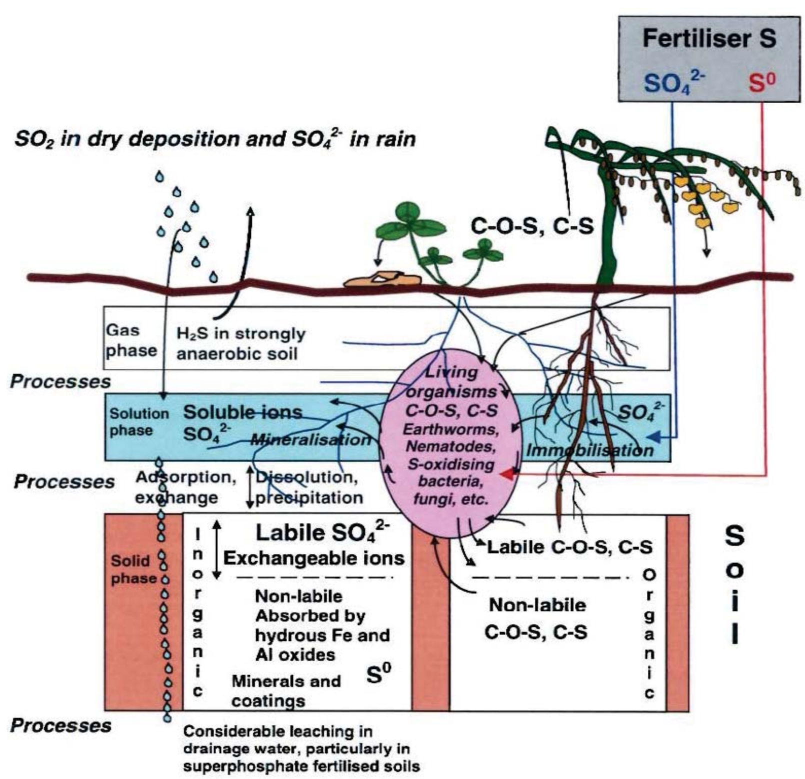
Additionally, H^+ ions are produced during microbial transformations involving the production of nitrate (NO_3^-) and sulphate (SO_4^{2-}) ions as protein decomposes to NH_4^+ and nitrification converts NH_4^+ to NO_3^-. In effect, nitric and sulphuric acids are produced during these processes, both acids being strongly dissociated (see Figures 5 and 6). (McLaren & Cameron, 1996).

Figure 5 Nitrogen cycle in mixed agricultural systems



Source: Fertilizer & Lime Research Centre (Massey University) & Fertilizer Manufacturers' Research Association (2010)

Figure 6 Sulphur cycle in orchard systems



Source: Fertilizer & Lime Research Centre (Massey University) & Fertilizer Manufacturers' Research Association (2010)

3.6.1.3 Release of hydrogen ions by plant roots

The uptake of basic cations by plant roots often involves the simultaneous release of H+ ions from the roots into the soil solution. (McLaren & Cameron, 1996).

3.6.1.4 Dissociation of functional groups on soil colloids

The dissociation of H^+ from edges of clay minerals, Al and Fe oxides (inorganic), and soil OM (organic) surfaces contributes to reserve soil acidity and pH buffering. The edges of clay minerals such as kaolinite (1:1) and montmorillonite (2:1) can buffer soil pH.

3.6.1.5 Aluminium hydrolysis

The aluminium ion (Al^{3+}) is regarded as an acidic cation because of the way in which it undergoes hydrolysis to produce hydrogen ions. A considerable amount of Al is released into the soil during the weathering of aluminosilicate minerals, and in acid soils, a substantial proportion of the cation exchange sites may be occupied by Al^{3+} ions. The hydrolysis reactions of Al are described by the following reaction.

$$Al^{3+} + H_2O \rightleftharpoons Al\,(OH)^{2+} + H^+ \qquad \text{Equation 3.6}$$

$$Al\,(OH)^{2+} + H_2O \rightleftharpoons Al\,(OH)_2^{\ +} + H^+ \qquad \text{Equation 3.7}$$

$$Al\,(OH)^{2+} + H_2O \rightleftharpoons Al\,(OH)_3 + H^+ \qquad \text{Equation 3.8}$$

$$Al\,(OH)^{3} + H_2O \rightleftharpoons Al\,(OH)_4^{\ -} + H^+ \qquad \text{Equation 3.9}$$

Each of the above reactions is driven to right by the neutralization of H^+ ions through reaction with OH^- ions added with liming materials. In unlimed soils, it is more common to view these reactions as pH buffering reactions as soil surface aluminium hydroxide consumes protons (H^+) and drives reactions to the left. The various hydroxy aluminium complexes have a significant influence on the buffering capacity of the soil. (McLaren & Cameron, 1996).

3.6.1.6 Fertilizer application

The interaction of certain fertilizers with the soil can result in the production of H^+ ions and the lowering of soil pH. One of the most common examples is the use of fertilizers containing N in the ammonium (NH_4^+) form (see the discussion above in Section 3.6.1). Some phosphate fertilizers may also create extremely acid conditions in small volumes of soil (pH approximately 1-2) surrounding individual fertilizer granules. In other words, use of elemental sulphur as a fertilizer is known to have resulted in significant decreases in the overall soil pH. (McLaren & Cameron, 1996).

3.6.1.7 Acid rain

Polluted rain is one of the sources, which create acidity in soils. Acid vapours, primarily sulphuric (H_2SO_4) and nitric (HNO_3), form in the atmosphere as a result of the emission of sulphur dioxide (SO_2) and nitrogen oxides from natural and anthropogenic sources. The largest anthropogenic sources of these gases are from the burning of fossil fuels (source of sulphur gases) and the exhaust from motor vehicles (source of nitrogen oxides). These emitted gases return through precipitation. They cause the pH of the precipitation to be less than 5.6 and to become an acid precipitation (Foth & Ellis, 1997; Steel, et al., 1980).

Therefore, the development of soil acidity originates from oxidation reactions in nutrient cycling, formation of organic and carbonic acids through microorganisms' and plant activity and respiration, release of H^+ by plant roots leading to leaching of basic cations, association of H^+ with functional groups on soil colloids including aluminium and iron hydroxides and the weathering of other soil minerals, which act as pH buffers.

3.6.2 Sources of soil alkalinity

Some parent materials and soils are calcareous because they contain carbonates. They can be recognised in the field because when treated with dilute hydrochloric acid (HCl), carbon dioxide gas (CO_2) is produced (Foth, 1990).

3.6.2.1 Carbonate hydrolysis

Soils become alkaline when the calcium carbonate is hydrolysed and produces hydroxide ion (OH^-), which is released into soil solution.

$$CaCO_3 + H_2O = Ca^{2+} + HCO^{3-} + OH^- \qquad \text{Equation 4.0}$$

Calcium carbonate is only slightly soluble, and this reaction can produce a soil pH as high as 8.3, assuming equilibrium with atmospheric carbon dioxide. In calcareous soil, carbonate hydrolysis controls soil pH. When a soil contains Na_2CO_3, the pH may be as high as 10 or more, which is caused by the greater production of OH^- by hydrolysis in a similar manner. Sodium-affected soils with 15% or more of the CEC saturated with Na^+ are called sodic and are also highly alkaline. (Foth, 1990).

3.6.2.2 Mineral weathering

The weathering of many primary minerals contributes to alkalinity and they act as buffers to ongoing acidification. This is the result of the consumption of H^+ and the production of OH^-. For instance, the hydrolysis of anorthite (calcium feldspar), produces a moderately strong base:

$$3CaAl_2Si_2O_8 + 6H_2O = 2HAl_4Si_6O_{10}\,(OH)_2 + 3Ca\,(OH)_2 \qquad \text{Equation 4.1}$$

In the reaction, an aluminosilicate clay mineral was formed together with the moderately strong base, calcium hydroxide. The net effect is basic. The generalized weathering reaction, in which M represents metal ions such as calcium, magnesium, potassium, or sodium, is

$$\text{M – silicate mineral} + H_2O = \text{H – silicate mineral} + M^+ + OH^- \qquad \text{Equation 4.2}$$

As long as a soil system remains calcareous, carbonate hydrolysis dominates the system and maintains a pH that ranges from 7.5 to 8.3 or more. Mineral weathering is minor under these conditions, and the mineralogy and pH of the soils change little, if at all, with time. The development of soil acidity requires the removal of the carbonates by leaching. When acidity develops, the weathering of primary minerals is greatly increased, causing an increase in the release of cations-calcium, magnesium, potassium and sodium. Leaching of these cations in humid regions, however, eventually results in the development of permanent soil acidity. (Foth, 1990).

3.7 Processes and/or factors that decrease soil productivity

Changes in soil chemical properties may take soil from a favourable to an unfavourable state, decreasing soil productivity. This may occur due to increasing soil acidity, inadequate fertilization, flooding, practicing monoculture for long periods on the same field, deterioration of soil physical properties through erosion, accumulation of salts in harmful concentrations, release of allelochemcicals, and indiscriminate use of pesticides (Fageria, et al., 2011). This section discusses nutrient stress, soil acidity, saline-sodic soils, allelopathy and indiscriminate use of pesticides.

3.7.1 Nutrient stress

Nutrient stresses refer to deficiencies of essential plant nutrients as well as toxicities (Ledgard, et al., 2000; Saggar et al., 1992). They are more common than toxicities in many arable lands in tropical and sub-tropical regions of the world (Fageria et al., 2011). Nutrient deficiencies can be caused by leaching, run-off, fixation and low native nutrient content. If nutrient stress is not alleviated, crop or plant yields are decreased and soils cannot support adequate plant growth. Poor and/or lack of nutrient management strategies are a factor that can create nutrient stresses in any farms. Therefore, nutrient stresses can be alleviated with adequate application of the right type of fertilizer.

3.7.2 Soil acidity

As described earlier, soil acidification refers to a complex set of processes that result in the formation of an acid soil (pH less than 7) (Clay, 2011; Saunders, 1965). It is a major degrading factor of soils and affects extensive areas both in the tropics and temperate zones. There are some factors, which contribute towards this for instance, P deficiency is a major limiting factor for crop yield in highly weathered acid soils and calcareous alkaline soils (Demers, 2005; Longley, et al., 1999). This can result from low native soil P content and high P-fixation capacity (Fageria et al., 2011). For instance, in a comparative studies on adaptive strategies of *Medicago falcate* and *M. Truncatula* to phosphorus deficiency in soil, Yan, et al (1996) found that the lateral root length and total root length of (Steel & Whiteman, 1980) grown in P-deficient medium were markedly reduced to those grown in P-sufficient. The other limiting factors of plant growth and fertile soils are: Al toxicity, Mn toxicity, poor management of soil acidity, no liming application and incorrect use of tolerant species and/or cultivars (Fageria et al., 2011). Osborne, et al., (1980) found that the effects of high Al levels in solution on subterranean clover are reduction of both shoot and root growth root length and increase in the uptake and translocation of Al. The uptake of Ca and P into both roots and shoots are reduced. Hence, soil acidity is a chemical degradation factor of soils as it is determined by certain complex toxic chemical reactions within the soil.

3.7.3 Other factors

The other factors, which can chemically degrade soils, are saline-sodic soil conditions, allelopathy, and indiscriminate use of pesticides. Soil salinity is a major environmental constraint to crop productivity worldwide (Kamphake, et al., 1967). They are salt affected soils that are common in arid and semiarid regions where evaporation is higher than precipitation (Fageria et al., 2011). Crop production on such soils cannot be successful when there is lack or poor management of soil, water, and plant. For example, Mensah, et al., (2006) found that cowpea has a low yield (7.4-19.2*10 cfu/mL) at higher salinity (0.050-0.200 M) and low pH. Allelopathy is also a degrading factor, which refers to direct or indirect effect of one plant on another through the production of chemical compounds that are released into the soil environment (Lavalle & Spain, 2001). The accumulation of the released compounds must be in sufficient quantity to affect other plants. Nevertheless, the allelochemical effects can be reduced by adopting certain management practices (Putnam & Duke, 1978). These include the use of appropriate crop rotations, improving OM content of soil, planting of resistant cultivars, and fallowing. The indiscriminate use of pesticides (insecticides, fungicides and herbicides) has effects on soil biology and may also pollute groundwater. However, the rise of soil degradation can be avoided by advising farmers to ensure the rational use of these materials based on experimental evidence for each agroecological region. Therefore, in the evaluation of current soil productivity past land management history that may have created soil salinity, allelopathy and toxicities due to indiscriminate use of pesticides must be considered.

3.8 Soils and Soil fertility maintenance in the Solomons

The types of soils found in the Solomon Islands differ according to the three types of landscapes in the country. They are coral atolls, rugged volcanic mountains, and coastal plains (see description of Soils for Malaita and Guadalcanal provinces in Section 2.7, Chapter 2). Most of the soils have formed from basaltic rock1, andesitic lavas clastic, and limestone sediment or coral (Hansell & Walls, 1974). The major rock types are Meszoic metamorphics, and Tertiary intrusives (gabbro, diorites and ultramafics), volcanics (andesites and basalts), and calcareous and non-calcareous sediments. There are also areas of Pleistocene reef limestone and recent sediments (organic accumulations and alluvium). The soil formation patterns of the Solomon Islands are influenced by the weathering processes caused by rain, wind, water, and volcanic activity (Chase, 1976). These weathering processes have played a part in the leaching of soil nutrients and general low soil fertility, particularly in the high rainfall areas of the country (Baker, 1984). Time is an additional soil-forming factor. These landscapes are more than 1000 years old, with the period of soil formation restricted to the Quaternary (Rapaport, 1999). Continuous cultivation on the same area of land can exhaust the soil nutrients, in particular, nitrogen, phosphorus, and potassium, which deplete organic matter contents.

In the Solomon Islands, the sources of nutrients are the natural components of soils, which are organic matter and minerals, whereas the use of fertilizer is rare, especially in an agriculture system as shifting cultivation, which is widely practiced under crop farming system. The use of machinery for tillage prior to pasture establishment under beef cattle system is not common for individual farmers due to its high cost. Some studies (Gangaiya & Morrison, 1998; Wall & Hansell, 1973) have indicated that the total contents of K of some soils in the Solomon Islands are low to very low at 0-10 cm and 25-35 cm depth and fertilization in these sites is needed if continuous (as opposed to shifting) cultivation is practiced. These soils are predominantly derived from coral but are strongly influenced by volcanic deposits. Some soils also require S and Mn.

3.8.1 Traditional methods to improve/maintain soil fertility

Over hundreds of years, the local population has developed sustainable farming techniques or agricultural practices (although not all agricultural soils in the Solomon Islands have been documented on their fertility status). Besides the shifting cultivation method, there are traditional methods, which have been developed as alternatives to maintain soil fertility, to accommodate the country's increase in population. These methods include brush and hoe, alley cropping integration, improved Temotu traditional tree planting, seaweed fertilizer, selection of healthy plants, Hohoto gardening, and others (Aloatu et al., 2011).

Shifting cultivation and bush fallowing

Many farmers in the rural areas of Melanesia including the Solomon Islands still follow the traditional method of shifting cultivation, also known as 'slash-and-burn' or bush fallow agriculture. Under this method, an area of bush is cleared, burned, and cultivated to make food gardens. When all the crops have been harvested and sometimes there are two to three crop cycles, the area used is left to grow back into bush over a period of 7 or more years while the farmers move on to clearing another area for planting. This method is no longer possible given the rate of increase in population. The current huge demand for land use has caused this period to be reduced to only 2 or 3 years. As a result, weeds are major plants that have grown in these lands and little soil improvement takes place to increase soil fertility. Shifting cultivation therefore requires a lot of land and contributes to greenhouse gases emissions to the atmosphere through burning activities (Aloatu et al., 2011).

Brush and hoe

Brush and hoe is a method used for growing sweet potato crops in some densely populated areas in the country where food gardens or farms are left fallowed for only a very short time. It has been regarded as a much better method than 'slash-and-burn' because the area is cleared by cutting away the vegetation using bush knife to just above the ground level. Under this system, weeds, shrubs, and young trees are also shredded and used for mulch and compost. Rather than burning the cleared secondary bush, the area is cleared and the slashed organic material is left to cover the ground. The soil is then cultivated with either a hoe or stick into mounds for the sweet potato. Sometimes, the organic matter is heaped into rows between the mounds. During growth, weeded weeds are laid on the ground as mulch instead of burning them (Dola, 2011).

Integrated alley cropping and improved Temotu traditional tree planting

The integrated alley cropping and improved Temotu traditional tree planting methods are combined methods used on some small islands in the Solomon Islands. Both systems are used and involve: traditional and improved tree crops, and modern gardens of annual crops that use alley cropping to keep the soil fertile. The alley cropping involves legume trees whereas the improved Temotu traditional tree planting, use fruit trees. Native fruit and nut trees are not cleared under this system. The 'Improved Temotu Traditional Agriculture' (ITTA) method was developed in the 1980s and 1990s as a method for farmers to improve degraded land and also to increase food production.

Alley cropping was introduced in 2006 using Gliricidia (*Gliricidia sepium*) as a hedgegrow tree for improving soil fertility. 'Hedgegrow' refers to a row of legume trees planted in wide-spaced rows through the garden. The trees are regularly cut back and the nitrogen-rich leaves and branches are used as mulch on the alley crops to improve the soil fertility. As plants are provided with enough sunlight, green manure, compost, and space for growth, the combination of alley cropping and ITTA has been regarded suitable for crop plants such as cassava, and kumara (sweet potato) in annual crop farms. Integrated Alley cropping and Improved Temotu Traditional tree planting systems were developed to enable the continuing use of the land without the need for farmers to move to other land areas. This is particularly important given that land area is fixed, which is continually subject to increasing demands of the country's growing population (Leyinga & Bonie, 2011).

Seaweed fertilizer and healthy plants

In some coastal communities in the South Pacific, soil fertility is very low. On the eastern end of the Solomon Islands, communities have found a unique technique for increasing soil fertility and controlling pests with the use of seaweeds. The seaweeds collected from the lagoons are used as fertilizers after going through a process of mulching. The areas where seaweeds are commonly used are on coral reef islands, high raised atolls, artificial islands, and any other farms located close to the sea (Sui, 2011).

Hohoto gardening

The Hohoto gardening method is developed on the premise that nothing is wasted. It involves pruning of trees to allow leaves of fallen branches to decompose and increase the fertility of the soil. The fallen branches are used as stakes for yam vines to creep on. This method is common in mountainous regions; however, it can also be used on flat areas, hillsides and any areas that have high rainfall (Sese, 2011).

Other methods

The other methods that have been used to improve and/or maintain soil fertility on most farms in the Solomon Islands are: (i) 'fix' gardening, which involves planting legume trees for contour planting and is used in either small or larger farm areas; (ii) gardening on sloping land, which reduces soil erosion by contour of stick rows and hold up stack leaves, branches and other organic matter materials; (iii) integrated farming, which combines nursery management, mulching, crop rotation, seed saving and feeding of local poultry; (iv) household compost, which does not require much work and provides compost soil for use on small food gardens; and (v) building soil fertility with legumes, where the legume crops (beans and peanuts) are used as cover crop with a few *Gliricidia* spaced 3 m apart (Aloatu et al., 2011).

3.9 Fertilizer use

The Solomon Islands is one of the Pacific island countries that imports inorganic fertilizers as a result of the effect of the population pressure on soil fertility. This is mainly due to the reduction of the fallow period in shifting cultivation and overusing (cultivation) the land (Oliouou & Tutua, 1997). Inorganic fertilizers are imported from various countries, which include Australia, New Zealand, Germany, and United Kingdom. Throughout the country's history, fertilizers have been used only on (i) commercial farms such as rice (Ojala, 1946) and palm oil (Gautam, 2001); (ii) in pot and field trials (Metcalfe, 2002; Steel & Whiteman, 1980) for grasses and trees; and (iii) in some demonstration farms (Akipu et al., 2010). However, the present level of fertilizers used in the islands of the Pacific region, including the Solomon Islands, is extremely low (see Tables 7 and 8). This is due to several reasons such as: (i) the farmers' unwillingness to use fertilizers, (ii) the lack of information and poor extension services, and (iii) the unavailability of the right type of fertilizers in the right place, the quantity and at the right time (United Nations, 1991). Moreover, the increase in the cost of fertilizers may have limited its use in small-scale farming systems because most individual farmers cannot afford it. Between 1984 and 1992, the amount of fertilizers imported in the Pacific region slowly decreased however, a rapid increase was experienced between 1993 and 1994 with its value (see Table 7).

Table 7 National Fertilizer imports for period 1984-1994 in Pacific

Year	Amount (tons)	Value (SL$'000)
1984	3600	615
1985	3489	760
1986	2215	504
1987	2120	620
1988	1810	480
1989	1720	884
1990	1267	846
1991	2522	1650
1992	990	550
1993	3197	2493
1994	4490	3854

Source: Gautam (2001)

Table 8 Fertilizer imported by Solomon Islands Plantation Limited in tonnes

Year	1990	1991	1992	1993	1994	1995	1996	1997
Sulphate of ammonia (SA)	1100	1400	0	1850	1534	1800	4520	1800
Muriate of Potash (MOP)	0	0	0	180	596	1400	350	700
Triple superphosphate (TSP)	100	0	0	20	69	0	0	0
Urea	0	0	0	0	2	0	0	0
Compound NPK	0	0	0	0	0	7	7	7
Total/Year	1200	1400	0	2050	2201	3207	4877	2507

Source: Gautam (2001)

The types of fertiliser imported by the Solomon Islands are: Compound NPK Triple superphosphate (TSP), Muriate of Potash (MOP) and Sulphate of ammonia (SA). Sulphate of ammonia (SA) fertilizer is imported in the largest quantity by the Solomon Islands Plantation Limited (palm oil Company). The highest level of imports was recorded in 1996 with 4520 tonnes.

3.10 Previous Research on pastures in Solomon Islands

More than 13,000 hectares of pasture in Solomon Islands are under coconuts and trees and 4,000 ha are under open pastures system (Wate, 1995). Most smallholder owned farms are about 5-15 hectares and land purchase cooperatives (tribal or communal owned) are around 50-100 hectares of coconut (Wahananiu et al., 1993). Over decades, Government's efforts to develop the cattle industry have been hampered by a number of problems mainly with regards to pasture development hence the focus of this research.

3.10.1 Pasture under light/heavily shaded conditions

In Solomon Islands, the climatic condition is mostly tropical and coastal regions have maximum temperatures which seldom exceed 32˚C with minimums rarely below 23˚C (Gutteridge & Whiteman, 1978a). It is common in these regions for pastures to be established under coconut plantations where light and/or heavily shaded conditions can be regarded as influencing factors on their growth. However, in order to establish a pasture under any pasture system in the field, it is vital to understand that different pasture species cannot perform well under all environmental and/or soil conditions. For instance, Gutteridge and

Whiteman (1978a) examined pasture species trials of five tropical grasses and eight tropical legumes at five regional sites (of different soil types, fertility and acidity, and environmental conditions) in the Solomon Islands. They found that under heavily shaded (young coconut plantations, 4 years) conditions on a coral soil of pH 6.4, grass species such as Batiki Blue and Signal; and legume species- Puero and Centro were best adapted. Panicum maximum cv. Hamil (*Guinea grass*)/Centro (11.7 t ha^{-1}) and Batiki/Puero (10.8 t ha^{-1}) were the highest yield combination that maintained a good legume/grass. Signal was highly competitive and suppressive for legume combinations. Under old coconuts (70 years) on a coral rubble soil of pH 8, they found that Koronivia was best among grasses, which formed dense swards and Siratro among legumes, which maintained its yield. Hence, each pasture species can perform well under different environmental conditions in "pasture under coconut" with good combination. Pasture grass/legume species such as Batiki blue, Signal, Puero and Centro can perform well on coral soils with low pH under heavily shaded conditions whereas Koronivia and Siratro can grow well on coral rubble soil with high pH under light shaded conditions.

3.10.2 Light transmission, stocking rate and weed control

The standard spacing for coconuts used in Solomon Islands is between 5-7 or 10 meters using a triangular method. Planting density, weeds, and stocking rate are essential factors to consider during pasture establishment and operation under coconut. Litscher and Whiteman (1982) surveyed light transmission and pasture composition under fourteen smallholder coconut plantations in Malaita that were subdivided into twenty seven uniform sub-units. At densities of 160-200 palms ha^{-1} with a median light transmission of 50-55% in most (seventeen) units, they found low soil K, poor palm growth with average copra yields of 540 kg ha^{-1} and Batiki blue yields were not significantly directly related to light transmission but were associated with stocking rate and weed control. Stocking rates above 1.6 au ha^{-1} of actual pasture deteriorated a number of pasture units beyond recovery. Any plant species other than those sown or volunteered pasture species were termed as "weeds", which rapidly invaded and found at average of 50% content of all pasture units by the time of the survey. Thus, weeds and stocking rate have an effect on pastures' performance under coconut. Although providing useful information, the above study did not include other appropriate pasture species. The proposed study will include an analysis of other pasture species that have been sighted on the areas of study.

3.10.3 Soil nutrient content of some pasture soils

An appropriate pasture species cannot perform well or obtain good yield under a suitable environmental condition unless its soil nutrient content is adequate. During the pasture species trials of five tropical grasses and eight tropical legumes at five regional sites in the Solomon Islands, Gutteridge and Whiteman (1978a) found that the soil nutrient contents under coconut plantations (heavily shaded and less shaded) were the lowest with overall low pasture yields (dry matter). They found that a symptom of K deficiency was apparent on evaluated pastures and this was because fertilizer application was not included in the trial. Also, some legumes suffered and failed to establish due to iron deficiency under less shaded condition's soil. Hence, although the pasture species had been identified as suitable for under coconut conditions with good combinations, their yields were low due to the low soil nutrient contents and pastures expressed some deficiency symptoms. In other words, the soil lacked or has less supply of nutrients to meet the appropriate pasture species' nutrient requirements. However, soil tests on S, Mg, Ca, Mo, selenium (Se), B, copper (Cu), Mn and cobalt (Co) were not included in this research, which makes the study irrelevant when considering pasture nutrient requirements and the insufficient soil fertility information provided. Hence, a more complete analysis of nutrient elements will be considered in the current study.

3.10.4 Determination of components of yield in "pasture/coconut system"

Overall, the determination of the yield for each component (pasture, stock and coconut palm) in "pasture under coconut system" is important and needs to be considered. Watson and Whiteman (1981), under stands of 65 year old coconuts on fertile soil in Solomon Islands, compared naturalized and sown pasture at 3 stocking rates (1.5, 2.5, or 3.5 animals ha^{-1}) over 3 years. They found that applications of up to 400 kg N ha^{-1} yr^{-1} over 2 years to Signal grass had no significant response. In terms of live weight-gain between the pastures, it had no significant difference throughout. They observed that the live weight gain $head^{-1}$ decreased linearly with increasing stock rate. They also found that copra yields had no effects from pasture treatments or stocking rate due to available substitutes of natural grasses and legumes under coconuts. They stated that the introduction of exotic pasture species could not be recommended and pasture improvements, such as weed control and standard 1.5-2.5 animal ha^{-1} stocking rates were favourable. Therefore, the determination of the yield of pasture (dry matter), stock (live weight gain) and coconut (copra) can be better off with appropriate pasture species and pasture treatments other than weed invasions and over stocking rate. This research only included signal grass out of other pasture species that can perform well under shades of coconut plantations (Gutteridge & Whiteman, 1978a). The inclusion of one pasture species (Signal) in the research is insignificant for cattle production, unless the other species are not included. Levine and D'Antonio (1999) and Elton (1958) worked on more than one plant species, which can reduce invasion of weeds.

3.10.5 Pasture management practices

Some pasture improvement practices were recommended to maintain pasture performance and soil fertility for good yield under coconut. For Fe deficiency, Gutteridge (1978) compared the response of selected pasture species to additions of Fe and indicated differential species tolerance to Fe deficiency, particularly among legumes. This was carried out by diagnosing Fe in some pasture species growing on a coralline rubble soil (Troporthent) of high pH. He found that Siratro and Phasey bean (*M. lathyroides*) gained good yields without Fe applications while other legumes could not. Gutteridge and Whiteman (1978a) found an apparent K deficiency symptoms on the pastures during examination of pasture species trials of five tropical grasses and eight tropical legumes at five regional sites (of different soil types and environmental conditions) with no fertilizer application in the Solomon Islands. They brought in additional potassium fertilizer to maintain strong legume component and prevent weed invasion. From each study, Litscher and Whiteman (1982) and others identified control of stocking rate and proper weed management as the most critical factors in maintaining pastures to boost high yield. Therefore, alternative methods of using Siratro and Phasey bean without Fe addition, K addition and control of stocking rate and proper weed management are the required and best practices for the farming system. The pasture improvement practices would have been more relevant if soil nutrient analysis and the identified appropriate pasture plant species were included in the past research.

3.11 Conclusion

From the sections discussed, soil fertility refers to the capacity of soil to provide an adequate and balanced supply of nutrients for plant growth. However, a fertile soil is not necessarily a productive soil therefore it is important to know about other factors that may support or limit productivity of pasture and how these factors can be changed to ensure that the soil is productive. This review highlights a range of soil physical and chemical characteristics that must be considered in this research project along with a good understanding of land management history that may have influenced potential soil productivity.

The soils in the Solomons are mostly developed from volcanic materials with a few from coral. Nutrients are obtained from decomposed organic matter and weathering soil minerals but increasingly other sources of nutrients such as imported fertilizer are required. Cultivation with machinery and the use of inorganic fertilizers are not common nationwide; conversely, there are traditional methods that are used to maintain and/or improve the fertility of the soil.

In Solomon Islands, a number of studies have been carried out on some soils and pasture species where gaps have been identified. In terms of soils and pastures, not all major and trace element availabilities were assessed in conjunction with the vigour of pasture species. This study on pastures on Malaita and Guadalcanal provinces will address those gaps by carrying out; (a) location specific soil and herbage tests for a range of important nutrients, (b) location specific survey of existing pastures with separation into grass, legume and weeds (before undertaking a complete elemental analysis of selected materials), (c) taking soil samples for a subtractive nutrient glass house trial using a common legume species from the four farms involved in the survey. The suite of studies will provide knowledge to enable the formulation of strategies that can improve the soil condition and soil productivity of the farms involved in the study.

The suite of soil and plant tests to be undertaken is described in Chapter 4, Methodology.

CHAPTER 4 General Research Methodology

4.0 Introduction

The research method consists of seven parts: (a) Solomon Islands; (b) general review of Soil Fertility Principles; (c) interviews; (d) soils and herbage sampling, and marking of boundary and collection points; (e) processing, packaging, and shipment of samples; (f) 'subtractive nutrient' glass house trial, soil, and herbage analysis; and (g) data analysis and the writing of the thesis. The research started with general information on Solomon Islands in Chapter 2 and a general review of Soil fertility Principle in Chapter 3. The purpose of this Chapter is to describe the methods used in activities from c to g. This begins with the selection of four cattle farms, all of which are currently operated by smallholders, have no records on soil fertility and acidity, and have faced difficulties in improving pasture management.

Precise information on farm operation, soil and pasture resources in the four selected farms is required to obtain objective knowledge on how to improve the management of fertility and acidity status of the pasture soils and growth.

4.1 Chapter Overview

Section 4.2 describes the four selected pasture farms involved in this study. Section 4.3 outlines the process of contacting farm owners and/or managers. Marking of boundary and sampling points, collection, processing and packaging of soils and herbage samples are outlined in Section 4.4. Section 4.5 describes soils and herbage analysis in laboratory followed by creation of soil tests maps in Section 4.6 and subtractive nutrient glass house trial in Section 4.7. The data analysis is described in Section 4.8.

4.2 Study Areas

Although cattle numbers have dropped over the past 30 years, the provinces of Malaita and Guadalcanal have been selected as the ideal locations for the study because both regions have more beef cattle farmers compared to other provinces. There are several cattle farms, which operate within these provinces however; four (see Table 9) have been selected for this study. These farms have been selected because they have easy access to road, sea, and the urban centres (Auki and/or Honiara) within the two provinces. In this study, only the productive and/or effective sites have been chosen for sample collection and marking of sampling points.

In Malaita Province, the selected farms were Ila (ILA) farm and Asi (ASI) farms. The ILA beef cattle farm is located (8°43'17.26" S 160°42'10.09" E) in the Central Kwara'ae region, about 10 km from Auki. The ASI farm is located (8°50'30.19" S 160°45'28.03" E) approximately 3 kilometres away from Auki, the urban centre of the Province.

For Guadalcanal Province, the farms selected were Saint Joseph Tenaru School farm (STJT) and Nazareth Apostolic Catholic School Farm (NAC). The NAC School Farm is located (9°26'55.91" S 160°04'57.99" E) approximately 2 kilometres east of the STJT farm. The STJT farm is located (9°26'47.91" S 160°04'13.64" E) on the west Guadalcanal Plains or east of Honiara in Guadalcanal.

Table 9 A brief description of four study areas

Location	Site	Code	Land use type	Slope	Elevation above sea level (m)	Av. Annual temperature (C°)	Average annual rainfall (mm)
A	Ila farm	ILA	Pastures, coconut, cocoa, low shrubs, low ferns and weeds	16 - 20°	23	24.9	3,292
B	Asi farm	ASI	Pastures, coconuts, cocoa, low shrubs, weeds	0 – 3	15	24.9	3,292
C	Nazareth Apostolic Catholic Sch. farm	NAC	Pastures, trees and weeds	0 – 3	13	24	2,384
D	Saint Joseph Tenaru School farm	STJT	Pastures, trees, lower shrubs and weeds	0 – 3	26	24	2,384

4.3 Surveys of inputs/outputs productivity

Prior to the actual field research or survey, the farm owners and/or farm managers were notified of the study through information sheets and they also signed consent forms. On arrival, face-to-face interviews were carried out to obtain the inputs, and outputs on the productivity of the farms.

4.4 Boundary points marking, sampling, processing, packaging and shipping

As there were no maps available, the boundary of the farms were firstly marked by using hand-held Garmin Geographical Positioning System (GPS) equipment (see Plates 2 and 3, Figure 7). Prior to sampling, this has helped in familiarization, and mostly identification of effective and productive sites of the farms. For soils, a total of 120 soil cores were taken from two depths (0-7.5 cm and 7.5-15 cm). These were extracted using a soil corer (see Plate 1, Figure 7 and Figure 8). The soils from 0-7.5 cm layer represent the surface horizon and the others from 7.5-15 cm layer represent the subsurface horizon. After collection, the samples and bulk soils were sun and/or air dried (see Plate 5, Figure 7), identified, and packed ready for shipment.

For herbage, a total of 40 herbage samples were taken from each farm to make one herbage sample (see Plate 4, Figure 7). These were collected with a sharp and clean knife at the height of about 5 cm above the ground. The sampling points were selected at random by selecting a particular number of places along a transect (see Figure 8). After collection, the samples were identified, sun dried (see Plate 5, Figure 7), chopped, and packed ready for shipment.

All the selected areas of the four farms were covered with pasture and have been used for grazing. Sampling sites were geo-referenced by the GPS equipment. The samples of soils and herbage were packed into five pails and were sent to the soils laboratory at Massey University, Palmerston North in New Zealand. Upon arrival, the samples were checked by a senior technical manager and stored in a biosecurity room. The composite soil samples were further air-dried on trays in the room for a few days, ground in a bowl, and passed through a 2-mm stainless steel mesh ready for analysis. The bulk soil samples of the four farms were stored in the biosecurity room awaiting results from the analysis of composite samples for further analysis in a glasshouse trial. The herbage samples were oven dried at 60 °C for three days (for herbage), and ground to 1-mm ready for analysis. All the foreign samples were incinerated by Transpacific Technical Services (NZ) Limited after the experiments.

4.5 Sample analysis

Analysis of composite soil samples was carried out at the Soil Science central laboratory at Massey University in Palmerston North, New Zealand while herbage samples were analysed at the Hills Laboratories in Hamilton, New Zealand. The soil analyses conducted were soil pH, Olsen P and CEC. Based on the range of Olsen P soil test values for a location, three samples of grass and legumes from each farm were analysed for major and minor nutrients. Note that the ILA and ASI farms are mixed pastures, therefore, only two samples or species of legumes were analysed.

4.5.1 Soil chemical analysis

Soil pH, Olsen-P and exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}) were measured for soils sampled from the GPS locations within each of the four farms. Phosphate retention and organic carbon were measured in the bulk soil samples, formed by combining soil from each GPS location within a farm. Standards were used and the summary of the results are shown in the Appendices.

Soil pH was measured using a glass electrode on PHM 83 AUTOCAL pH METER (Stevenson & Cole, 1999) with a soil: water ratio of 1:2.5. The Olsen available P (Olsen-P) in the soils was determined by extraction with 0.5M sodium bicarbonate ($NaHCO_3$) at pH 8.5 (Olsen, et al., 1954). Exchangeable cations (Ca, Mg and K) were extracted from soils by leaching at 1:50 with 1M ammonium acetate (NH_4OAc) at pH 7. Exchangeable acidity was determined for the soils during extraction from the pH depression of the extractant (Schollenberger & Simon, 1945). Phosphate retention was measured using Saunders (1965) method and organic carbon and nitrogen were determined by LECO (1996) method.

4.5.2 Herbage chemical analysis

Tests for N, P, K, S, Ca, Mg, Na with a few trace elements (Fe, Mo, Co, Se, Mn, Zn, Cu, B,) were carried out in all the herbage species of the four farms.

N was estimated by NIR, calibration based on N by Dumas combustion. The rest of the major elements and the trace elements were measured by nitric acid/hydrogen peroxide digestion followed by ICP-OES. All herbage analyses were conducted by Hill Laboratories, Hamilton, NZ.

4.6 Soil tests maps

Soil test maps on soil pH and Olsen P at the depths of 0-7.5 cm and 7.5-15 cm for each farm were created on ArcGIS by using a kriging process. It is a method of interpolation, which predicts unknown values from data observed at known locations. Kriging used variograms to express the spatial; variation, and it minimises the error of predicted values which are estimated by spatial distribution of the predicted values (Clay, 2011; Demers, 2005; Longley et al., 1999). The coordinates and soil test values were put into ArcGIS and the process was used to draw the maps.

4.7 'Subtractive nutrient' glasshouse trial

The experiment was carried out with 50% shading in the Plant Growth Unit, Massey University, Palmerston North (see Plate 6, Figure 7) from 2nd November to 13th December 2011, during which time temperatures were maintained between 21 and 38ºC. The techniques used in this trial are similar to those used by Saggar et al. (1992) and Wang et al. (1996). The soils used were passed through stainless steel mesh (< 5mm particle size) and 230g weighed into plastic bags. Due to field soil and some herbage tests indicating low sulphur, phosphates at some sites of each farm, the fertilizer materials and/or treatments used were monocalcium phosphate (MCP), Elemental S, potassium sulphate (K_2SO_4), potassium chloride (KCl) and control (see Appendix III). The fertilizer treatments were weighed respectively into polycarbonate, auto analyzer cups using a 4 place electronic balance scale, mixed with soil in inflated plastic bags for 15 seconds and transferred into (10 cm diameter x 7.5cm height) pots. The weights required for the treatments (P0S1, P1S1, P2S1, P1S1KCl and P1S1K_2SO_4) were; 0 mg for P0, 23 mg for P1, 46 mg for P2, 6 mg for S1, 56 mg for K_2SO_4 and 48 mg for KCl. These treatments were replicated 3 times for the soils of each farm (see Table 10) and were for P, K and S. These were based on the need to determine whether the soil was P deficient and K deficient, but with adequate amount of S.

Table 10 Experimental Design

	3 reps x 4 soils			3 reps x 4 soils	
mgP\mgS	0 mg/pot S0 (S^0)	5 mg/pot S1 (S^0)	10 mg/pot S2 (S^0)	S^0KCl	K_2SO_4
0 mg/pot P0	P0S0	P0S1	P0S2	P0S0KCl	
5 mg/pot P1	P1S0	P1S1	P1S2	P1S1KCl	P1S1K_2SO_4
10 mg/pot P2	P2S0	P2S1	P2S2		

White clover is common in some grazed pastures in Solomon Islands and was chosen as a plant species for this trial. The seeds were tested for germination and sown at 20 seeds per pot for 144 pots and thinned to 17 seedlings per pot after two weeks. Pots were watered daily with sufficient distilled water to maintain moist until germination and then maintained at 80% of field capacity (*c.* 50% available soil moisture; asm). As of the fifth week of growth, trace element solutions were applied with the water required per pot once per week. The total amount of trace element solution added was 90 mls pot^{-1}. Three yellow insects (white fly) traps were hanged in the glasshouse to reduce white fly infestation. After six weeks and three days, the white clover plants were harvested; oven dried at 60 ˚C for 3 days and weighed for their dry weights. After harvest, soils were collected from each pot, soil from each P treatment was pooled and Olsen P extractions undertaken (see Figure 20).

Figure 7 Plates 1 to 6

Plate 1Soil sampling at ILA farm

Plate 2 Marking of boundary points at ASI farm

Plate 3 Marking of boundary points at NAC farm

Plate 4 Soil and herbage sampling at STJT farm

Plate 5 Air drying herbage and soil samples

Plate 6 Glasshouse trial at Massey University

4.8 Statistical analysis

All the data of the chemical characteristics of the soils analysed were statistically compared using Microsoft excel 2010 aiming at obtaining their mean, the range of variations (minimum and maximum), and frequency distribution. The herbage (legumes and grasses) average values were respectively compared against the chemical soil characteristic's most frequent values. The mean dry weights of white clover (leaf and stem) were statistically analyzed by using a General Linear Model Analysis of Variance (ANOVA) in Minitab 16 Statistical Software. The differences among the means were deemed significant at the 95% confidence level.

CHAPTER 5 Survey of Land Use and Chemical Analysis of Soils and Herbages

5.0 Introduction

The productivity of farm soils depends on their nutrient status, which exists under influences from the environment and human activities. As discussed in the previous chapters, nutrient status refers to the amounts of nutrients that are present in the soil and are required by plants. However, not all nutrients are available for plant uptake because they can appear in different chemical forms in the soil, depending on the soil environment and/or the soil development status. To understand the need to improve the productivity of a farm soil, there are nutrient budgeting techniques (Ledgard et al., 2000), and soil and plant testing techniques that have been developed by chemists and agronomists (Hedley, 2008). Some techniques determine those portions of chemical compounds in soils that readily release essential elements (nutrients) for uptake by the roots of plants. Other techniques are used to quantify nutrient acquisition by plant roots. This Chapter and the following will describe the results of farm surveys, soil and plant testing, and a plant bioassay, all designed to assess the soil fertility and acidity status of the four pasture soils in Solomon Islands.

5.1 Chapter Overview

This Chapter consists of two main sections and are subdivided into different sections respectively describing the four farms involved in this study. Section 5.2 outlines land use and management, which involves general land use, maps of sampling points for herbage and soil samples, and discussion on aspects of the field survey questionnaire. Section 5.3 describes the current soil fertility status of each farm, which includes soil analysis, summary of soil test results with some maps, and pasture analysis.

5.2 Land use and management

5.2.1 General land use

At the design stage of this project, it was proposed that sufficient information on each of the farms should be collected in order to assemble nutrient budgets for each farm. The following descriptions of each farm are the result of the information gathering survey.

5.2.1.1 ILA beef cattle farm

The Ila cattle farm is owned and managed by a single farmer. The topography of the farm is rolling to steep or approximately 16-20º, which is suitable only for pasture production (see Table 11). The farm, which has seven animals operated partially under 'pasture under coconut plantation system'. However, even though 2 hectares of the farm have just been re-established with pasture (11 years old), its quality is still poor and this is due to high competition from weeds, which are not controlled due to low labour input. To manage this problem, the animals were allowed to graze the available pasture only for a week and were taken outside the farm daily over the next two weeks to allow regrowth. Outside the farm, the grazing methods used were 'tethering' and 'cut and carry' where animals have access to various herbages to feed on from surrounding bushes of the farmer's village (Ngaligaragara). On the other parts (2 Ha) of the farm, some areas have been overgrown with high and low shrubs while the rest have been converted for cropping by other people. Generally, the land has been permanently used for pasture and coconut plantations with temporary cropping over the past years. The existing cocoa crop under some parts of the coconut plantation was recently introduced.

Table 11 Available stock at ILA farm

Stock	Type	No.	Month On	Age On	Month Off	Age Off
Cows	Jersey	1	June (2001)	10 years	Unknown	Unknown
	(Jersey x Santa gertrudis) cross	2	June (2004)	7 years	Unknown	Unknown
Bulls	Jersey	1	September (2010)	1 year	Unknown	Unknown
	(Jersey x Santa gertrudis) cross	1	August (2007)	4 years	Unknown	Unknown
Heifers	(Jersey x Santa gertrudis) cross	2	August (2009)	2 years	Unknown	Unknown

5.2.1.2 ASI beef cattle farm

The Asi beef cattle farm is owned and managed by a single farmer. The farm has been operating both under 'pasture under coconut system' and 'open pasture system' since the arrival of beef cattle in 1970s and 1980s. Its topography is flat or less than 3 degrees. The total area of the farm is 16 hectares, which has been divided into 11 hectares for cocoa and coconut plantations and 5 hectares for mixed pastures of carpet grass (*Axonopus affinis*), T-grass (*Paspalum conjugatum*), white clover (*Trifolium repens*) and mimosa (*Mimosa pudica*) (Steel et al., 1980). Thirteen animals (see Table 12) have been raised and were allowed to graze whole year round using the 'open pasture system.' The quality of the pasture is very poor due to poor pasture management, low labour inputs required to reduce the outgrowing weeds such as sedge, lack or limited funds for rehabilitation, and mostly being too old (more than 20 years old). For supplementary purposes, the animals were fed with some bush vines, shrubs, and grasses in the evenings using cut and carry method. On hot sunny days, the animals looked for shelter under the plantations. Inside the cocoa and coconuts plantations, there were various high and low shrubs available, which the animals helped themselves (browse) to feed on. In general, the land has been partially and permanently used for pasture and cocoa/coconut plantations with temporary cropping for sweet corn over a year on a small area.

Table 12 Available stock at ASI farm

Stock	Type	No.	Month On	Age On	Month Off	Age Off
Cows	Santa gertrudis	5	March (2009)	2 years	Unknown	Unknown
Bulls	Santa gertrudis	1	March (2009)	2 years	March (2011)	2 years
	Santa gertrudis	2	July (2010)	8 months	Unknown	Unknown
Heifers	Santa gertrudis	5	July (2010)	8 months	Unknown	Unknown

5.2.1.3 NAC beef cattle farm

The NAC School Farm is owned by the Christian Catholic Mission Church. The topography and the setting of the landscape is flat or less than 3 degrees and assessed suitable for general agricultural use. The cattle farm was firstly operated at the school for milk and weed control purposes after the arrival of Christian missionaries. It was then converted into beef cattle farming including a goat unit when the Solomon Islands government had an interest in the industry between 1970s and 1980s. The pasture of the farm consists of paragrass (*Brachiaria* *mutica*) and centro (*Centrosema pubescens*) (Steel et al., 1980), with moderate weeds and surrounding shrubs and trees. A total of 12 animals (see Table 13) are raised and have been grazing the pasture using rotational grazing system. In this study, only 5 hectares of the land were effective where soils and herbages have been sampled. The other parts of the farm have been densely overgrown with bushes of shrubs and trees because of under stocking after the ethnic crises between 1999 and 2003.

Table 13 Available stock at NAC farm

Stock	Type	No.	Month On	Age On	Month Off	Age Off
Cows	Unknown	5	Unknown	Unknown	Unknown	Unknown
Bulls	Unknown	1	Unknown	Unknown	Unknown	Unknown
Heifers	Unknown	3	Unknown	Unknown	Unknown	Unknown
Calves	Unknown	3	Unknown	Unknown	Unknown	Unknown
Goats	Unknown	4	Unknown	Unknown	Unknown	Unknown

5.2.1.4 STJT beef cattle farm

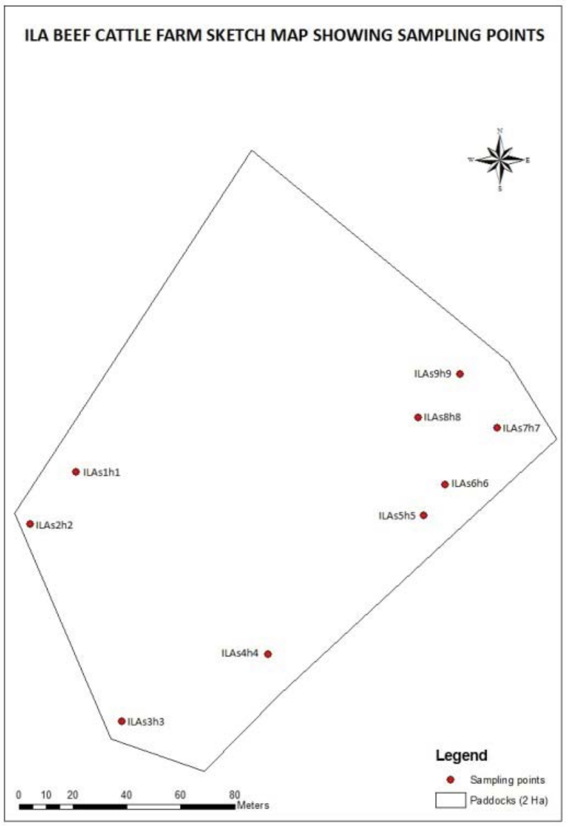
The STJT School Farm is also owned by the Christian Catholic Mission Church. The topography of the area is flat or less than 3º and is suitable for cropping and other agricultural activities. The beef cattle farm at the school has operated since the arrival of Christianity in the mid-19th century. Currently, the farm provides a source of protein for students and staff, and mostly income for the school. The students who attended the school are privileged in terms of having the opportunity to develop practical skills on cattle farming compared to other schools that have no cattle farms. A total of 24 animals (see Table 14) are raised, which graze the pasture using rotational system. Besides cattle farming, there are other parts of the land, which are not included in the study but have been used for rice production and processing, planting of a variety of vegetable crops, small livestock farming (poultry and piggery), and cocoa and coconut plantations. In the cattle farm, although moderate weeds have been sighted, the domination of the paragrass (*brachiaria mutica*), centro (*Centrosema pubescens*) and a few puero (*pueraria phaseloides*) (Steel et al., 1980) has shown the availability of surplus feed for the animals. The other parts (paddocks) of the farm have not been included in the survey because of overgrowing bush of trees and shrubs, which damaged the pasture.

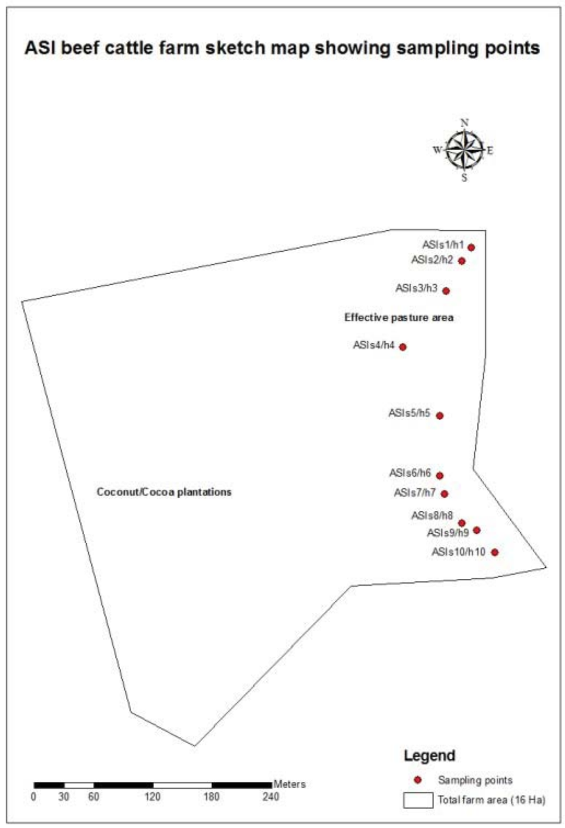
Table 14 Available stock at STJT farm

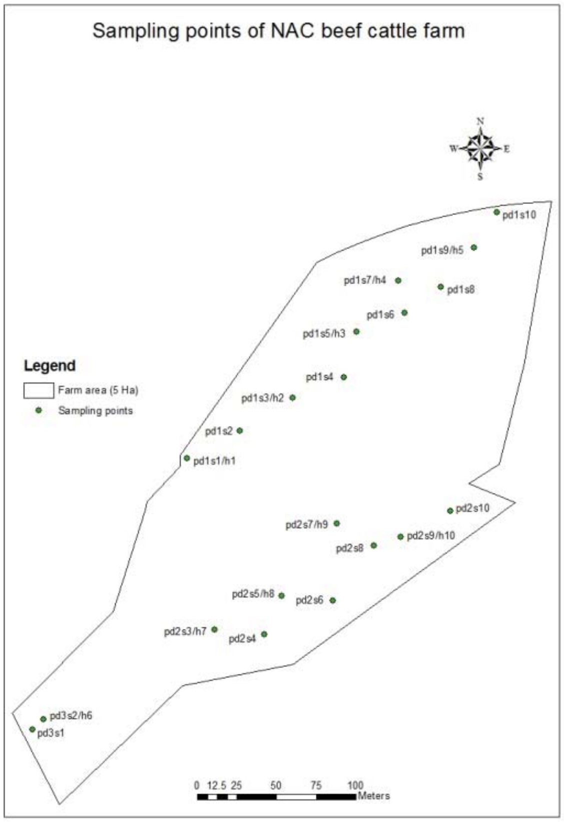
Stock	Type	No.	Month On	Age On	Month Off	Age Off
Cows	Unknown	19	Unknown	>10 years	Unknown	Unknown
Heifers	Unknown	2	Unknown	≈ 3 years	Unknown	Unknown
Calves	Unknown	3	Unknown	< 1 year	Unknown	Unknown

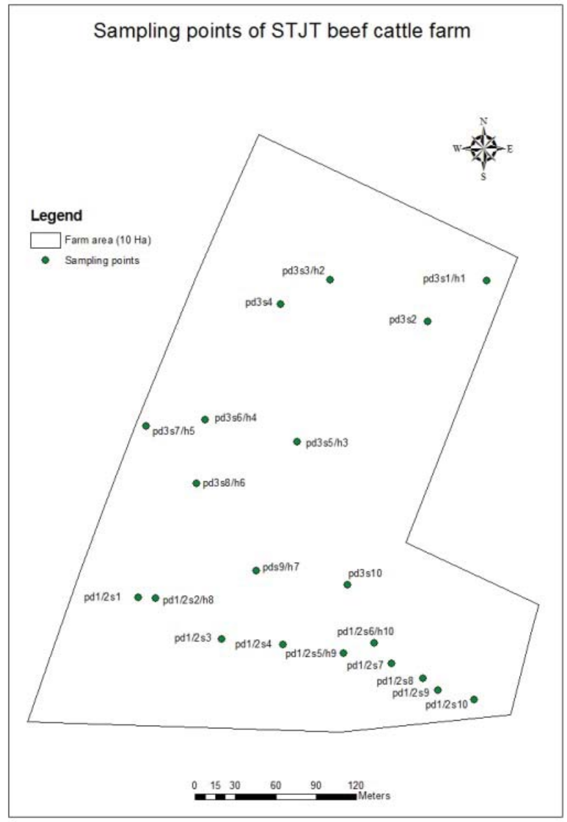
5.2.2 Maps of soil and herbage sampling sites of the four farms

Figure 8 Sampling points for herbage and soil samples on the areas that have effective pasture on the four farms. The samples for herbage (h) and soils (s) are collected from the sampling points as marked on the map.









5.2.3 Outcome of field survey questionnaires of the four farms

Responses to the questionnaire (see Appendix VI) used during the field survey did not provide all the information required for each farm.

5.2.3.1 ILA farm

The ILA farm has operated under the smallholder subsector production system, oriented towards subsistence and cash income. The farm has no history of fertiliser use and depends only on the rain for irrigation. The pasture grass and legumes species used on the farm are: Carpet grass (*Axonopus affinis*), Centro (*Centrosema pubescens* Benth.) and Puero (*Pueraria phaseoloides*). It is difficult to collect information on amounts of feed produced on or brought into farm; weight of animals; and the amounts (tons ha^{-1}) of other crop on plantation systems on average over 5 years because the farmer has no records. However, information on soils, farm production, area in crop (on average over 5 years), and area in coconut plantation (on average over 5 years) were obtained. For soils, the farm has good soil drainage, less than 1 metre depth to stone or gravel and the colour is reddish brown according to the Munsell Soil Colour Charts (Sillanpaa, 1982). For farm production, there are seven animals (see Table 11) with various ages and breeds. Selling of current stock is impossible at this stage as the farmer is still working on reviving the farm. About 2 hectares of the land, which is not included in this study, has been converted to cropping (on average over 5 years). For the area (2 ha) studied, the total area in coconut plantation (on average over 5 years) is 0.5 ha where the quality of pasture is poorer than other parts of the farm.

5.2.3.2 ASI farm

The ASI farm has been operating under the smallholder subsector production system under cattle industry in Solomon Islands. The farm depends on rain for irrigation and has no history in fertilizer usage since its establishment. Although animals were fed with introduced herbages from the surroundings, there have been no records on feed produced on, or brought into, the farm. However, in terms of cropping, sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) is the only crop, which was grown once (in 1998) in the history of the farm. The size of land used for the crop was 0.25 ha, where the crop was grown three times during the year using rotational cropping system. For soils, the farm has poor drainage and is prone to flooding due to its location by the river. It is less than 1 metre depth to water table and the soil colour is brown. As the farm is currently in need of rehabilitation, selling of current stock is impossible at this stage.

5.2.3.3 NAC farm

For the NAC farm, some information on pastures, soils, and farm production were given. For pastures, the farm is operated as an ‘open pasture system’ and is divided into three paddocks. Although the grass and legume species grown on the farm are more than 40 years old, they are of good quality as there were free labour inputs from students. The animals graze each paddock per week using rotational grazing system to allow re growth of pastures and control weeds. The rest of the farm has not been included in the study because of under stocking issue, which resulted in loss of available pasture when suppressed by over-growing weeds or bush shrubs. For soils, the farm has no fertilizer application history; nutrients were only obtained from mineralized nutrients from the decomposition of organic matter and atmospheric reactions such as N fixation. The soil depth stones and ground water level is more than 1 meter and has good drainage. The farm depends on rain as the source of irrigation. Information on feed produced on or brought into farm and other crop on plantation systems were not provided as the farm operates under smallholder subsector production system.

5.2.3.4 STJT farm

The STJT farm has operated under the smallholder subsector production system and rotational grazing system has been used to avoid over grazing. In this study, only 10 hectares of pastures were considered effective whereas the rest of the farm (other paddocks) has been left unutilized, overgrown with bushes. This is because of under stocking issues, theft, and cultivation of land by some illegal settlers. Although not all the required information was provided, some information on pastures, soils, and farm production were made available during the interviews conducted. About 50 % of the pasture was covered with moderate weeds, which made its quality poor. Weed infestation, which is one of the major problems evident, is due to the low labour inputs; in this case, the only labour provided is by the small number of students who took agriculture as their elective subject. Animals were allowed to graze the pasture 3 weeks in each paddock. In terms of the soil, it is dark brown in colour, the drainage is poor, the depth to stones and ground water level is more than 1 meter, and it has no fertilizer application history. Irrigation (flooding) was applied only to a rice farm that is adjacent to the farm. The beef cattle farm depends on rainfall as its source of water. The animals were sold domestically to the locals and sometimes slaughtered for the students and staff to eat. There has been no feed produced or brought to into the farm. About 2 hectares of land previously used for pasture was converted into rice farming. Since its establishment, the residues from the harvested rice have never been given to the stock to graze.

5.2.3.5 Summary of field survey for all farms

A survey of the four farms provides summary information on the characteristics of each farm (see Table 15). All farms operate as smallholders and none had used fertiliser nor have access to any irrigation other than reliance on rainwater.

Table 15 Information collected from the four farms

	Farm			
	ILA	ASI	NAC	STJT
Effective pasture	2 ha	5 ha	5 ha	10 ha
Non-effective /other	0.3 ha	11 ha	-	-
Type of stock	Jersey & (Jersey x Santa gertrudis) cross	Santa gertrudis	Unknown	Unknown
Fertilizer history	No	No	No	No
Irrigation	No	No	No	No
Cut-carry-method	Yes	Yes	No	No
Supplement	Grasses & general bush shrubs	Bush shrubs/vines	No	No
On-farm feed production	No	No	No	No
Crop production	No	Only once	No	No
Soil drainage	Good	Very poor	Good	Poor
Pasture type	Mixed	Mixed	Para/Centro	Para/Centro/Puero
Vegetation	Pasture, coconuts, bush shrubs	Pasture, coconuts, bush shrubs	Pasture, trees	Pasture, trees
Production system	Small holder subsector	Small holder subsector	Small holder subsector	Small holder subsector

5.2.4 Survey conclusions

Unfortunately, there was insufficient information returned in the survey to construct a nutrient budget for each farm. The information required were inputs of supplementary feed in terms of quantities, product removal (low), and boundaries to blocks in terms of effective growing areas. This information is not recorded by the farmers. Only information on climate, soil, and current stocking rate has been given and in general, nutrient inputs and losses are very low. Apparent levels of product removal indicate that nutrient losses through livestock sales are insignificant. Losses through other processes such as dung and urine transfer, leaching, and immobilisation may be significant and therefore require more detailed information on feeding regimes, stock management, boundaries, and grazing behaviour in mixed pasture/plantation tree systems.

5.3 Current soil fertility status

5.3.1 Soil analysis and soil maps of ILA farm

The frequency and range of soil test values, from the analysis of the ILA pasture soil, are shown in Figures 9 and 10, and Appendix Ia. Soil test methods have been described in section 4.5.1 of Chapter 4.

Olsen P soil test values range from 0 to 29 μgPg^{-1} (Fig. 9). The mean is 10 μgPg^{-1} (App. Ia). Low values 0-5 μgPg^{-1} deficient in P cover 50% of the sampling sites. Only 30% P values were in the range from 15 to 20 μgPg^{-1} pasture growth responsive to P fertilizer and these samples have been collected from the shoulder of the slope part of the farm. Only one sampling site had P values ranging from 25 to 29 μgPg^{-1}, which are optimum for pasture growth (Morton & Roberts, 1999). These are camping sites and are shallow in depth. The bulked soil sample for this farm gave an anion sorption capacity (% P retention) value of 50 %, mean P retention on the scale used for New Zealand soils (Saunders, 1965).

The mean pH value is 6.7 while the maximum value is 7.7 (App. Ia), with the most frequent values between 6.5 to 7. These values cover 50 % sampling sites of the farm (Fig. 9), which are beyond the optimum for pasture growth (Morton & Roberts, 1999). The pH value ranges of 5.5 to 6 (optimum for pasture growth), 7 to 7.5 and 7.5 to 8 are least frequent and are from sites located on slope with rocks moderate rocks exposed. Besides, the soil depth of those sampling sites is shallow.

The mean content of exchangeable K was 0.19 $me100g^{-1}$, with a maximum of 0.9 $me100g^{-1}$ (App. Ia). For K, the most frequent values range from 0 to 0.25 $me100g^{-1}$, and cover 90% sampling sites of the farm (Fig. 9). These values indicate that K could be limiting pasture growth (Morton & Roberts, 1999). Only one exchangeable K value is in the range 0.75 to 1 $me100g^{-1}$, which is adequate for pasture growth. The sampling sites of this value are located on a slope part of the farm with higher organic matter materials. This indicates that a few exchangeable K ions could be held on negatively charged cation exchange sites on the organic matter surfaces. Others are lost through leaching and surface runoff.

Regarding the exchangeable Ca levels, the mean value is 8 $me100g^{-1}$, with the maximum of 22 $me100g^{-1}$ (App. Ia). The most frequent exchangeable Ca values ranges from 2.5 to 5 $me100g^{-1}$, indicating that Ca uptake may be limiting (Morton & Roberts, 1999). These values represent 40% of the sampling sites (Fig. 9). The other Ca values that align to each other range from 2.5 to 5 me100g^{-1}, 5 to 7.5 me100g^{-1} (responsive for pasture growth) and 10 to 12.5 me100g^{-1} (optimum for pasture growth). Most of these parts of the farm are dominated by weeds and rocks. The site with exchangeable Ca values of 20 to 22.5 is located on slope. These values exceed the optimum for pasture growth.

The mean value of exchangeable Mg is 1.8 me100g^{-1}, with maximum of 4.6 me100g^{-1} (App. Ia). For Mg, the ranges of values that are aligning to each other mostly are 0.5 to 0.75 me100g^{-1}, 7.5 to 1 me100g^{-1} and 1.25 to 1.5 me100g^{-1} (Fig. 9). They cover 60% of the studied area. 0.5 to 0.75 me100g^{-1} is optimum for pasture growth (Morton & Roberts, 1999). The other higher ranges of values (3 to 4.75 me100g^{-1}) exceed the optimum. They cover 30% of the sampling sites and could be toxic for pasture growth. The sampling sites of these values have possible competition for the element from weeds, slope and moderate exposing rocks.

The CEC mean value of the ILA pasture soils was 9 me100g^{-1}, with the maximum of 11 me100g^{-1} (App. Ia). The most frequent values range from 5 to 10 me100g^{-1}, which covers 60% of the soil samples indicating a low capacity to hold exchangeable cations on the majority of the area. The rest of the values ranges are 10 to 15 me100g^{-1}, 25 to 30 me100g^{-1} and 30 to 35 me100g^{-1} (Fig. 9). These parts of the farm are slopes and contain exposed rocks.

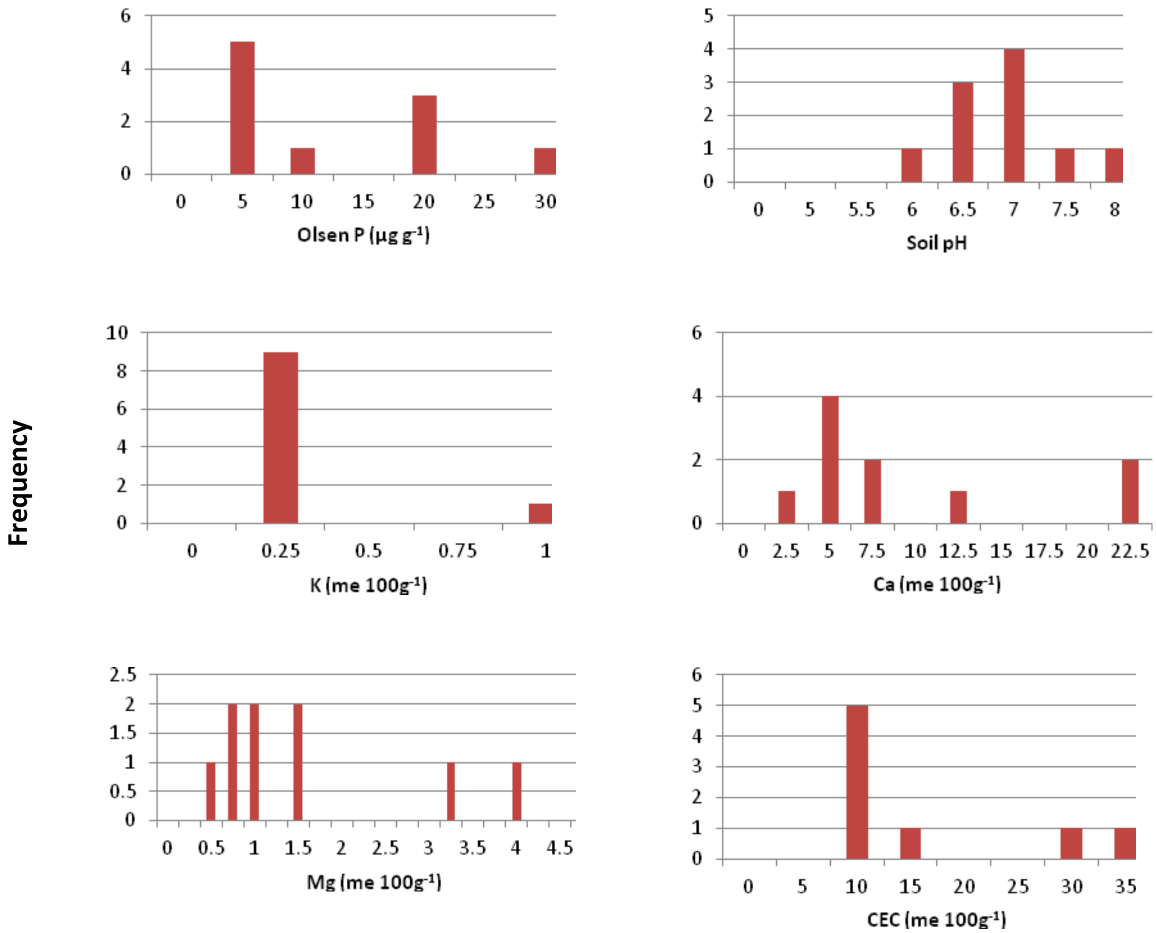


Figure 9 Frequency and range of soil test values (Olsen P, soil pH, exchangeable K, Ca, Mg and CEC) collected from pastures at the ILA farm.

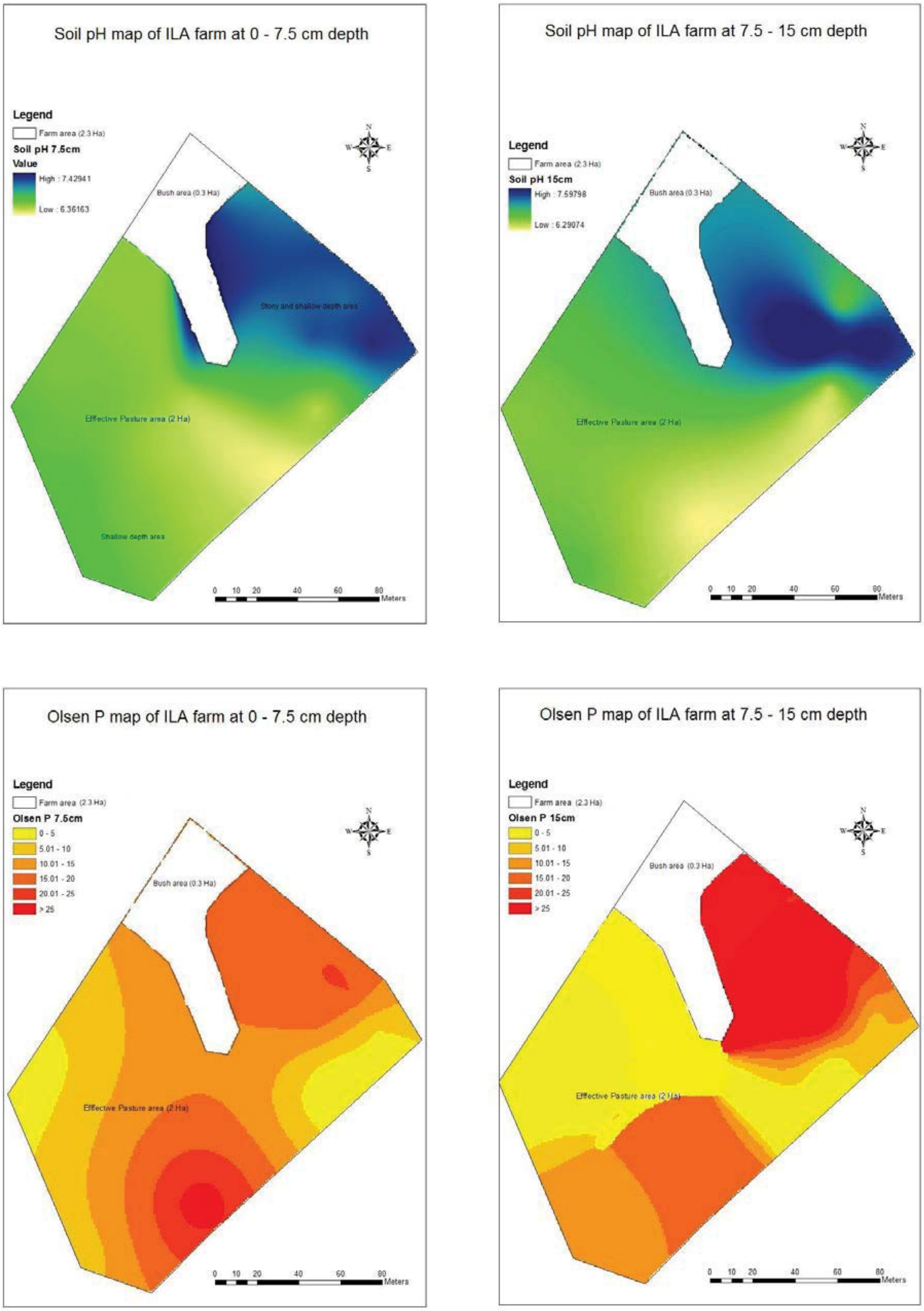


Figure 10 Maps indicating areas of differing soil pH and Olsen P values produced by Kriging the observed Soil pH and Olsen P values at 0-7.5 and 7.5-15 cm soil sampling depths at ILA farm.

The spatial distribution of soil pH is consistent between the two soil depths (Figure 10) sampled, a similar result is achieved for the Olsen extractable P (Figure 10) but the spatial distribution of pH and Olsen P are unrelated. The highest pH is associated with the dry rocky area and its rolling landscape. In the rocky dry area, the plant cannot utilize the P very well due to low solubility, so soil P status remains high (Troeh & Thompson, 1993). The other reasons for the higher Olsen P are because some parts at farm are low lying areas with high drainage, shallow depth (< 1 m to stones) and camping sites for animals.

5.3.2 Soil analysis and soil maps of ASI farm

The frequency and range of soil test values, from the analysis of the ASI pasture soil, are shown in Figures 11 and 12, and Appendix Ib.

Olsen P soil test values range from 0 to 25 μgPg^{-1} (Fig. 11 and 12). The mean is 17 μgPg^{-1} (App. 1b). High values 20 to 25 μgPg^{-1}, which are optimum for pasture growth cover 50% of the sampling sites (Morton & Roberts, 1999). Test values of 15 to 20 μgPg^{-1}, which indicate pasture growth may still be responsive to added P cover 20% and P values ranging from 0 to 5 μgPg^{-1} cover 30% of the sampling sites and indicate a deficiency of plant available P. The sites with lowest range of values are water logged areas and are occupied with moderate weed cover. The bulked soil sample for this farm gave an anion sorption capacity (% P retention) value of 52%, mean P retention on the scale used for New Zealand soils (Saunders, 1965).

The ASI pasture soil has a mean pH value of 7 and maximum value of 8 (App. 1b). The most frequent values range from 6.5 to 7, which cover 50% of sampling sites. These values exceed the optimum and could be inadequate for pasture growth (Morton & Roberts, 1999). Values from pH 7.5 to 8 (exceed the optimum) cover 30% of the area. They are close to water logged areas and buildings. Only 20% of the sampling sites have pH values from 6 to 6.5 (Fig. 11 and 12), which are optimum for pasture growth.

The mean and the maximum values of K are 0.08 $me100g^{-1}$ and 0.09 $me100g^{-1}$ (App. 1b). The most frequent exchangeable K values range from 0 to 0.25 $me100g^{-1}$ (Fig. 11), which cover all sampling sites. This indicates that pasture growth is likely to be responsive to added plant available K (Morton & Roberts, 1999).

Regarding exchangeable Ca, the most frequent values range from 2.5 to 5 $me100g^{-1}$, which cover 70% of the sampling sites (Fig. 11). These values are optimum for pasture growth (Morton & Roberts, 1999). Low Ca values 0 to 2.5 $me100g^{-1}$ (deficient for pasture growth) are less frequent as are medium to high values of 5 to 7.5 $me100g^{-1}$ and 7.5 to 10 $me100g^{-1}$ (optimum for pasture growth). The sampling sites for these values respectively cover 10% of the area and are close to high water logged areas and moderate weeds. The mean and maximum values of Ca are 3.9 $me100g^{-1}$ and 8.9 $me100g^{-1}$ (App. 1b).

The mean exchangeable Mg is 1 $me100g^{-1}$ with maximum value of 3 $me100g^{-1}$ (App. 1b). The most frequent exchangeable Mg values range from 0.5 to 1.5 $me100g^{-1}$, which cover 60% of the sampling sites (Fig. 11). These values exceed the optimum for pasture growth (Morton & Roberts, 1999). These sites have fewer weeds and are low water logged areas. Only 10% of the area has exchangeable Mg values ranging from 0 to 0.5 $me100g^{-1}$, which are optimum for pasture growth. These sites are close to the farm boundary posts and the road. Twenty % of the area has exchangeable Mg values ranging from 1.5 to 2 $me100g^{-1}$ and followed by 2 to 2.5 $me100g^{-1}$ (10% of the area). Both ranges exceed the optimum values.

The CEC mean value of the ASI soil was 9 $me100g^{-1}$, with the maximum of 11 $me100g^{-1}$ (App. Ib). The most frequent exchangeable CEC values range from 5 to 10 $me100g^{-1}$ (Fig. 11), which cover approximately 60% of the sampling sites. The CEC values range from 10 to 15 $me100g^{-1}$ are located on sites covered with moderate weeds.

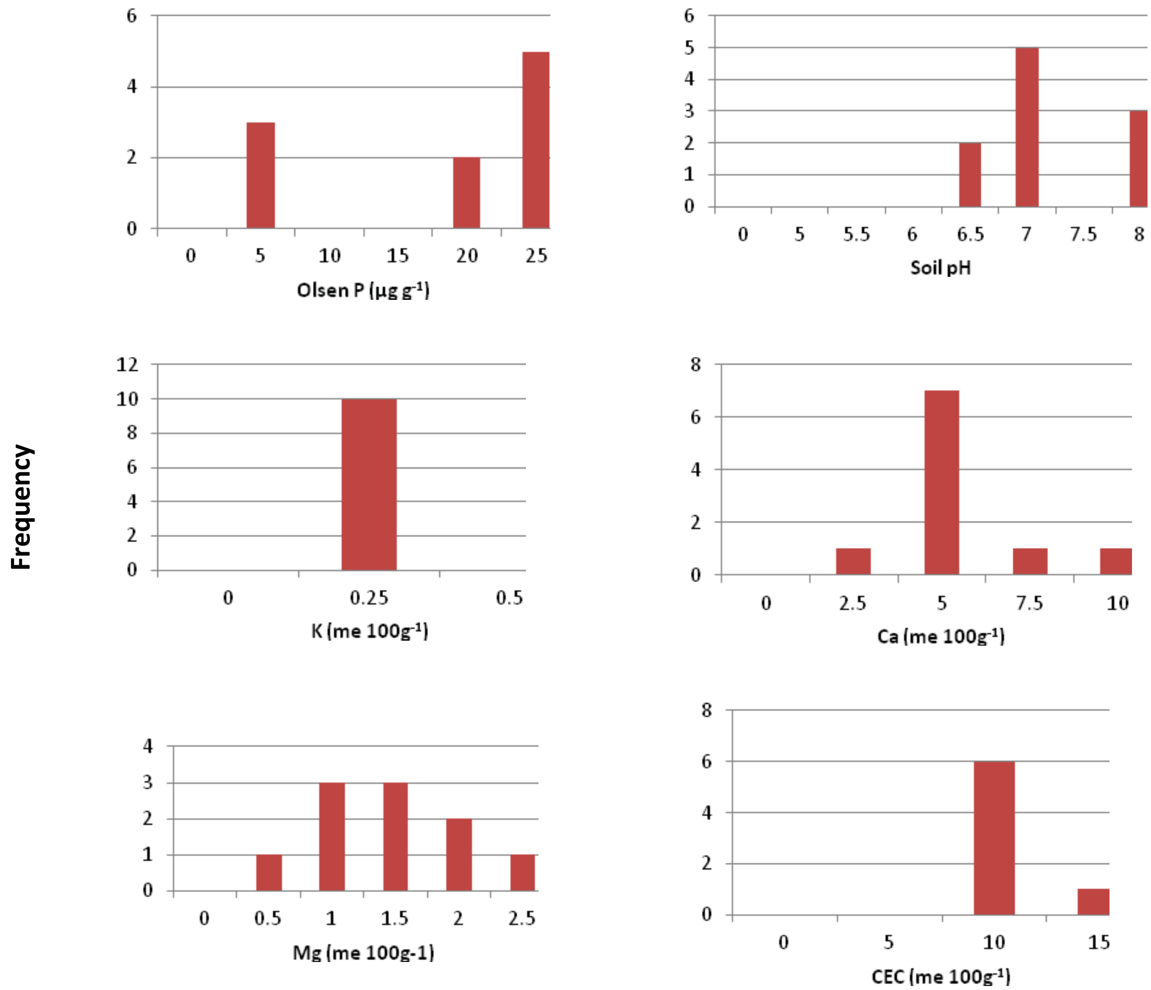


Figure 11 Frequency and range of soil test values (Olsen P, soil pH, exchangeable K, Ca, Mg and CEC) collected from pastures at the ASI farm.

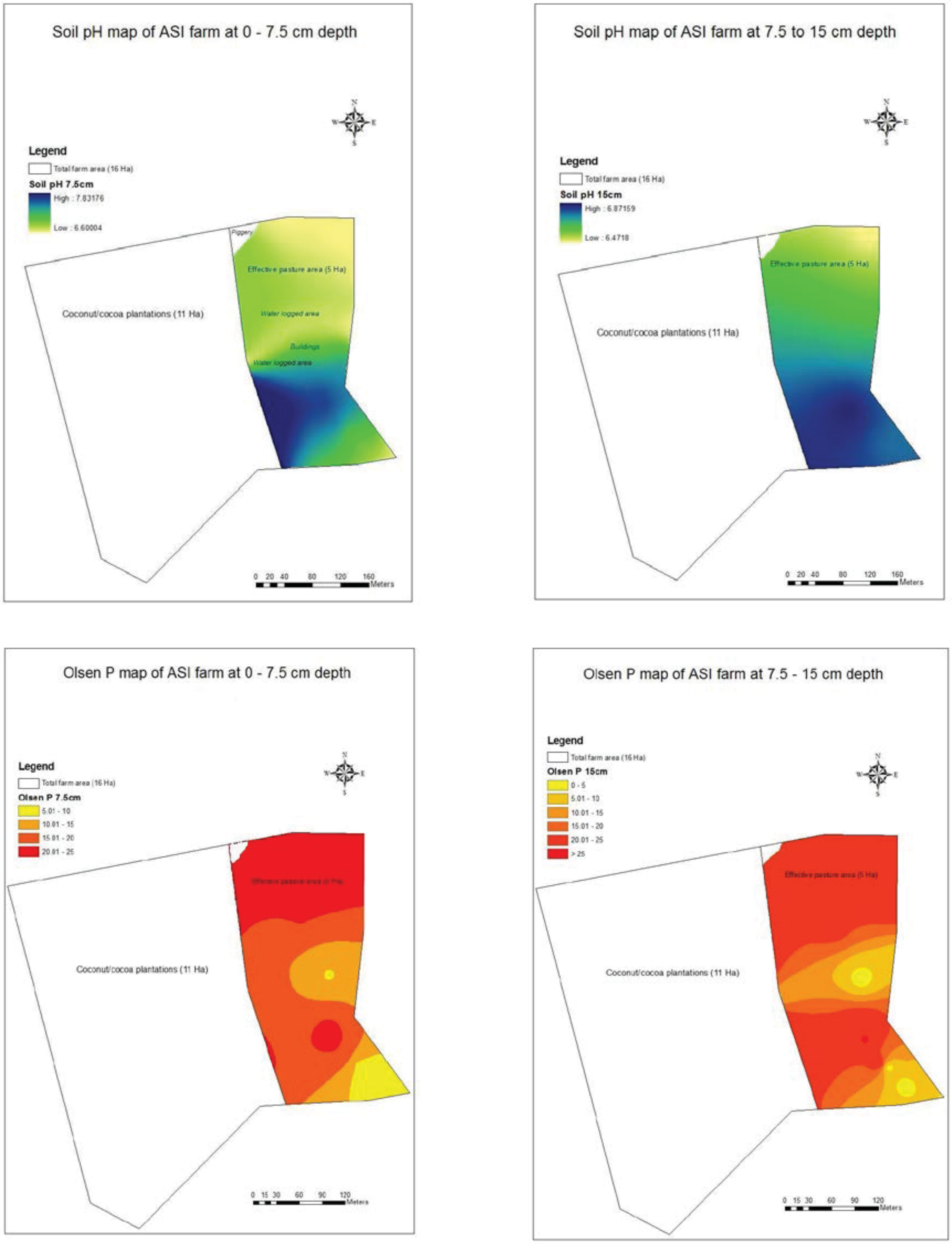


Figure 12 Maps indicating areas of differing soil pH and Olsen P values produced by Kriging the observed Soil pH and Olsen P values at 0-7.5 and 7.5-15 cm soil sampling depths at ASI farm.

The spatial distribution of soil pH is similar between the two soil depths (Figure 12) sampled, and the result achieved for the Olsen extractable P (Figure 12) is similar. However, there is no relationship between the spatial distribution of pH and Olsen P. The highest pH is associated with severely water logged areas and buildings (farmer's residence). Areas with highest Olsen P and low pH are less water logged and are close to a piggery pen (Figure 12). Olsen P is highly accumulated compared to other areas because of disposal of piggery wastes into the pasture. At lower pH areas, organic P is held more tightly to the surface of soil particles due to high content of organic materials in the soil (Troeh & Thompson, 1993).

5.3.3 Soil analysis and soil maps of NAC farm

The frequency and range of soil test values, from the analysis of the NAC pasture soil, are shown in Figures 13 and 14, and Appendix Ic.

Olsen P soil test values of pasture soil at NAC farm range from 0 to 9 μgPg^{-1} (Fig. 13 and 14). The mean is 4 μgPg^{-1} (App. Ic). Low values 0 to 5 μgPg^{-1} deficient in plant available P cover 80% of the sampling sites (Morton & Roberts, 1999). Some of the sampling sites are covered with moderate weeds. Olsen P soil test values ranging from 5 to 10 μgPg^{-1} are from camping sites and/or close to transfer gates. They also indicate soils deficient in P for pasture growth. The bulked soil sample for this farm gave an anion sorption capacity (% P retention) value of 30%, mean P retention on the scale used for New Zealand soils (Saunders, 1965).

The most frequent pH values range from 6 to 6.5 and 6.5 to 7 (Fig. 13 and 14), where the mean and maximum values are 6.5 and 6.8, respectively (App. Ic). Both ranges of pH value cover 50% of all sampling sites. These values exceed the optimum for pasture growth (Morton & Roberts, 1999).

The mean content of exchangeable K was 0.5 $me100g^{-1}$, with the maximum value of 2.2 $me100g^{-1}$ (App. Ic). The most frequent exchangeable K values range from 0.25 to 0.5 $me100g^{-1}$, which cover 60% of sampling sites on the farm (Fig. 13). In this range the K values are optimum for pasture growth (Morton & Roberts, 1999). Twenty five % of the area has 0 to 0.25 $meK100g^{-1}$, which are deficient. Exchangeable K values range from 1 to 1.25 $me100g^{-1}$ and 2 to 2.25 $me100g^{-1}$ (Fig. 13), these are above the optimum for pasture growth. These values are from soils collected from camping sites, those that are close to coconut trees and transfer gates.

For exchangeable Ca, the mean value is 4.2 me100g^{-1}, with a maximum of 5.5 me100g^{-1} (App. Ic). The most frequent range of exchangeable Ca values range from 2.5 to 5 me100g^{-1}, which cover 90% sampling sites. This indicates that the Ca values are responsive for pasture growth (Morton & Roberts, 1999). These sites have healthy swards and decomposing fallen trees. Only 10% Ca values were in the range from 5 to 7.5 me100g^{-1} (Fig. 13), which are optimum for pasture growth.

Regarding the exchangeable Mg levels, the mean value is 1.3 me100g^{-1}, with the maximum of 2 me100g^{-1} (App. Ic). From Fig. 13, the most frequent (60% of the area) exchangeable Mg values range from 1.4 to 1.6. The values exceed the optimum for pasture growth (Morton & Roberts, 1999). Other exchangeable Mg values' ranges of 0.8 to 1 me100g^{-1}, 1 to 1.2 me100g^{-1}, 1.2 to 1.4 me100g^{-1}, 1.6 to 1.8 me100g^{-1} and 1.8 to 2 me100g^{-1} are also beyond the optimum. These high values are from sites with decomposing fallen trees. Exchangeable Mg values 0 to 0.2 me100g^{-1} cover 5% the area and indicate potential Mg deficiency. Values 0.2 to 0.4 me100g^{-1} also cover 5% of the area where Mg values are in the optimum range. These values are from camping sites and the transfer gates.

The CEC mean value of the NAC pasture soils was 11 me100g^{-1}, with a maximum of 15 me100g^{-1} (App. Ic). Most frequent CEC values ranges from 10 to 15 me100g^{-1} followed by 5 to 10 me100g^{-1} (Fig. 13). The most frequent values range cover 55% of the farm while the least is 45%. The least frequent values ranges are from sites with camping and gates.

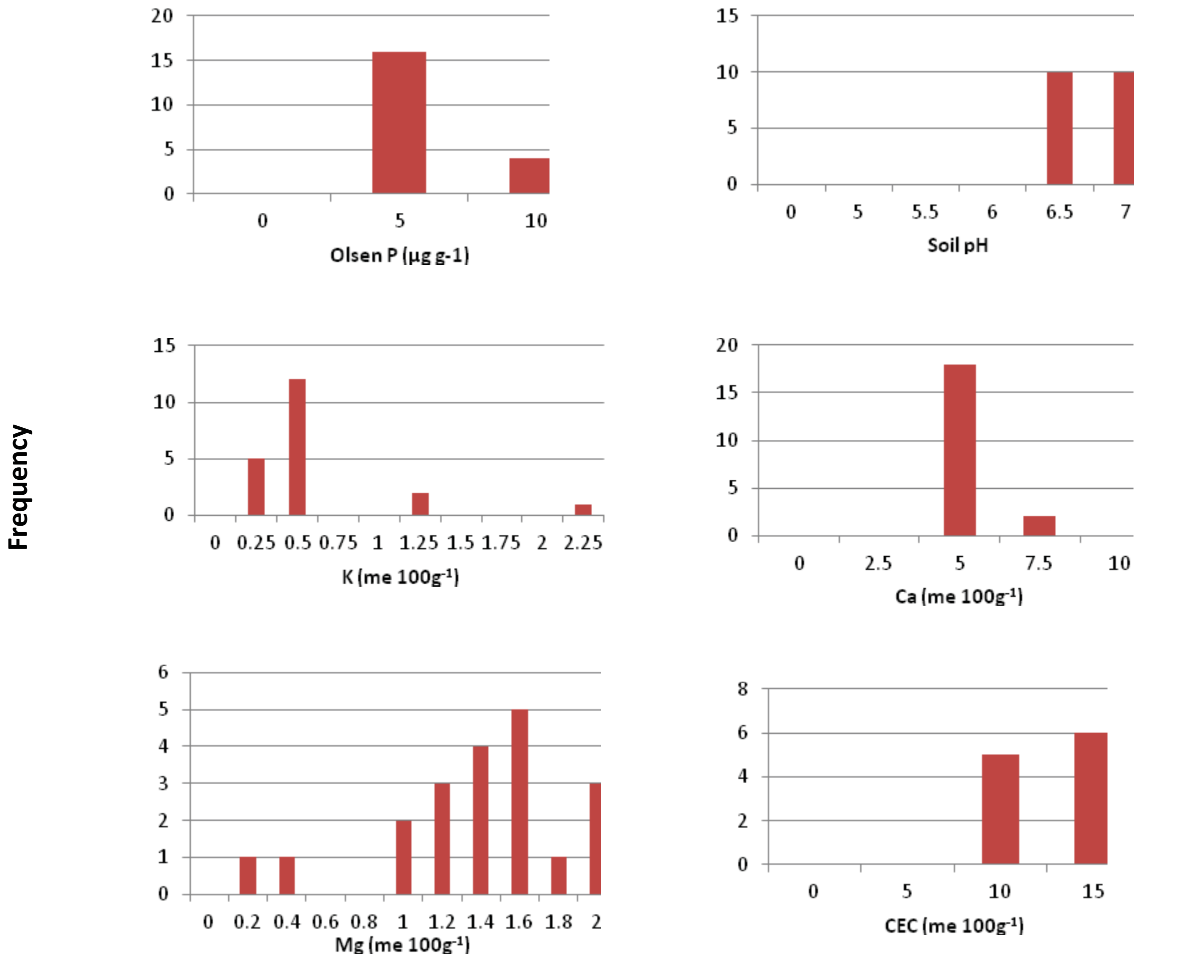


Figure 13 Frequency and range of soil test values (Olsen P, soil pH, exchangeable K, Ca, Mg and CEC) collected from pastures at the NAC farm.

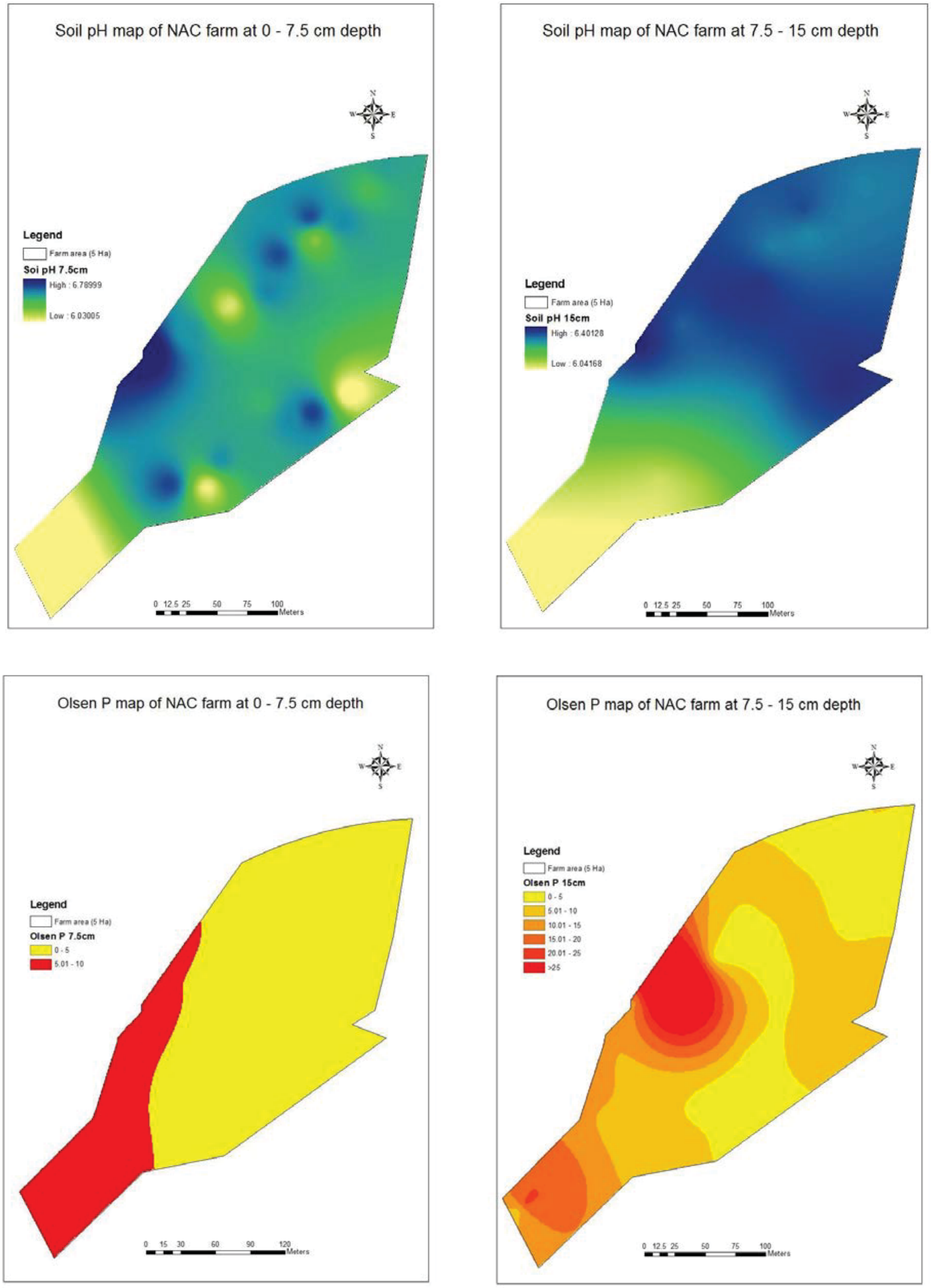


Figure 14 Maps indicating areas of differing soil pH and Olsen P values produced by Kriging the observed Soil pH and Olsen P values at 0-7.5 and 7.5-15 cm soil sampling depths NAC farm.

At NAC farm low Olsens seem to be spatially distributed with lower soil pH between the two depths (see Figure 14), although there are no relationships between their respective total spatial distributions. The high Olsen P areas are associated with trees, stockyard and holding yard, which are regarded as camping sites for animals. As well as active camping sites, the growth of trees in the area has shaded pasture growth, which probably results in unutilized P raising the extractable Olsen P in the soil (Troeh & Thompson, 1993). The soils at the holding yard area turned dry as a result of overgrazing, which also contributes to high Olsens (low solubility) and lower soil pH (from SOM decomposition) (Foth & Ellis, 1997). It is not normal to have high Olsen P values at the below depth (7.5-15 cm) (Figure 14), which appears to be associated with buildings and may result from previous human activity, gardening or burial of wastes, and more intensive feeding of livestock (goats).

5.3.4 Soil analysis and soil maps of STJT farm

The range and frequency of soil test values, from the analysis of the STJT pasture soil, are shown in Figures 15 and 16, and Appendix Id.

The mean and maximum values of P of STJT pasture soils are 5 μgPg^{-1} and 8 μgPg^{-1} (App. Id). Most frequent P values range from 0 to 5 μgPg^{-1}. They cover 75% of the farm area and are deficient for pasture growth (Morton & Roberts, 1999). Olsen P values 5 to 10 μgPg^{-1} (Fig. 15 and 16), cover only 25% of the area and also indicate deficiency. These values were from samples taken from sites close to trees and old paddock boundary lines. The bulked soil sample for this farm gave an anion sorption capacity (% P retention) value of 37 %, mean P retention on the scale used for New Zealand soils (Saunders, 1965).

For pH, the most frequent values range from 6 to 6.5 (Fig. 15 and 16), which are slightly above the optimum for pasture growth (Morton & Roberts, 1999). These values cover 70% of the farm. Soil pH values range of 6.5 to 7 cover 20% of the farm and could be inadequate for pasture growth. Soil pH values in the range 5.5 to 6 cover only 10% of the area, which is optimum. These are soils located close to camping sites and trees. The mean and maximum values for pH are 6.3 and 6.9 (App. Id).

The mean content of exchangeable K was 0.3 $me100g^{-1}$, with a maximum of 0.8 $me100g^{-1}$ (App. Id). The most frequent values for exchangeable K range from 0 to 0.25 $me100g^{-1}$, and cover 55% of the farm (Fig. 15). These values indicate that K could be limiting pasture growth (Morton & Roberts, 1999). Thirty five % of the area has exchangeable K values 0.25

to 0.5 $me100g^{-1}$, which are optimum for pasture growth. Other exchangeable K values of 0.5 to 0.75 $me100g^{-1}$ and 0.75 to 1 $me100g^{-1}$ are above optimum values and appear to be associated with animal camping sites.

Regarding the exchangeable Ca levels, the mean value is 4 $me100g^{-1}$, with a maximum of 6 $me100g^{-1}$ (App. Id). For exchangeable Ca, the most frequent values range from 2.5 to 5 $me100g^{-1}$, which cover 95% of the farm. This indicates that Ca uptake may be limiting (Morton & Roberts, 1999). Only one sampling site had Ca values ranging from 5 to 7.5 $me100g^{-1}$, which is optimum for pasture growth. Generally, moderate weeds have been cited all around the farm.

The mean value of exchangeable Mg is 0.8 $me100g^{-1}$, with maximum of 1 $me100g^{-1}$ (App. Id). For Mg, the most frequent exchangeable Mg values range from 0.5 to 1 $me100g^{-1}$ that cover 85% of the farm (Fig. 15). This indicates that exchangeable Mg values are optimum for pasture growth (Morton & Roberts, 1999). Exchangeable Mg values ranging from 1 to 1.5 $me100g^{-1}$, which are above optimum values, occupy 10 % of the area. Mg exchangeable values from 0 to 0.5 $me100g^{-1}$ occupy only 5% of the area.

The mean CEC value of the STJT pasture soil was 21 $me100g^{-1}$, with the maximum of 32 $me100g^{-1}$ (App. Id). There are two ranges of most frequent values for CEC. They are 15 to 20 $me100g^{-1}$ and 25 to 30 $me100g^{-1}$, followed by 10 to 15 $me100g^{-1}$, 20 to 25 $me100g^{-1}$ and 30 to 35 $me100g^{-1}$. Those values that are lowest are from soils collected from areas of moderate camping sites, transfer gates and some are close to trees.

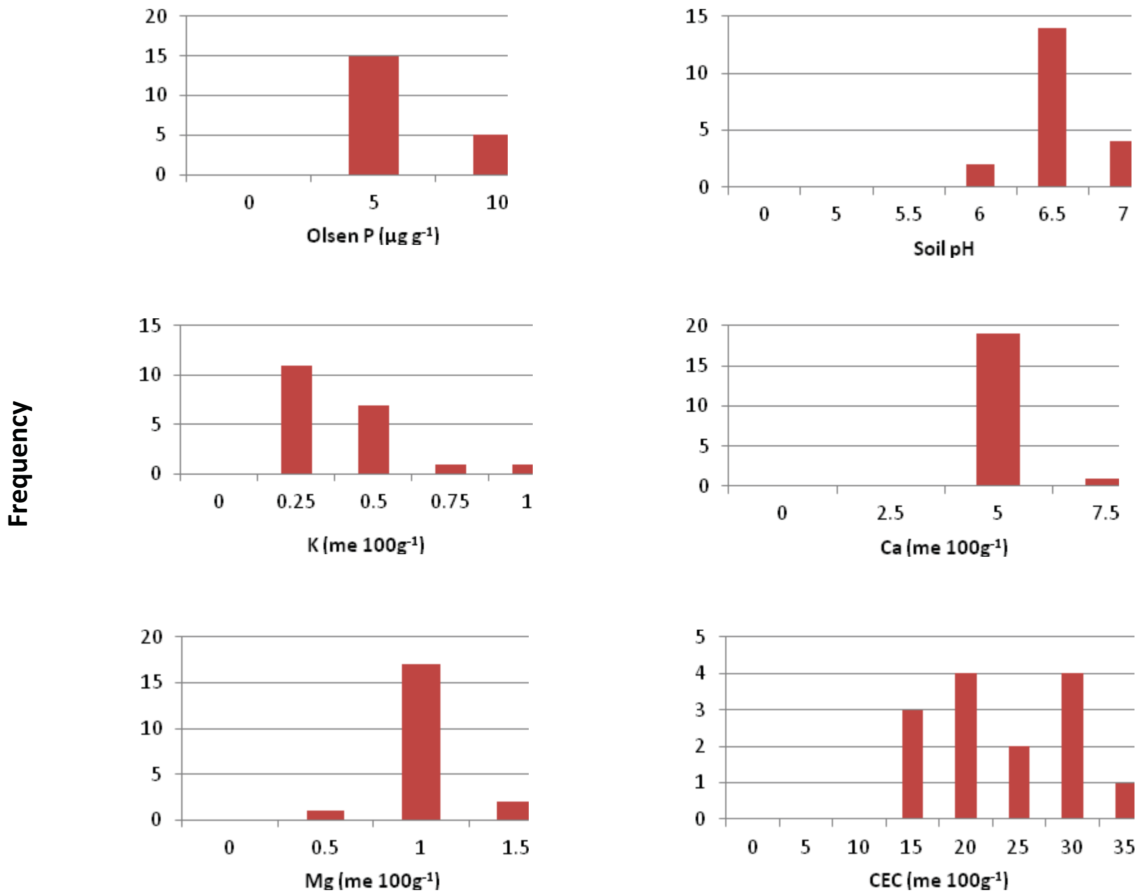


Figure 15 Frequency and range of soil test values (Olsen P, soil pH, exchangeable K, Ca, Mg and CEC) collected from pastures at the STJT farm.

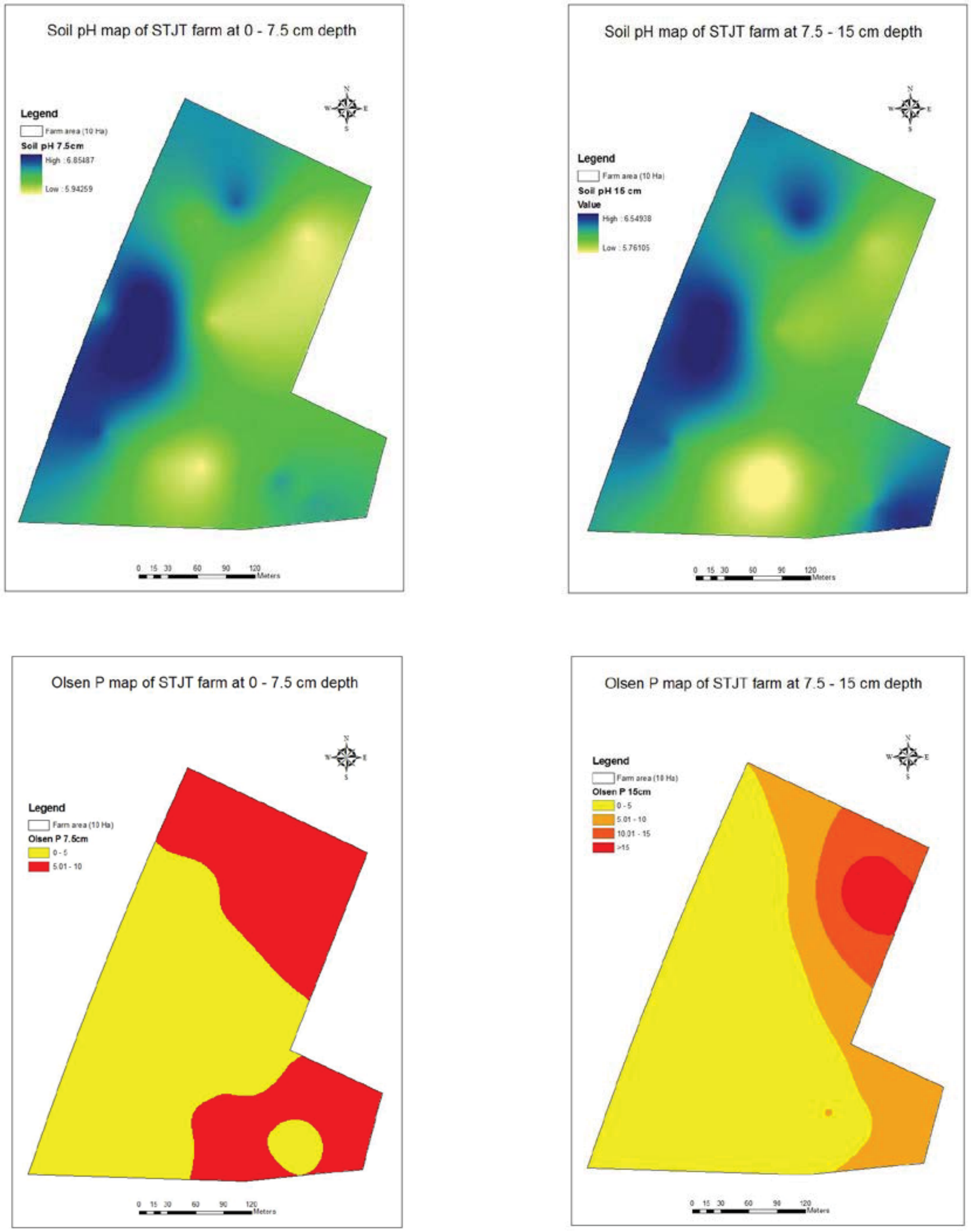


Figure 16 Maps indicating areas of differing soil pH and Olsen P values produced by Kriging the observed Soil pH and Olsen P values at 0-7.5 and 7.5-15 cm soil sampling depths from the STJT farm.

The spatial distribution of soil pH is consistent between the two soil depths (see Figure 16) sampled, a similar result is achieved for the Olsen extractable P (see Figure 16) but the spatial distribution of pH and Olsen P are unrelated. The highest pH is associated with number of big trees growing in and around particular areas. The decomposition of high amounts of SOM can increase soil acidity due to an increase in acidic groups resulting in an increase in charge (Troeh & Thompson, 1993). The highest Olsens are associated with the slightly water logged condition (poor drainage) of the soil, which are caused by surface runoff from other parts of the farm during flooding (Stevenson & Cole, 1999). The farm has flat landscape and it has no proper drainage to avoid or reduce flooding during wet seasons.

5.3.5 Summary table of main soil fertility status effects

The key points arising from the soil testing activity are illustrated in Table 16 below.

Only one farm (ASI) appears to have soil P status that would not limit pasture growth. Low soil pH values that may limit root growth are non-existent on all farms. Soil pH, however, is high (6.5-7) on all farms and may hinder essential metal uptake by pasture plants (i.e. Cu, Fe, Mn and Zn (Foth, 1990; Sillanpaa, 1982)). In general, the maps show that the patterns of soil pH on the top soil are confirmed by the patterns of soil pH on the subsoil. Only the NAC farm has adequate soil K status. Low Ca status is an issue on two farms ILA and STJT. Whilst ILA and ASI farms have low soil CEC, values these are not expected to influence pasture growth if fertiliser K application is managed at an appropriate frequency.

These trends in nutrient availability are explored further in Section 5.3.6 with comparisons with plant nutrient content analyses.

Table 16 Main soil fertility status of each farm

	Soil test values					
Farm	Olsen P	Soil pH	Exch. K	Exch. Ca	Exch. Mg	CEC
	μgPg^{-1}		$me100g^{-1}$	$me100g^{-1}$	$me100g^{-1}$	Cmoles kg^{-1} soil
ILA	Deficient	Exceed opt.	Deficient	Deficient	Optimum	5 – 10
ASI	Optimum	Exceed opt.	Responsive	Optimum	Exceed Opt.	5 – 10
NAC	Deficient	Exceed opt.	Optimum	Responsive	Exceed Opt.	10 – 15
STJT	Deficient	Exceed opt.	Deficient	Deficient	Optimum	15 – 30

5.3.6 Pasture analysis

Herbage P (%) values for both legumes and grasses of the four farms (see Figure 17) are above the critical P concentration of 0.16% for legumes (Shelton, et al., 1986). The herbage generally contained high P concentrations whereas Olsen P values were low to extremely low (see Table 16). The legumes contained a higher percentage of P (Figure 17) than grasses but no significant correlation existed between increasing Olsen P values and herbage % P.

Herbage K (%) values for both legumes and grasses are above the critical K concentration of 0.75% for legumes (Humphreys, et al., 1990; Shelton et al., 1986). Although the exchangeable K ($mg100g^{-1}$) is low, increasing soil values per farm resulted in a non-significant (no correlation) increase in herbage K (%) for grasses and legume K%.

Herbage Ca (%) are above the critical Ca concentration of 0.8% for legumes (Gutteridge & Whiteman, 1978b), whereas for grasses they are below critical values. The herbage Ca (%) for grasses decreases and legumes increases as the exchangeable Ca values increase. The high supply of Ca is associated with the low acidity of the soil (Osborne et al., 1980). Tropical legumes generally tolerate low Ca better than temperate legumes (Osborne et al., 1980). There was no relationship between the herbage Ca (%) and the exchangeable Ca ($me100g^{-1}$).

Herbage Mg (%) in legumes across all farms is above the critical Mg concentration of 2.8% (Andrew & Robins, 1969; Pearson & Ison, 1997), whereas some grasses are below critical values. Generally, the linear relationship between the herbage Mg (%) and exchangeable Mg is significant. Comparatively, although legumes have higher Mg (%), the Mg (%) increases faster as the exchangeable Mg increases.

In terms of relationship between Mn and soil pH, the herbage Mn (mg kg^{-1}) for legumes and grasses is mostly below the critical value of 151 (mg Mn kg^{-1}) for legumes (Far'ia-M'armol, Morillo, & Chirinos, 2005), excluding one farm with legumes that have Mn ($mgkg^{-1}$) above this level. Legumes have low concentrations of Mn compared to grasses. The amount of herbage Mn (mg kg^{-1}) is lower than expected probably because of the low soil acidity (high pH) condition (Osborne et al., 1980). As soil pH is relatively high, high levels of available Mn could be due to the waterlogged conditions, which increase its solubility (McLaren & Cameron, 1996). This may cause toxicity symptoms in legumes (Putnam & Duke, 1978). As the soil pH increases, the rate of herbage Mn (mg kg^{-1}) for legumes increases rapidly than grasses.

The linear relationship between the herbage Mo (mg kg^{-1}) and soil pH shows no significance in both legumes and grasses although they are mostly above the critical concentration of 0.2 ($mgkg^{-1}$) for legumes (Underwood, 1966). Generally, in each farm, legumes have higher Mo (mgkg^{-1}) than grasses. However, with increasing soil pH, the grass concentrations Mo (mgkg^{-1}) increase rapidly than legumes. Mo availability increases as alkalinity increases. Deficiency in Mo is a relatively common micronutrient problem in tropical legumes (Osborne et al., 1980; Sustainable nutrient management in New Zealand agriculture, 2010) but it does not appear to be an issue at this site.

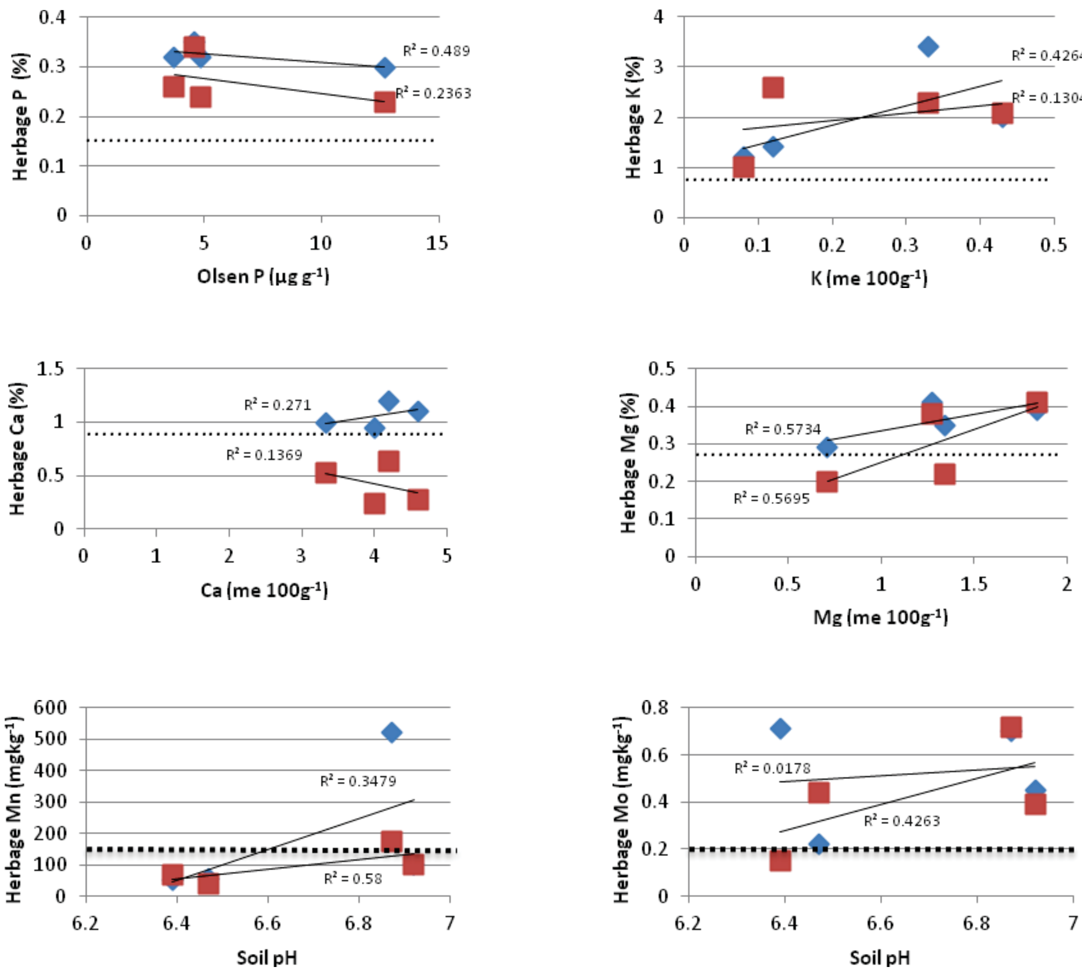


Figure 17 Graphs of relationship between herbage nutrient concentrations and soil test values for legumes (◊) and grasses (□) at different (ILA, ASI, NAC & STJT) farm (points are means of 4-5 samples).

5.3.7 Summary of plant analysis

The plant analysis and the soil tests indicate some conflicting evidence. The herbage analysis indicates that the P concentration in both legumes and grasses and the herbage K concentration are above the optimum level, despite soil test values showing deficiencies.

Because of this conflicting evidence, a glasshouse trial was designed to evaluate legume growth response to P, S, and K in soils taken from the selected farms.

5.4 Conclusions

The field survey showed that there was insufficient information obtained from the survey to construct a nutrient budget for each farm. This was a result of lack of training provided for farmers to develop the necessary knowledge, and to recognise the value of record keeping in running successful operations. The nutrient inputs and losses are very low and apparent levels of product removal indicate that nutrient losses through grazing are insignificant. Losses through other processes such as leaching and immobilisation were suggested as significant. The pasture grass/legume species identified growing at the farms are T-grass (*Paspalum conjugatum*), Carpet grass (*Axonopus affinis*), Paragrass (*Brachiaria mutica*), White clover (*Trifolium repens*), Puero (*Pueraria phaseloides*), Centro (*Centrosema pubescens*) and Mimosa (*Mimosa pudica*). Centro is common in three of the farms (ILA, NAC and STJT) studied.

Factors such as human activity, other livestock and effluent could alter (increase) the amount of P at the soil depth of 7.5-15cm at some sites of a farm compared to P amount in 0-7.5cm soil depth. The soil tests showed that most of the areas of the four farms are soil P deficient (Humphreys et al., 1990; Shelton et al., 1986). However, the herbage analysis of field pasture samples could not provide further evidence of P deficiency, which conflicted with the low soil test P values. Therefore, a glasshouse trial was designed to evaluate legume growth response to P, S, and K treatments in soils taken from the studied farms. The outcome of the glasshouse trial is described in Chapter 6.

CHAPTER 6 GLASSHOUSE TRIAL

6.0 Introduction

The Glasshouse methodology is described in section 4.7 of Chapter 4. The growth response (dry weight) of white clover to different rates of P and S and limited rates of KCl and K_2SO_4 fertilizers to different pasture soils (ASI, ILA, NAC and STJT) are shown (see Figure 18). Below are descriptions of the glasshouse trial results for each farm and a graph (see Figure 19) comparing P and S treatments between the farms.

6.1 Chapter Overview

This Chapter consists of six sections. Section 6.2 describes white clover dry matter yield, which looks at main soil fertility status effects. Section 6.3 outlines dry matter yields of white clover grown in each farm. Relationship between soil and Olsen P and added P at S1has been described in Section 6.4. Section 6.5 outlines relationship between soil Olsen P and and white clover dry yield. Section 6.6 describes summary of glasshouse pot trial. Conclusions to the Chapter has been described in Section 6.7.

6.2 White clover dry matter yield

6.2.1 Main soil fertility status effects

A general linear model (yield is a function of farm, rates of P, rates of S) was used to explain the variance in dry matter yield observed in the glasshouse trial, across 4 farm soils differentially fertilized at 3 rates of P and S fertilizer. Seventy four % of the variation in yield is explained (see Table 17) by different soils from different farms, which is highly significant. Twenty one % of the variation is explained by the response to additional P and only a small but significant 0.4% is explained by S.

The response of white clover to P on each pasture soil is shown (see Figure 18 and Table 18). The % response (slope of line) of white clover to P is higher on ILA soils compared to response to P on NAC soils followed by STJT soils and ASI soils.

Table 17 Analysis of variance of white clover dry matter yield (For detailed description of treatments (Source of error), see Figure 18)

Analysis of Variance for Dry, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Farm	3	8.6579	8.6579	2.8860	554.14	0.000
P	2	2.5102	2.5102	1.2551	240.99	0.000
S	2	0.0501	0.0501	0.0251	4.81	0.010
Error	100	0.5208	0.5208	0.0052		
Total	107	11.7390				

S = 0.0721665 R-Sq = 95.56% R-Sq(adj) = 95.25%

Based on Table 17 all farms responded to P. There was double the response on NAC, STJT and ILA soils compared to ASI soils given by the slopes (Figure 18 and Table 18)

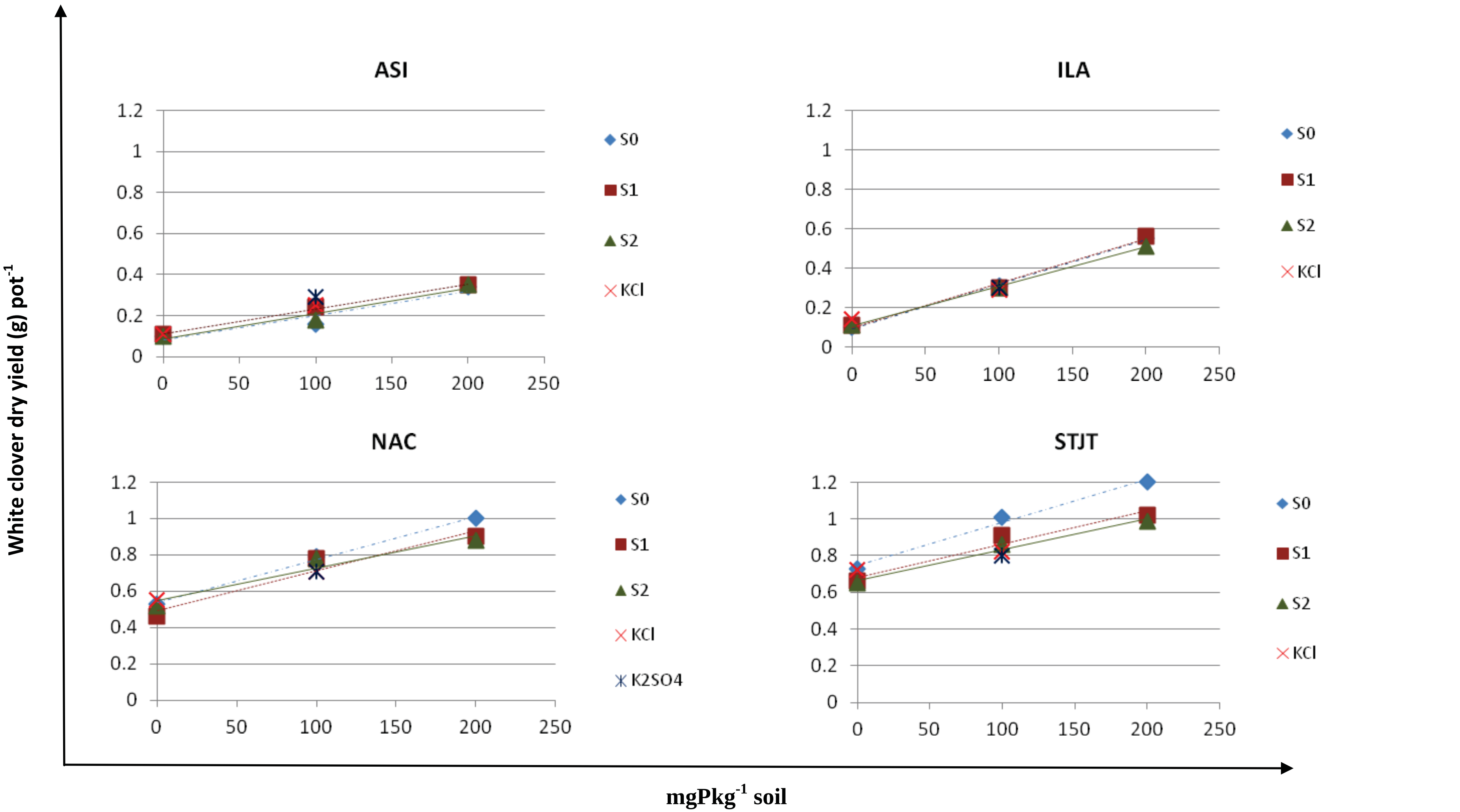


Figure 18 Dry matter yield (g pot^{-1}) of white clover (*Trifolium repens*) grown on pots of soils from four farms (ASI, ILA, NAC & STJT) fertilised with 3 different levels of monoclacium phosphate (P) and elemental sulphur (S) plus potassium applied in two different forms (KCl at the level of $_{P0,100}$, $S_{0,1}$ level and K_2SO_4 at the level of P_{100}, S_1 level).

Table 18 Linear regression model of Phosphorus growth response (shown in Figure 18)

Farm		Intercept	Slope	R^2
ASI	S_0	0.08	0.0012	0.9231
	S_1	0.1133	0.0012	0.9977
	S_2	0.085	0.0013	0.9586
ILA	S_0	0.095	0.0023	0.9985
	S_1	0.0983	0.0023	0.992
	S_2	0.1067	0.002	0.9992
NAC	S_0	0.5383	0.0024	0.9962
	S_1	0.4933	0.0022	0.9356
	S_2	0.5467	0.0018	0.9382
STJT	S_0	0.745	0.0024	0.9879
	S_1	0.6833	0.0018	0.952
	S_2	0.6633	0.0017	0.9819

An observation on nodulation of roots of white clover after harvest was to assess the effect of fertilizer treatments on the four pasture soils. There was no formation of nodules in all treated soils during the trial. This indicated that the white clover was dependent upon N mineralized from the organic matter of the pasture soils (Troeh & Thompson, 1993). Thus, the effect of the dominant soil on yield may result from the ability of the soils to supply N. However, as discussed later in section 6.5, the initial and final Olsen P status of the soils also explains 58% of the variation in clover yield.

Addition of S made no significant difference to slope. Difference in P response (Δ dry weight/Δ $mgPkg^{-1}$ soil) for soils is shown in Figure 18.

6.3 Dry matter yields of white clover grown in each pasture soil

Figure 19 illustrates the main effects of different P rates under different rates of S treatments on white clover yield (dry weight) on four different pasture soils (ASI, ILA, NAC and STJT). As mentioned earlier the soil type has a major influence on the growth of clover on unfertilized soil. Generally, the P response by white clover under different rates of S treatment is higher on STJT soils, than NAC followed by ILA and ASI pasture soils. The yields increase as the rate of P applied increases. The addition of S, however, appears to have no consistent positive effects on clover yield either in soils with or without P fertilizers. The P response to zero P application under different rates of S applied is the same on ILA and ASI soils while P response to zero P application under different rates of S is still higher on STJT soil than on NAC soil and the two farms (ILA and ASI). In summary, there is a clear response to applied P on all soils but soil S status does not appear to be presenting a major limitation to clover growth, nor can a S deficiency be induced by removing the P limitation to growth. Due to limited time available, analysis on herbage for other effects has not been done. Thus, the study only looked into details on effects of soil P status.

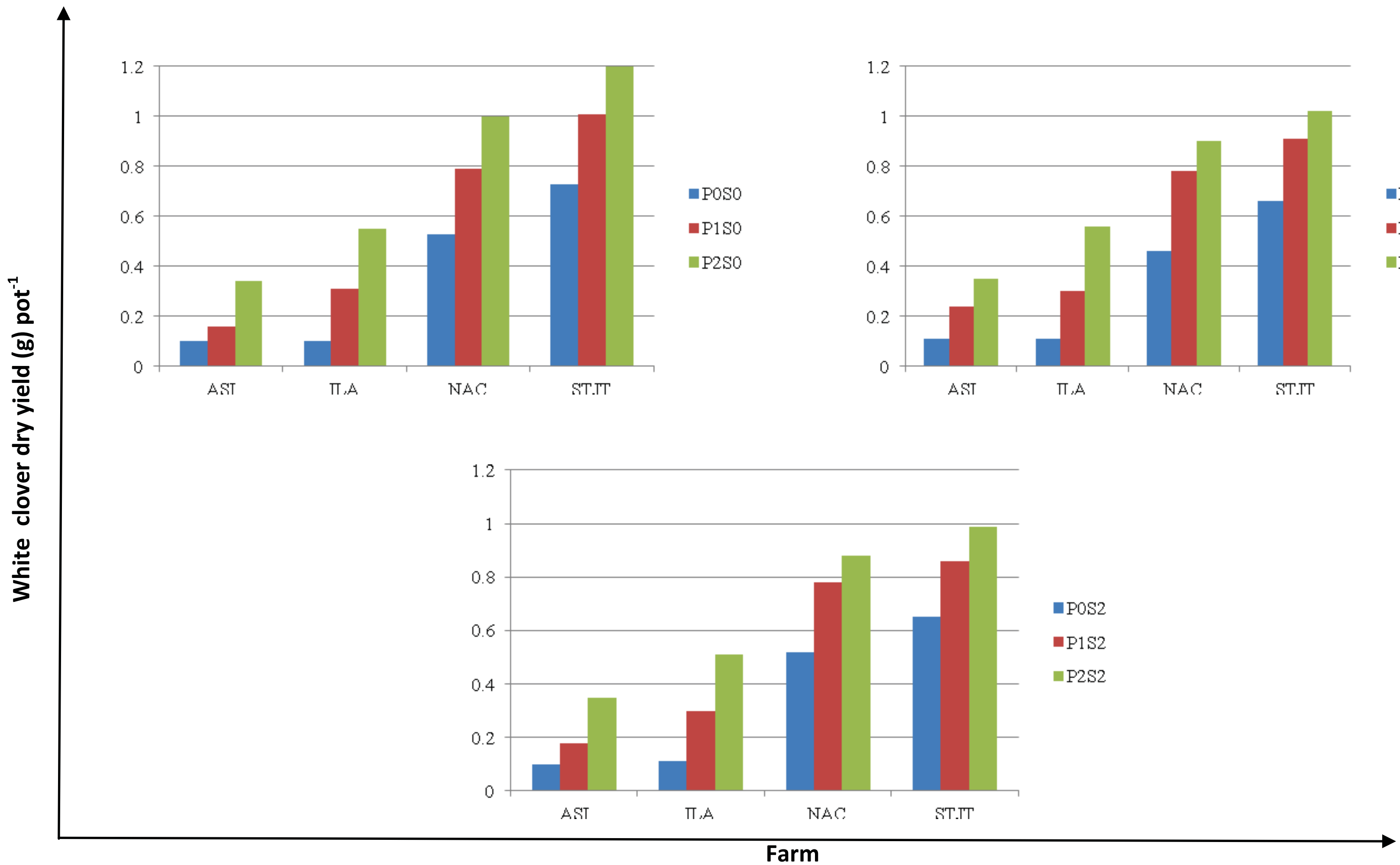


Figure 19 The yield of white clover grown on pots of soil from four farms (ASI, ILA, NAC, STJT) fertilized with 3 rates of P and S and two forms of K fertilizers (see Table 10, Figure 18 and Appendix III for details of rates of fertilizer).

6.4 Relationship between soil Olsen P and added P at S_1

Irrespective of the rates applied, P application significantly increased soil Olsen P values and the dry yield of white clover (Figures 18 and 20). Figure 20 illustrates the relationship between Olsen P ($mgPkg^{-1}$ soil) and different P rates at S_1 (22 mg S kg^{-1} soil) in each farm, and/or the amount of P required changing the soil test values. Generally, the relationship between Olsen P and the P rates at S_1 in STJT is higher than in NAC followed by ILA and ASI farms. According to the slopes, to raise P per unit; STJT requires 6, NAC soils requires 10, ILA requires 4 and ASI requires 3$mgPkg^{-1}$ soil. The higher slope values are associated with soils having slightly lower anion adsorption capacities (Appendix V).

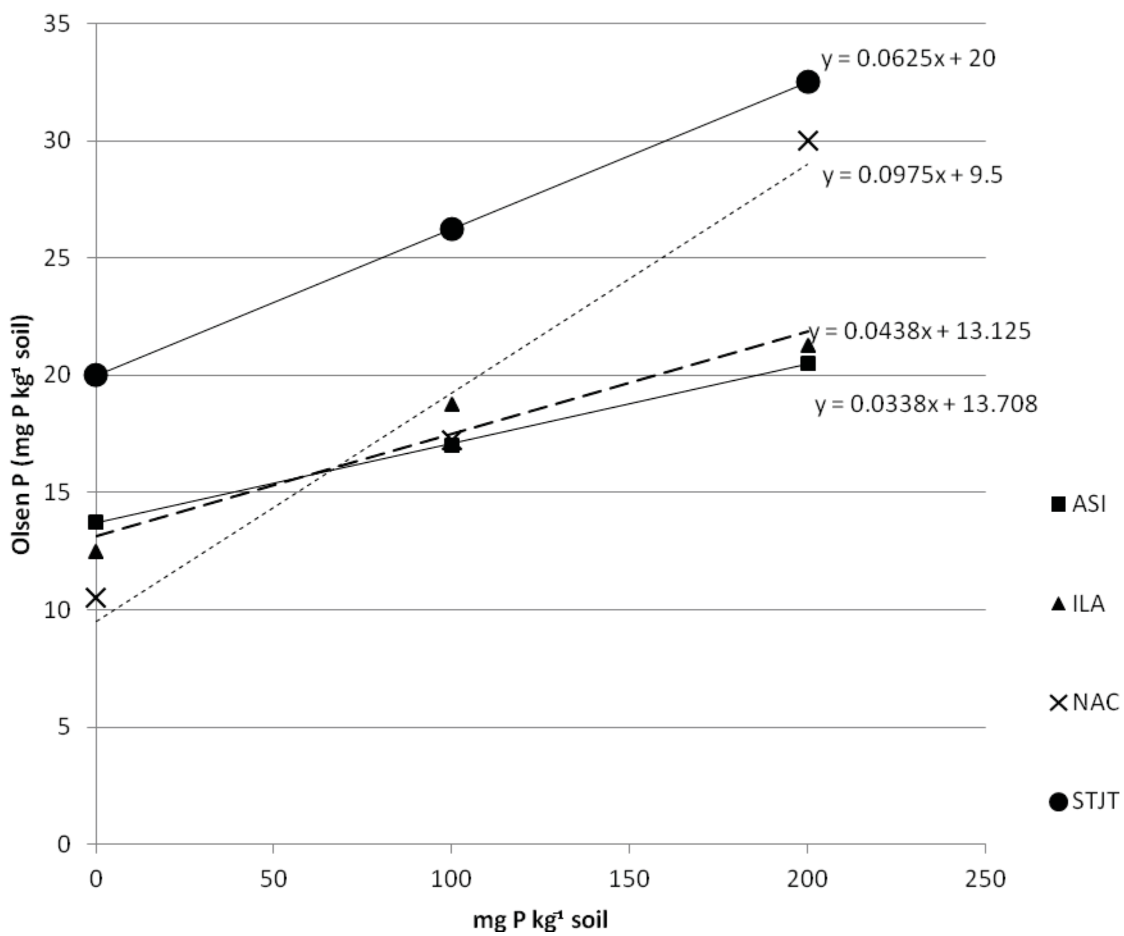


Figure 20 Effect on extractable Olsen P values of fertilising soils from 4 different farms with 3 levels of monocalcium phosphate at one level of elemental S° addition (S_1 22$mgSkg^{-1}$ soil).

6.5 Relationship between soil Olsen P and white clover dry yield

To explore the potential of using Olsen P values as an indicator of the P limitation on pasture plant yield, clover yields in the pot experiment were plotted against soil Olsen P values (Figure 21). The alignment of data along a trend line (Figure 21) is showing a significant increase in yield with increasing Olsen P in each farm. In general, from low to high values, the yield increase is consistent with increasing Olsen P values and bears a resemblance to the responsive part of the yield curve for New Zealand pasture soils described by Saggar et al. (1992). The soil Olsen P status explains 58% (R^2 0.58) of the variation observed in clover yield. The robustness of this relationship is similar to that observed by Saggar et al. (1992).

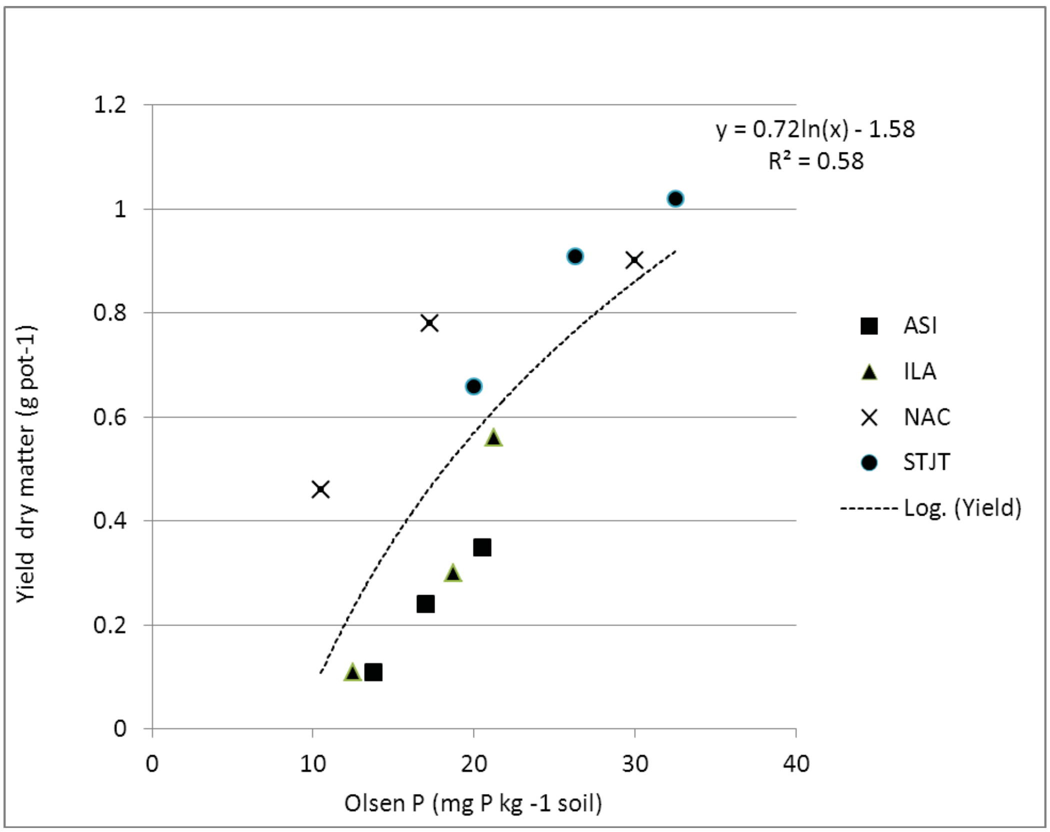


Figure 21 Effects of Olsen P on DM yield of white clover growing in pots of soils from 4 different farms (ASI, ILA, NAC & STJT).

6.6 Summary of glasshouse pot trial

The glasshouse trial definitely shows the growth limiting effect of soil P however, it is found that K and S are not significant limiting factors. Comparatively, STJT has the highest range of white clover growth response to P treatments than the plant responses in NAC, followed by ILA and ASI. Growth on all soils responded faster to P application and the responsive

Olsen soil P test range is consistent with the results of Saggar et al. (1992). However, generally, the P amount added was insufficient to produce maximum plant response on all farm soils. Yield, however, may be limited by the lack of clover nodulation. Therefore, it is suggested that perhaps the main soil effect was caused by different availabilities of soil mineral N. In hindsight, for further studies, the initial mineral soil N should be measured using the pasture soils with 2 M KCl extraction (Kamphake et al., 1967) and/or mineralisable N by anaerobic incubation (Bremner, 1965).

6.7 Conclusions

The glasshouse experiment has resolved that plant (legume) growth was highly responsive to soil type, initial soil P status, and added P fertiliser. Plant growth in the glasshouse was also non-responsive to application of K, which was consistent with adequate K% in field herbage analysis.

The soil survey reported in Sections 5.3 of Chapter 5 did show that some areas of the ASI and ILA farms had elevated soil P status, in the optimum range for pasture growth. The main features of those sites are associated with animal campsites, buildings, trees, intensive farming of livestock (pigs and goats), rocky sites, surface runoff, high drainage and so forth. These high nutrient statuses of patches of soil within each farm could be managed to their advantage in relation to growing high quality forage in these areas.

This study demonstrates that these (farms) can increase yields through the use of P fertilizer on these P responsive soils. However, the current level of management and low productivity, would suggest that farmers are unlikely to be able to pay off the cost of P fertilizers given their low level of incomes. Also, the use of nutrient budgeting as a tool to assist sustainable nutrient management could not be explored in this study because the farm owners do not have farm records and in many cases grazing management boundaries are not clear. It would require a significant period of observations to capture such data.

Other than just purchasing P fertilizer, there are techniques that are more suited to the management level and which could help improve the P content (soil fertility) and the pasture productivity of each farm. For ASI and ILA farms, growing of improved (suitable) pasture species on higher nutrient status patches of soil can improve the feed quality rather than relying on P fertilizer. Besides, proper drainage and removal of weeds is highly recommendable for ASI. For NAC and STJT farms, there are no issues with the pasture species grown, except for their low P status. Generally, for all farms, inputs of P through animal manure, fish processing wastes, and tree wastes (brought in from off farm) are definitely manageable where they can be collected, composted and then applied thinly and uniformly. Also, soil fertility can be improved by the application of strip grazing on the low fertility sites where animals are fed using the cut-and-carry method. Most importantly, training on the techniques mentioned and different aspects of farm recording should be organised for farmers, which may help to monitor soil fertility and pasture performance of their farms in the future.

CHAPTER 7 Conclusions and Implications for Future Work

7.0 Introduction

This thesis reviewed the development of primary industries in the Solomons, with emphasis on the cattle industry based on grazed pastures. Research was undertaken to investigate soil fertility status and constraints preventing the development of pastures and/or farming of beef cattle on four pasture soils on Malaita and Guadalcanal Islands in Solomon Islands. Below are summaries of the studies carried out in relation to the objectives stated in Chapter 1.

7.1 Solomon Islands and its Agricultural Developments

In Chapter (2), the review concluded that the agricultural sector in the Solomon Islands comprises mostly plantation and food crop industries with small holders comprising most of the livestock production.

About 4% of the total land area is considered suitable for agriculture; however, most suitable land remains uncharacterised and unrecorded.

Most soils have volcanic parent materials while a few have formed from coral. Cultivation with machinery and the use of inorganic fertilizers are not common nationwide; conversely, there are traditional methods that are used to maintain and/or improve the fertility of the soil. Crops and pastures mostly derive nutrients from decomposed organic matter and weathering soil minerals but increasingly require nutrients from imported fertilizer as other sources.

A survey of land suitable for agricultural uses and pastures should be conducted nationwide to formulate a database to help with the development of a strategic plan, which provides an audit of lands in the Solomon Islands, protect land highly suited to agriculture, and identify land more suited to non-agricultural activities.

Generally, most farmers cannot afford machinery use and imported fertilizers. Thus, hiring of labour on a casual basis for cultivation, maintaining, and improving the current traditional methods for fertilizing the soil using domestic animal and fish processing wastes may be more affordable and sustainable.

7.2 Field survey

In Section 5.2 of Chapter 5, the study concluded that unfortunately there was insufficient information provided by farmers to construct a nutrient budget for each farm. It would require more time and lengthy observations to collect the necessary information from each farm. The information required but which were not recorded are inputs of supplementary feed in terms of quantities, product removal, and boundaries to blocks in effective growing areas. Only information on climate, soil, and current stocking rate were received and in general, nutrient inputs and losses are very low. Apparent levels of product removal indicate that nutrient losses through livestock sales are insignificant. Losses through other processes such as nutrient transfer by stock, leaching, and immobilisation could be significant.

In general, priority should be targeted at improving the management of the farms. This could begin with the provision of training for farmers on farm record keeping to documenting technical and financial management information thus providing them with a foundation for good decision making on how to manage their farms.

7.3 Soil fertility status

In Chapters (4 and 5), soils and herbage samples were collected from their respective study areas (ASI, ILA, NAC and STJT farms) and chemically analyzed in New Zealand. The pasture grass/legume species identified are T-grass (*Paspalum conjugatum*), Carpet grass (*Axonopus affinis*), Paragrass (*Brachiaria mutica*), White clover (*Trifolium repens*), Puero (*Pueraria phaseloides*), Centro (*Centrosema pubescens*) and Mimosa (*Mimosa pudica*). The most commonly grown legume species on three of these farms is Centro.

The soil tests showed that all soils had high pH (6.5-7). Low soil P status was more prevalent across the four farms than low K status, whereas the herbage analysis of field pasture samples did not show an inadequacy in P. A glasshouse trial was proposed to resolve this difference.

To some extent, the glasshouse trial resolved the conflict by confirming legume growth was highly responsive to soil type, and the addition of P fertiliser to low P status soils. Legume growth was also non-responsive to application of K, which was consistent with field herbage analysis. A limitation of the glasshouse trial was the inability of the test species to nodulate during the experiment. In hindsight, a rhizobia inoculum should have been provided at planting.

The current study showed that some areas of the ASI and ILA farms do have elevated soil P status, in the optimum range for pasture growth. The main features of those sites are associated with animal campsites, buildings, trees, intensive small livestock farming, rocky sites, surface runoff, high drainage and so forth.

Hence, this study concluded that although it demonstrates these farms could increase yields using P fertilizer on these P responsive soils, analysis of the effect of P addition to the soils used in the glasshouse study showed that soil from the ASI farm required 3 mg P kg^{-1} soil to raise the Olsen P test one unit. In other farms, ILA required 4, NAC required 10, and STJT required 6 mgPkg^{-1} soil to raise P per unit. Paying off the cost of P fertilizers in the absence of substantial income would be unlikely under the current management level and low productivity. Also, the use of nutrient budgeting to guide manure and fertilizer use could not explored in this study because of a lack of farm records.

Alternative farm management strategies

The outcomes of this study have led to a number of recommended alternative strategies to help improve the P content (soil fertility) and the pasture productivity of each farm. For ASI and ILA farms, growing of improved pasture species on higher nutrient status patches of soil can improve the feed quality rather than relying on P fertilizer. Besides, proper drainage and removal of weeds are highly recommendable for ASI. For NAC and STJT farms, there are no issues with the pasture species grown, except for their low P status.

Generally, for all farms, inputs of P through animal manure, fish processing wastes and tree wastes (brought in from off farm) is definitely manageable where they can be collected, composted and then applied thinly and uniformly when the plants are small and ready if quick growth is to be attained. Also, soil fertility can be improved by the application of strip grazing on the low fertility sites where animals are fed using cut-and-carry method. The higher nutrient status patches of soil within each farm could be managed to their advantage in relation to growing high quality forage in these areas. Most importantly, the Ministry of Agriculture and Livestock should as a matter of priority consider offering training on the above strategies and on farm record-keeping practices through its field officers. This may help farmers to maintain and improve soil fertility and pasture performance in the future.

7.4 Future Work

This study highlights several areas where further research could be considered in the future.

The use of coated local (NZ) white clover seeds in the current study could be a factor for the lack of formation of nitrogen fixing nodules on the glasshouse grown plants. Further work could investigate either inoculating the soils brought from Solomon Islands with rhizobia from NZ soils or using white clover seeds from Solomon Islands in future studies. Alternatively, studies could be conducted in the Solomon Islands using subtropical legumes such as Centro, Puero, and white clover.

Further research/extension is required in the Solomon Islands to develop sustainable soil fertility management strategies. The knowledge of how much P is required to raise the soil P test values to optimum value, and the combined tools of soil testing will give means for P fertilizer (or manure, compost and application rates) requirements and suggestions for farmers. One of the issues, nevertheless, is that the beef cattle farmers in Solomon Islands have no knowledge on the available P status (Olsen-P value) of their pasture soils. Hence, limited soil P testing (including N, K, S and so forth) could be implemented in the country. The other concern is, in the absence of soil testing and imported fertilizers, farmers need simple and clear advice on the optimum rate of manure application. Thus, trainings on farm record keeping must be carried out for farmers thus enabling them prepare nutrient budgets and provide necessary information for effective (productive) soil fertility management, which will help future studies.

The Ministry of Agriculture and Livestock Development must further develop and promote alternative strategies on the use of local organic fertilizers by conducting field trials. The outcomes should encourage farmers to manage the productivity of their pasture soils at lower costs.

A field trial in relation to the current study (glasshouse) should be carried out in the future to develop more constructive and practical strategies for improving the fertility of pasture soils. Furthermore, a study on the behaviour of the identified pasture species in future similar trials would be helpful.

Any consideration to undertake the recommended strategies in this study depends on the Solomon Islands Government's policies and priorities towards the beef cattle and small livestock industry in the future.

Finally, knowledge on the role of soil in providing essential elements for plant growth and how to maintain a sustainable supply of those nutrients in the agricultural soils of the Solomon Islands should be included in a general education/extension package to rural small holders and their families.

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Appendices

Appendix I Summary of soil tests results for all beef cattle farms

Table a

Soil test method		Sampling sites (ILAs1-9) depth	
		7.5 cm	15 cm
Soil pH	Max	7.8	7.6
	Mode	6.8	6.5
	Mean	6.7	6.6
Olsen P	Max	29	44
	Mode	5	7
	Mean	10	14
Ca	Max	22	11
	Mode	5	4
	Mean	8	5
Mg	Max	4.6	1.1
	Mode	1	0.5
	Mean	1.8	3.0
K	Max	0.9	0.2
	Mode	0.2	0.1
	Mean	0.2	0.5
CEC	Max	33	19.6
	Mode	10	15
	Mean	14	11.5
P retention		49.5%	

Table b

Soil test method		Sampling sites (ASIs1-10) depth	
		7.5 cm	15 cm
Soil pH	Max	8	8
	Mode	7	7
	Mean	7	7
Olsen P	Max	25	25
	Mode	25	25
	Mean	17	18
Ca	Max	8.9	9.3
	Mode	5	5
	Mean	3.9	4.7
Mg	Max	3	2.3
	Mode	0.8	1.5
	Mean	1	1.1
K	Max	0.1	0.2
	Mode	0.1	0.1
	Mean	0.1	0.1
CEC	Max	11	12
	Mode	10	10
	Mean	9	10
P retention		51.5%	

Table c

Soil test method		Sampling sites (NACpd1s1-10, pd3s1-2, pd2s3-10) depth	
		7.5 cm	15cm
Soil pH	Max	6.8	6.7
	Mode	6.6	6.3
	Mean	6.5	6.3
Olsen P	Max	9	64
	Mode	5	5
	Mean	4	9
Ca	Max	5.5	5.1
	Mode	5	4.9
	Mean	4.2	4.2
Mg	Max	2	1.9
	Mode	1.5	1.5
	Mean	1.3	1.4
K	Max	2.2	2.6
	Mode	0.5	0.4
	Mean	0.5	0.5
CEC	Max	15	21
	Mode	12	15
	Mean	11	13
P retention		30%	

Table d

Soil test method		Sampling sites (STJTpd3 – pd1/2) depth	
		7.5 cm	15 cm
Soil pH	Max	6.9	6.6
	Mode	6.3	6.3
	Mean	6.3	6.2
Olsen P	Max	8	18
	Mode	4	6
	Mean	5	6
Ca	Max	6	6
	Mode	5	5
	Mean	4	4
Mg	Max	1.1	1.1
	Mode	1	1
	Mean	0.8	0.8
K	Max	0.8	1.7
	Mode	0.3	0.3
	Mean	0.3	0.5
CEC	Max	32	29
	Mode	16	18
	Mean	21	21
P retention		36.5%	

Appendix II Soil tests comparing standard soil values between lab/expected values & Simon's results

Soil test	Std. soil name	Standard soil		Std. dev.	Mode
		Lab expected value	Simon's results (mean)		
Olsen P	QC June 2009 A	8 µgP g^{-1}	13	1.8	12 meCEC $100g^{-1}$
	QC Sept. 2010 A	40 µgP g^{-1}	40.8	4.55	37.5 meCEC $100g^{-1}$
Soil pH	Ramiha	4.4	4.4	0.01	4.4
	Egmont Gold	5.6	5.61	0.04	5.6
Ex. Bases (K, Mg & Ca)	QC Apr. 2010 A	0.4 meK $100g^{-1}$	0.3 meK $100g^{-1}$	0.03	0.2 meCEC $100g^{-1}$
		8.2 meCa $100g^{-1}$	8.2 meCa $100g^{-1}$	4.05	8.2 meCEC $100g^{-1}$
		1.2 meMg $100g^{-1}$	1.1 meMg $100g^{-1}$	0.06	1.1 meCEC $100g^{-1}$
	QC Apr. 2010 B	0.5 meK $100g^{-1}$	0.4 meK $100g^{-1}$	0.04	0.4 meCEC $100g^{-1}$
		12.3 meCa $100g^{-1}$	12.9 meCa $100g^{-1}$	3.72	14.3 meCEC $100g^{-1}$
		1.3 meMg $100g^{-1}$	1.4 meMg $100g^{-1}$	0.04	1.4 meCEC $100g^{-1}$
CEC	QC Apr. 2010 A	17 meCEC $100g^{-1}$	16.5 meCEC $100g^{-1}$	2.94	20.7 meCEC $100g^{-1}$
	QC Apr. 2010 B	28 meCEC $100g^{-1}$	29 meCEC $100g^{-1}$	4.39	32.6 meCEC $100g^{-1}$

Appendix III Fertilizer treatments

Fertilizer: Monocalcium phosphate (MCP)

Phosphate fertilizer treatment	Weight of MCP pot^{-1} (mg)	Approx. Weight of P pot^{-1} (mg)
P0	0	0
P1	23	5
P2	46	10

Fertilizer: Elemental Sulphur (S)

Sulphur fertilizer treatment	Weight of elemental S pot^{-1} (mg)	Approx. Weight of S pot^{-1} (mg)
S0 (S^0)	0	0
S1 (S^0)	6□	5
S2 (S^0)	11	10

Fertilizer: Potassium chloride (KCl) and potassium sulphate (K_2SO_4)

S and sulphate and Phosphate fertilizer treatment	W.t. of KCl pot^{-1} □(mg)	Weight of K_2SO_4 pot^{-1} (m□)	Approx. Weight of K pot^{-1} □□mg)	Approx. Weight of S pot^{-1} (m□)
S^0P1K_1 (S^0 KCl)	48	-	25	-
SP1 K_1 (K_2SO_4)	-	56	25	10.2

Appendix IV Herbage height, dry/fresh weight for each farm

a. Herbage dry weight for each farm

ASI herbage dry□ weight□(g)			
	Replicates		
Treatment□	1	2	3
P0S0	0.11	□.11	□.08
P0S1	□.13	0.09	0□1
P0S2	0.11	□□1	0.1
P1S□	0.□7	□.□5	□.16
P1S1	0□23	0.22	0.26
P1S2	0.2	0.18	0.16
P2S0	0.33	0.33	0.36
P2S1	0.32	0.35	0.37
P2S2	0.33	0.36	0.36
P0S0 KCl	0.09	0.11	0.12
P1S1 KCl	0.26	0.27	0.21
P1S1 K2SO4	0.29	0.31	0.27

ILA herbage dry weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	0.08	0.11	0.1
P0S1	0.11	0.11	0.12
P0S2	0.13	0.09	0.11
P1S0	0.25	0.32	0.37
P1S1	0.31	0.27	0.31
P1S2	0.27	0.28	0.27
P2S0	0.56	0.45	0.65
P2S1	0.59	0.52	0.57
P2S2	0.56	0.48	0.48
P0S0 KCl	0.13	0.1	0.2
P1S1 KCl	0.26	0.34	0.26
P1S1 K2SO4	0.26	0.33	0.3

NAC herbage dry weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	0.5	0.51	0.59
P0S1	0.48	0.42	0.48
P0S2	0.61	0.45	0.49
P1S0	0.84	0.81	0.72
P1S1	0.82	0.78	0.74
P1S2	0.82	0.77	0.76
P2S0	0.84	1.1	1.07
P2S1	0.85	0.98	0.88
P2S2	0.92	0.83	0.9
P0S0 KCl	0.73	0.52	0.41
P1S1 KCl	0.83	0.52	0.78
P1S1 K2SO4	0.66	0.67	0.8

STJT herbage dry weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	0.7	0.73	0.75
P0S1	0.69	0.62	0.66
P0S2	0.56	0.69	0.71
P1S0	0.97	1.07	0.99
P1S1	0.96	0.92	0.85
P1S2	0.96	0.91	0.7
P2S0	1.15	1.25	1.19
P2S1	1.11	0.93	1.02
P2S2	1.11	0.93	0.93
P0S0 KCl	0.68	0.69	0.79
P1S1 KCl	0.83	0.81	0.82
P1S1 K2SO4	0.82	0.75	0.82

b. Herbage fresh weight for each farm

ASI herbage fresh weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	0.7	0.5	0.5
P0S1	0.6	0.6	0.5
P0S2	0.6	0.6	0.4
P1S0	1	1.1	1.3
P1S1	1.6	1.4	1.6
P1S2	1.3	1.2	1.5
P2S0	2.1	2	2.2
P2S1	2	2.3	2.3
P2S2	2.1	2.1	2.2
P0S0 KCl	0.7	0.7	0.7
P1S1 KCl	1.7	1.7	1.2
P1S1 K2SO4	1.8	2.1	1.6

ILA herbage fresh weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	0.25	0.47	0.33
P0S1	0.52	0.39	0.5
P0S2	0.5	0.26	0.4
P1S0	1.1	1.6	1.77
P1S1	1.38	1.4	1.3
P1S2	1.21	1.37	1.25
P2S0	2.24	1.97	2.77
P2S1	2.62	2.23	2.69
P2S2	2.16	1.85	1.73
P0S0 KCl	0.53	0.4	0.69
P1S1 KCl	1.18	1.52	0.98
P1S1 K2SO4	1.17	1.57	1.37

NAC herbage fresh weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	3.9	4.2	4.9
P0S1	4.2	3.2	3.8
P0S2	5.1	3.9	4.3
P1S0	5.2	5	4.5
P1S1	5.2	4.9	4.8
P1S2	5	4.8	4.5
P2S0	4.9	5.8	6
P2S1	4.9	5.5	4.9
P2S2	5	4.7	5.1
P0S0 KCl	5.2	4.5	3.4
P1S1 KCl	5.1	3.8	4.9
P1S1 K2SO4	4.3	4.4	4.8

STJT herbage fresh weight (g)			
	Replicates		
Treatment	1	2	3
P0S0	4.6	5.1	4.8
P0S1	4.7	4.5	4.8
P0S2	4.2	4.7	4.8
P1S0	5.6	6	5.4
P1S1	5.5	5.1	4.8
P1S2	5.5	5.3	4.6
P2S0	5.8	6.1	6
P2S1	5.6	4.9	5.3
P2S2	6.1	5	5.2
P0S0 KCl	4.5	4.5	5
P1S1 KCl	5.2	4.8	4.9
P1S1 K2SO4	4.6	4.5	4.9

c. Heights of white clover in each farm

Sward Heights at harvest (cm)			
	Replicates		
Treatment	1	2	3
P0S0	6	5	5
P0S1	5	4	4
P0S2	3	5	5
P1S0	7	6	6
P1S1	7	6	7
P1S2	6	6	6
P2S0	7	7	7
P2S1	7	6	6.5
P2S2	7	6.5	6.5
P0S0 KCl	5.5	4.5	3
P1S1 KCl	6	6	5
P1S1 K2SO4	6	5	7

Sward Heights at harvest (cm)			
	Replicates		
Treatment	1	2	3
P0S0	3	6	4
P0S1	4	3	4
P0S2	5	4	4
P1S0	7	7	8
P1S1	7	7	8
P1S2	6.5	8	6.5
P2S0	10	10	9
P2S1	9.5	9	9
P2S2	9	10	10.5
P0S0 KCl	5	5	7
P1S1 KCl	6.5	7.5	6.5
P1S1 K2SO4	6	7	6

Sward Heights at harvest (cm)			
	Replicates		
Treatment	1	2	3
P0S0	10	8	9.5
P0S1	10	10.5	8.5
P0S2	10	7.5	9
P1S0	10	9	8
P1S1	10	10	11.5
P1S2	9	9	10.5
P2S0	10	8	10.5
P2S1	9.5	10	10.5
P2S2	11	10	10
P0S0 KCl	9	10	10
P1S1 KCl	9	11	8
P1S1 K2SO4	11	8	8

Sward Heights at harvest (cm)			
	Replicates		
Treatment	1	2	3
P0S0	8.5	10	11
P0S1	11	8	10
P0S2	9	11	9
P1S0	10	11	10
P1S1	11	12	9
P1S2	9	11.5	11.5
P2S0	10	14	13.5
P2S1	10.5	10.5	10.5
P2S2	11	11	9
P0S0 KCl	10	9.5	10.5
P1S1 KCl	9	9	10
P1S1 K2SO4	7.5	9.5	13

Appendix V White clover yield, Olsen P and added P at S_1 treatments on each farm soil

Farm	% ASC	Treatment code	P rate at S_1 (mg kg^{-1})	Yield (kg^{-1} soil)	Olsen P (mg kg^{-1} soil)
ASI	52	P0S1	0	0.1	14
		P1S1	100	0.2	17
		P2S1	200	0.4	21
ILA	50	P0S1	0	0.1	13
		P1S1	100	0.3	19
		P2S1	200	0.6	21
NAC	30	P0S1	0	0.5	11
		P1S1	100	0.8	17
		P2S1	200	0.9	30
STJT	37	P0S1	0	0.7	20
		P1S1	100	0.9	26
		P2S1	200	1.0	33

Appendix VI Questionnaire

MASSEY UNIVERSITY

Institute of Natural Resources, New Zealand

A SURVEY OF SOME BEEF CATTLE FARMERS IN THE SOLOMON ISLANDS

(May – June 2011)

1. Background Information

Province		Ward	
Village		Constituency	
Grid ref. location			
Client name	Mr./Mrs./Ms.		
Property name			
Total Area (ha/acre)		Effective farm area (ha/acre)	
Distance from Coast (km)		Annual rainfall (mm)	
		Annual Temperature (°C)	
Elevation/height above sea level			

2. Block/Farm Information

Block	Open Pasture			Pasture + trees/coconuts			Crop		
Area (acre/ha)									
Topography									
Years in pasture									
Pasture species									
Pasture dev± status	Age			Age			Age		
	Quality	Excellent		Quality	Excellent		Quality	Excellent	
		Very good			Very good			Very good	
		Good			Good			Good	

	Poor	Poor	Poor
Grazing system	Cut carry	Set stock	Rotational
Soil type			
Soil group/order			
Drainage	Good	Good	Good
	Poor	Poor	Poor
Depth to stone or gravels			
Irrigation (mm)			
Topsoil (soil texture)			
Deep/shallow/stony			
Fertilizer	Category	Fertilizer name	Amount (kg/ha)
When and last time N applied (kg/ha)			
Irrigation applied (mm)			

3. Farm/Block Production

Stock	Type	Number	Month on	Age on	Month off	Age off
Cows						
Bulls						
Steers						
Heifers						
Calves						

4. Feed produced on or brought into farm

Feed produced on Block/Farm	Amount estimated/ha or acre	Month		Fed to animals
		Start	Finish	
Fresh pasture removed				
Crop cut removed				
Crop grazed in situ				

Feed brought into block/farm	Type	Amount (kg/ha or acre)	Month	
			Start	Finish

5. Other crop on plantation systems

Area in crop (on average over 5 years)	Ha/acre
Area in coconut plantation (on average over 5 years)	Ha/acre
Yield of crops (on average over 5 years)	Tons/Ha or acre
Crop residues fed to animals (on average over 5 years)	Tons/Ha or acre
Crop residues retained (on average over 5 years)	Tons/Ha or acre