# 1. INTRODUCTION

## 1.1 Background

Soil acidification is a serious, world wide, land-degradation problem. It is often referred to as "a sleeper" as it is an insidious process that can go unnoticed (NLWRA 2001a). Soil acidification is a natural process that can be accelerated by management practices (Lockwood *et al.* 2003; Helyar and Porter 1989). The rate at which soil pH decreases in response to soil acidification depends on the soil parent material; the influence of weathering; the soil pH buffering capacity that determines the resistance, or susceptibility, of a soil to a change in pH; climatic factors; and agricultural managment practices. In the context of this thesis an *acid soil* is one in which the soil $pH_{Ca}$ is below 6.5, and the term *soil acidification* refers to the process under which soils become more acidic.

In Australia, the true extent of soil acidification and distribution of acid soils is not fully known. Soil pH maps modelled from soil test data estimate 50 million hectares of surface soils and 23 million hectares of subsoils are affected by soil acidity (NLWRA 2001a). Agricultural and pasture-management practices can accelerate soil acidification. In New South Wales, Queensland, Victoria and Western Australia, about half the area under intensive agriculture is affected by the impacts of soil acidity at an estimated cost of foregone agricultural production of $1 600 million (NLWRA 2001; Lockwood *et al.* 2003).

Pasture management practices that can affect soil acidification processes include growing legume pasture species, applying ammonium fertilizer and product removal. These practices influence the nitrogen and carbon cycles, which are major components of acidification processes in the soil. Soil acidification can cause reduced pasture productivity through aluminium and manganese toxicity, molybdenum, calcium and magnesium deficiencies, and reduced nitrogen fixation (Williams and Hook 1998; Upjohn *et al.* 2005). Symptoms of aluminium and manganese toxicity include poor root growth, shallow roots and stunted plants (Fenton *et al.* 1996). Yellowing leaves of legumes can indicate molybdenum deficiency, while calcium deficiency can affect the nodulation of subterranean clover (Fenton *et al.* 1996). Reduced nitrogen fixation can reduce the survival of legumes that in turn reduces dry matter production (Fenton *et al.* 1996).

Considerable research into the processes of soil acidification has been undertaken in parts of southern NSW, in particular the southwest slopes and plains area of NSW, where agriculturally-induced soil acidification is widespread. This area is around Wagga Wagga, which is west of Canberra (Figure 1.1). The climate is temperate with cold, wet winters and hot, dry summers. In a temperate climate, adequate rainfall can leach nitrate that builds up during the dry season, and this is an acidifying process. The NSW Northern Tablelands (Figure 1.1) is described as having a suitable climate, geography and land use for soil acidification. Yet, soil acidification is not well understood in the area as little research has been undertaken. It has been speculated that acidification processes in the north will vary from those in the south of the State because of differences in climate and pasture-management practices. However, no clear evidence of this variation existed. More research was needed in the Northern Tablelands area in order to understand better soil acidification in NSW.

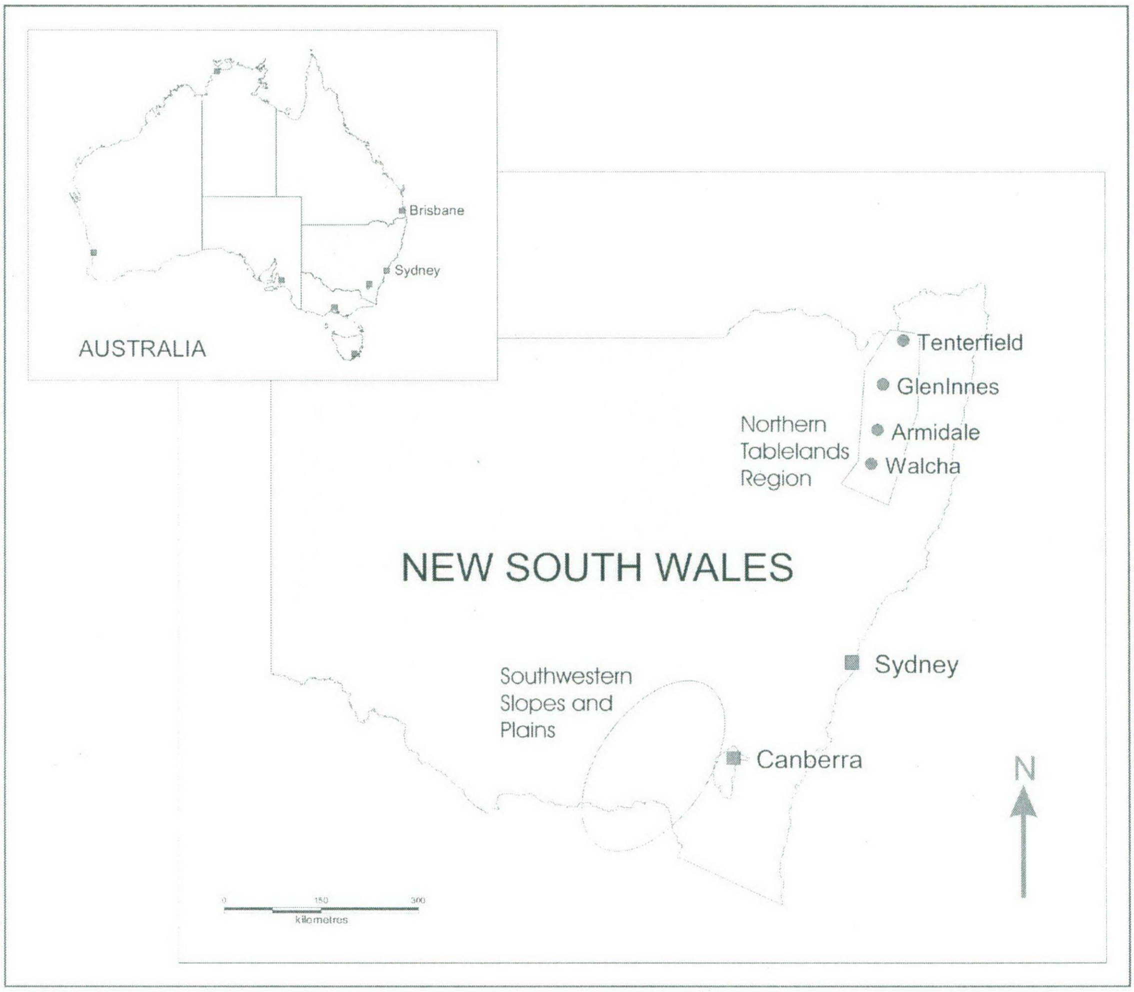

**Figure 1.1 Northern Tablelands study area in relation to NSW and Australia**

The Northern Tablelands of NSW, extend from the Tenterfield area (29°S, 151°50'E) in the north and south of Walcha to Nundle (30°25'S, 151°10'E), and are bounded by an escarpment along the eastern boundary and a steep erosion scarp in the west (Harrington 1977; Walker 1977). Altitudes of the tablelands range from about 800 m to 1 300 m (Walker 1977) and the climate is temperate with mild to warm summers and cool to cold winters (BoM 2005). Rainfall is prevalent in spring or summer and the annual long-term average rainfall of the area is 830 mm (BoM 2005). Soils of the tablelands are derived from basalts, granites and metasediment and include Dermosols, Vertosols, Ferrosols, Kandosols, Sodosols, Chromosols, Kurosols and Tenosols. These soils are termed using the Australian Soil Classification System (Isbell 1996)[1], and this system will be used throughout this thesis.

The project reported in this thesis was the first major assessment of soil acidity and soil acidification in northern NSW. Acid Soil Action (ASA) provided funding for the research. An initiative of the NSW Government, ASA involved the agricultural community, industry, various government agencies and universities to work on the negative effects of soil acidity on agricultural land. The brief was to assess the distribution, extent and severity of acid soils under pasture on the Northern Tablelands, and to learn whether these soils were becoming more acidic because of management. If acidification was occurring, the causes were to be investigated to identify and manage soil acidity and acidification. Soil acidification processes of the area were also to be investigated and compared with the processes from southern NSW.

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[1] The Australian Soil Classification System is available on the public domain at the following web site: http://www.clw.csiro.au/aclep/asc_re_on_line/soiusing.htm

## 1.2 Project Objectives

The overall objective of the project was to achieve a better understanding of acid soils and soil acidification processes on the Northern Tablelands of NSW. Specific objectives were to:

- Estimate the extent of acid soils under pasture on the Northern Tablelands.
- Investigate the impact of pasture management on soil acidification in the region.
- Examine soil acidification processes on the Northern Tablelands.

In the first part of the project the extent and severity of acid soils on the Northern Tablelands were estimated. Available data from the NSW Department of Natural Resources (DNR) and CSIRO (Commonwealth Scientific Investigative Research Organisation) were used to produce a soil pH map of the region to show the distribution and extent of these soils.

The impact of pasture management on soil acidification was investigated in a paired-site study. Forty-one sites, each comprising a roadside reserve area of native grasses and an adjacent exotic pasture of the same soil type, were used in the survey. Soil cores from the reserve areas were compared with cores from the pasture paddocks to assess temporal changes in soil chemical properties associated with pasture and grazing. Data were then used to assess the rate of acidification.

To examine the effect of rainfall and temperature on soil chemical properties on the Northern Tablelands, a field study was set up. Soil samples from five paddocks, each with a different management regime ranging from an exotic, fertilized, grazed pasture to an area with tree cover, were analysed. Sampling proceeded every four weeks over a fourteen-month period to assess seasonal variations on soil pH, electrical conductivity, and nitrate and ammonium concentrations.

Three incubation experiments were devised to further study nitrification in relation to soil acidification. Soil samples were amended with different rates of ammonium sulfate and incubated for set periods at specific temperatures before being analysed for nitrate and ammonium. In the first experiment, optimum incubation conditions to measure the rate of nitrification were determined. The second experiment examined the influence of soil $pH_{Ca}$, pasture management and soil depth on nitrogen mineralization and nitrification. Pasture management, temperature and soil moisture effects were investigated in the third experiment.

**Plate 1.1** **Rolling plains of New England countryside.**

**Plate 1.2** **Roadside reserve area adjacent to a paddock in the New England area.**

## 1.3 Outline of Thesis

Soil acidification in Australian grazing systems, with particular reference to NSW, is reviewed in Chapter 2. Comprehensive reviews on acid soils and soil acidification have been produced (Helyar 1991; Dann 1997; Scott *et al.* 2000; Lockwood *et al.* 2003) and preclude the necessity for a full review of the literature in this thesis, and only those aspects of acid soils and soil acidification relevant to this research are assessed. Geographical attributes of the Northern Tablelands are described and the bounds for the project are defined in Chapter 3. A report on mapping acid soils of the Northern Tablelands is also included in that chapter. Chapters 4, 5 and 6 are the experimental chapters. Details of the paired-site investigation are provided in Chapter 4. The field study on the effects of moisture and temperature on soil pH, and nitrate and ammonium concentrations is reported in Chapter 5. Chapter 6 describes the incubation experiments. Within each chapter, experimental procedures are set down, results are given, statistical analyses are discussed and conclusions proffered. Overall conclusions of the project, presented in Chapter 7, complete the thesis.

# 2. SOIL ACIDIFICATION IN AUSTRALIAN GRAZING SYSTEMS

## 2.1 Introduction

Soil acidification is recognised as a serious land-degradation problem worldwide and in Australia (NLWRA 2001a). It is an insidious process that develops slowly and is widespread throughout agricultural land in the higher rainfall areas of Australia, particularly in New South Wales, Queensland, Victoria and Western Australia (NLWRA 2001a). The objective of this section is to review soil acidification in Australian grazing systems with particular reference to NSW. The review commences with a broad overview of acid soils, and aspects of soil acidification that pertain to grazing land in Australia. Acid soils, soil acidity and soil pH are defined. Soil acidification processes as they relate to this project are then discussed. In the final section, on managing acid soils and soil acidification, diagnosis of the problem, ameliorative treatments, and preventive management practices are assessed.

Agricultural land in Australia has, for many years, been managed using fertilizer amendments and establishing legumes as a pasture supplement. The use of superphosphate as a pasture additive started around the 1920s when subterranean clover was used as a pasture legume to increase pasture production (Vimpany 1992). An additional benefit of clover is that it supplies nitrogen to the pasture system, but it requires phosphorus to be fully productive. Phosphatic fertilizer can be incorporated into the soil when seed is sown, or by broadcasting the fertilizer before cultivating the soil (Glendinning 1990). When fertilizer is applied, nutrients are supplied to the grazing system and pasture quality generally improves. Stocking rates can be increased with improvement in the quality and digestibility of pasture. Reuter *et al.* (1996) defined an ideal, sustainable grazing ecosystem as a closed system; nutrients do not leave the system except through agricultural products exported from the farm. This is rarely the case in an actual farming situation because with intensive grazing, the supply of nutrients is increased, and this increases the "leaking" of nutrients from the system (Reuter *et al.*1996). Nutrients are "leaked" through pathways and processes determined by geomorphological elements, soil properties, pasture management, fertilizer application and rainfall patterns (Williams and Hook 1998). Nutrient "leakage" could be defined as the indeterminate loss of nutrients in runoff, subsurface flow, leaching, or with product export. A principal soil acidification process assessed in this review, is considered to be the leaching of nitrate that has been nitrified from ammonium fertilizers or nitrogen fixation.

Potential problems with soil acidity in Australia were raised by Donald and Williams (1954) who observed that soil $pH_W$ fell with superphosphate application. They recognised that such a fall in soil $pH_W$ could effect legume nodulation or have an adverse effect on plant growth with decreased nutrient availability. Donald and Williams (1954) further suggested that because superphosphate was not an acid fertilizer, the fall in soil $pH_W$ resulted from an increase in the cation exchange capacity following a buildup of organic matter with the growth of subterranean clover. Williams and Donald (1956) confirmed that a decrease in soil $pH_W$ was accompanied by an increase in cation-exchange capacity and exchangeable hydrogen following the use of superphosphate and subterranean clover.

Research on acid soils and soil acidification gathered momentum in the 1980s and 1990s. Workshops were held, and between 1986 and 1992 the *Australian Soil Acidity Research Newsletter* was published by NSW Agriculture and Fisheries. Assessing the extent of the soil acidification problem in Australia, through soil test databases and soil surveys, was given the highest priority at a national workshop on soil acidity (Helyar 1988). In response, Federal funding was given to the States to provide information for a national database of soil pH (Ahern *et al.* 1992). Soil $pH_W$ maps for Queensland, using QDPI and CSIRO data from predominantly "virgin" soils, were published by Ahern *et al.* (1992; 1994). A map of surface agricultural soil $pH_{Ca(1:2)}$ for NSW was also produced (Helyar *et al.* 1990). Australia-wide maps of soil $pH_{Ca}$ and soil acidification risk were produced by NLWRA (2001a) using the data from the Australian Soil Resources Information System (ASRIS). ASRIS is a national database of soil and land resource data (Henderson *et al.* 2001).

Conferences and workshops on acid soils and soil acidification over this time included *The Acid Soils Affair* (AIAS and ATA 1981), *Acid Soils Revisited* (AIAS and ATA 1986), a workshop on the amelioration of acidity in non-arable soils (NSW Agriculture 1997), and the *National Soil Acidification Conference* (QDPI and QNR 1998). Research overviews and reports (Helyar 1987; 1988) gave updates of the research undertakings in NSW and Australia at the time. A fact sheet assessed the causes of agriculturally-induced soil acidification, the rates of soil acidification, the influence of soil acidity on plant growth and suitable control measures (Fenton *et al.* 1996). This fact sheet was later updated by Upjohn *et al.* (2005). Definitive papers at the time included those by Helyar and Porter (1989) on the processes responsible for soil acidification, and by Cregan and Helyar (1986) on the measurement of the rate of soil acidification and on the management practices that contribute to a reduction in soil acidification. Reviews that outlined the historical aspects of acid soils research with current recommendations and research priorities were written by Dann (1997) and Simpson (1997). Scott *et al.* (2000) reviewed soil acidification and evaluated various practices to manage soil acidity in long-term pastures in southeast Australia. Another comprehensive review, on the effects of soil acidity and acidification in Australia, and an assessment of management practices, was produced by Lockwood *et al.* (2003).

A series of nine leaflets on soil acidity published by NSW Agriculture and Acid Soil Action (ASA) between 1998 and 2002 provided information such as understanding soil pH (Lake 2000); the causes of soil acidity in different farming systems (Duncan 1999; Schumann 1999); determining the acidity status of a soil (Fenton 1999a); remedial action through liming (Fenton 1999b); and managing soil acidity (Schumann and Glover 2002). An initiative of the NSW Government, ASA was formed in 1997 and involved the agricultural community, industry, various government agencies and universities to work on the negative effects of soil acidity on agricultural land. A ten-year program was proposed to address acid soil problems and active research resulted. In 2002 a workshop was held in Wagga Wagga to review findings from ASA-funded projects, to assess the needs of ongoing projects and to identify future research needs. Unfortunately, shortly after the workshop, government funding was withdrawn and ASA was defunct. Research projects funded by ASA ranged from those that assessed plant tolerance to soil acidity and the development of new varieties of plants (Ayres and Kelman 2002; Harris 2002; Islam *et al.* 2002 ) to long-term trials such as MASTER (Li *et al.* 2002) and the effects of lime on pasture and animal production (Garden *et al.* 2002). MASTER (Managing Acid Soils Through Efficient Rotations) was designed to develop an economically viable and environmentally sustainable agricultural system on acid soils (Li *et al.* 2002). Data for the MASTER trial was collected from a field laboratory set up at Book Book near Wagga Wagga in southern NSW. The Wagga Wagga workshop culminated in a report (NSW Agriculture 2002) of key results from ASA-funded research projects and review papers. The aim of the report was to facilitate communication between research workers, extension staff, consultants and farmers.

Despite this research, overall the true extent and distribution of acidic soils in Australia are not known. Soil pH maps produced by the NLWRA (2001a) are based on an extrapolation and modelling of results from commercial soil testing of agricultural land, and soil survey data of State and Territory agencies. The maps are small in scale (Australia wide) and regional details are lacking. From these maps an estimated 50 million hectares of surface soils and 23 million hectares of subsoils are affected by the impacts of soil acidity ($pH_{Ca}$<5.5). This is about half the area under intensive agriculture, and the estimated cost of lost agricultural production is $1 600 million (Lockwood *et al.* 2003). It is predicted that another 29-60 million hectares will have a $pH_{Ca}$ of 4.8 or less, and 14-39 million hectares will have a $pH_{Ca}$ of less than 5.5 within a period of 10 years (NLWRA 2001a). Australia wide, lime additions of between 12 and 66 tonnes of lime per hectare would be needed to adjust the soil $pH_{Ca}$ to 4.8 and 5.5 respectively (NLWRA 2001a). AACM International (1995) indicated some 13.5 million hectares of [agricultural] land in NSW is highly acidic ($pH_{Ca}$ < 4.8), 5.7 million hectares are moderately acidic ($pH_{Ca}$ 4.9 - 5.5) and another 5.1 million hectares are at risk of becoming moderately acidic. For NSW, the NLWRA (2001a) assessed 5-7 million hectares of surface soils are strongly acidic ($pH_{Ca}$ 4.3 - 4.8) while 11-13 million hectares are moderately acidic ($pH_{Ca}$ 4.8 - 5.5); for subsurface soils 3.1 million hectares are below 4.8 for $pH_{Ca}$.

## 2.2 Soil Acidification and Other Terms Defined

### *2.2.1 Acid Soil, Soil Acidity and Soil pH*

The degree of acidity or alkalinity of a soil is measured by its pH. In this thesis, soil pH, as opposed to soil $pH_W$ or soil $pH_{Ca}$, is used as a general term. It is also used when the method for determining soil pH is not stated, nor can be discerned from a literary reference. An *acid or acidic soil* is one with a soil $pH_W$ less than 7.0, or soil $pH_{Ca}$ less than 6.5 (Slattery *et al.* 1999; Thomas and Hargrove 1984). This differs from NLWRA (2001a) where a soil with a $pH_{Ca}$ less than or equal to 5.5 is defined as acidic. The term *soil acidity* refers to the situation in which a greater concentration of hydrogen ions is present in the soil water as compared with a neutral soil (Lockwood *et al.* 2003). *Soil pH* is a measure of the hydrogen-ion activity, or concentration of hydrogen ions in the soil solution and is a logarithmic scale (Glendinning 2000; McKenzie *et al.* 2004).

Soil pH can be measured several ways. Commonly, in Australia, an electrode is used to measure the pH of a 1:5 soil:water suspension ($pH_W$) or the pH of a 1:5 soil:0.01 M $CaCl_2$ suspension ($pH_{Ca}$). Both $pH_W$ and $pH_{Ca}$ are recommended analytical methods (Slattery *et al.* 1999) that are routinely measured by commercial laboratories. On occasion, soil pH is determined using a 1:5 soil:1.0 M KCl suspension ($pH_{KCl}$). Prescribed, standard methods for measuring soil pH in Australian laboratories are set down in Rayment and Higginson (1992). Soil $pH_W$ is closer to that in which the plant roots are exposed, but can vary by up to 0.6 pH units with seasonal changes in soil moisture and salt concentrations in the soil (White 1969; Friesen *et al.* 1985; Slattery and Ronnfeldt 1992; Dolling *et al.* 2001). As soil moisture increases, the salt to water ratio can decrease; soil $pH_W$ can increase with this effective decrease in salt concentration. Seasonal variations in soil $pH_{Ca}$ measurements are less pronounced (Slattery and Ronnfeldt 1992). In NSW, $pH_{Ca}$ is the usual method as the 0.01 M $CaCl_2$ solution more closely approximates the ionic strength of the soil solution of non-saline soils (Schofield and Taylor 1955; Helyar and Porter1989). Provided the electrode is placed in the clear supernatant solution, soil pH measurements in salt solutions, such as $pH_{Ca}$, give more consistent and reproducible readings as the magnitude of the liquid junction potential is reduced (Sumner 1994). Because it is more robust, soil $pH_{Ca}$ is the preferred laboratory test in most Australian States (NLWRA 2001a; Slattery *et al.* 1999). Field soil pH ($pH_F$) can be measured with a probe and hand-held meter. It can also be colorimetrically assessed using a soil pH test kit. A small amount of soil is mixed with a few drops of pH indicator liquid, which develops a colour. To highlight the colour, white barium sulfate powder, is sprinkled onto the soil paste. The colour is matched against a chart of 16 colours, each representing a pH level from 4 to 10 units. Such field measurements can be correlated with laboratory measurements if the methods are calibrated against standard soils (Spouncer *et al.* 1996; Slattery *et al.* 1999). Corrections are usually within 0.5 pH units of $pH_W$ (Hazelton and Murphy 1992).

The pH scale ranges from 0 to 14, with 7 being neutral, and pH is $-\log_{10}C$, where C is the concentration, or activity, of hydrogen ions (moles per cubic decimetre) in the soil solution. Thus, a pH of $10^{-7}$ mol $dm^{-3}$ is equivalent to 7.0 pH units. As this is a negative logarithmic scale, the higher the concentration of hydrogen ions, the lower the pH, the more intense is the acidity. Compared with a pH of 6.0, a pH of 5.0 has ten times the concentration of hydrogen ions and is ten times more acidic, whereas a pH of 4.0 is one hundred times more acidic.

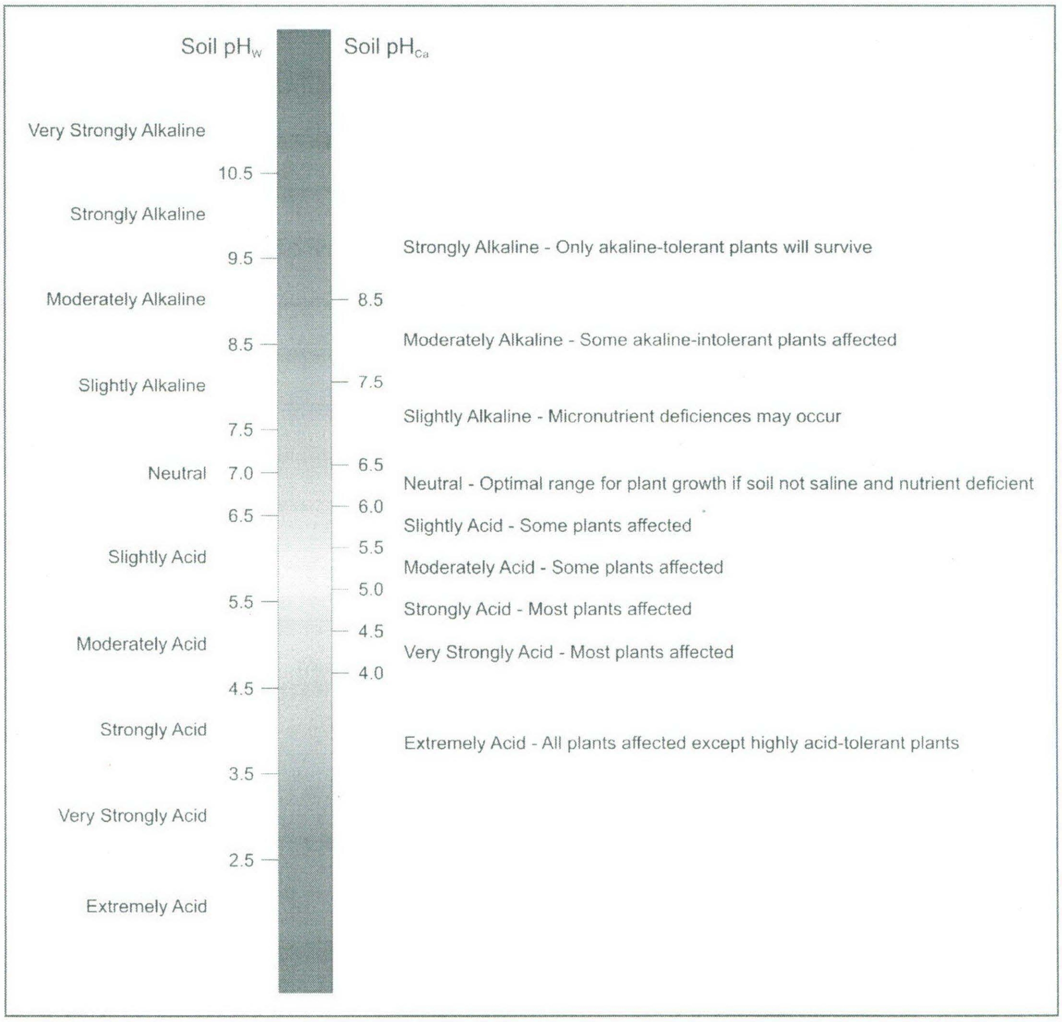

**Figure 2.1** **pH scale and ranges of soil acidity for soil $pH_W$ and $pH_{Ca}$ (after Slattery *et al.* (1999) and Fenton *et al.* 1996)**

Critical pH ranges are assigned to the relative acidification effects on plant growth (Figure 2.1). A $pH_{Ca}$ range of 6.0 to 6.5 is considered optimal for plant growth. When $pH_{Ca}$ falls below 5.8, aluminium and manganese become more soluble; toxicity can occur when the $pH_{Ca}$ below 4.8 units (Slattery *et al.* 1999). Soil $pH_{Ca}$ in the range 4.5-5.0 units is critical for sensitive plants yet optimal for acid-tolerant cultivars if adequate nitrogen and phosphorus is available (Slattery *et al.* 1999; Upjohn *et al.* 2005). Between 4.0-4.5 $pH_{Ca}$ units, significant soil acidification occurs and all plants are affected except highly acid-tolerant species (Fenton 1996; Slattery *et al.* 1999). At this stage, essential plant nutrients, including molybdenum, are less available and the activity of soil microorganisms, such as nitrifiers, is altered.

### *2.2.2 Soil Acidification and Soil Acidifying Processes*

*Soil acidification* is where more hydrogen ions are added to the soil through *acidifying processes*. This addition of acid to the soil, without any alkaline addition, causes the soil pH to fall.

Soil acidification is a natural process in which soils slowly acidify over time (Lockwood *et al.* 2003; Helyar and Porter 1989). The length of the process is dependant on the soil parent material, the soil pH buffering capacity, and the influence of weathering and other environmental factors. The pH buffering capacity of a soil determines the resistance, or susceptibility, of a soil to a change in pH. Acid soils usually develop from soil parent material of low buffering capacity, while a soil with a higher pH buffer capacity ($pH_{BC}$) can better withstand acidification. Environmental factors such as climate also affect the rate of soil acidification. Soils in warmer, higher rainfall areas often acidify faster than those in drier, colder areas. In areas of high rainfall, exchangeable cations (calcium, magnesium, potassium and sodium) are leached from the soil and an increase of adsorbed hydrogen and aluminium ions are produced by acid-forming reactions (McKenzie *et al.* 2004). High rainfall followed by higher water infiltration through the soil profile can also result in the leaching of nitrate and this is acidifying. Acidification in sandy soils is often high because of extreme leaching (McKenzie *et al.* 2004). Nitric, carbonic and organic acids added to the soil slowly dissolve basic (or alkaline) compounds that buffer soil pH (Helyar 1976). Inputs of acids into the agricultural ecosystem in Australia are principally water and carbonic acid in rainfall (Helyar and Porter 1989). Sulfate and nitrate ions in the atmosphere that mix with water particles and fall as acid rain can also acidify a soil. Sulfuric and nitric acids from acid rain are negligible (Helyar and Porter 1989) to nonexistent in Australia and are not discussed here.

Another process forms acid-sulfate soils from pyrite oxidation. Although acid-sulfate soils are prevalent in Australia, particularly in some coastal areas, they result from very specific and different processes. Thus they are not relevant to the project and not considered in this review.

### *2.2.3 Soil Acidification Risk and Soil pH Buffer Capacity*

While the term *soil acidification* refers to the addition of acid to the soil, the term *soil acidification risk* means the risk of a fall in soil pH. *Soil pH buffer capacity* ($pH_{BC}$) measurements can indicate the risk of soil acidification. Soil $pH_{BC}$ can be measured directly in the laboratory or estimated from other soil properties. For example, the Mehlich single buffer pH laboratory method (Mehlich 1976) for lime requirement determines the quantity of lime needed to neutralize a part or all the exchangeable acidity of a soil (Rayment and Higginson 1992).

Soil $pH_{BC}$ estimation has been the subject of research in Australia, for example Aitken *et al.* (1995), Aitken and Moody (1994), Aitken *et al.* (1990), Helyar and Porter (1989). Although soil:$Ca(OH)_2$ titrations and soil:$CaCO_3$ incubations are accurate for determining lime requirements, they are time consuming (Viscarra Rossel and McBratney 2001). In addition, it is generally accepted that soil $pH_{BC}$ is not a favoured laboratory procedure because of the difficulty in obtaining a universal standard across soil types. Aitken and Moody (c.1989) proposed that a universally acceptable method for $pH_{BC}$ be introduced for acidification studies and presented results to demonstrate that $pH_{BC}$ is very dependant on the measurement methodology.

As soil $pH_{BC}$ is not routinely tested, these measurements are often missing from data sets and this makes it difficult to assess soil acidification risk. To address the situation, soil $pH_{BC}$ estimates have been formulated on measurements of soil attributes that are readily available. A review of six methods for estimating $pH_{BC}$ was undertaken by Noble (2001) who evaluated these pedotransfer functions with data sets.

Two equations, (1) and (2) below, were ultimately recommended by NLWRA (2001a) as the preferred pedotransfer functions.[2] If organic carbon and clay content were known, then the regression equation developed by Aitken *et al.* (1990) was recommended as it had the best correlation ($r^2 = 0.7$ to $r^2 = 0.9$) for a wide range of surface soils:

$$pH_{BC}(t\ CaCO_3/ha.pH) = [0.955\ OC\% + 0.011\ clay\%] \times 1.2 \qquad (1)$$

For subsoils (30-40 cm) the following equation was recommended because it relied less on percent soil organic carbon for its evaluation:

$$pH_{BC}(t\ CaCO_3/ha.pH) = [12.79 - 0.19clay\% - 0.7OC\% - 0.03silt\% + 0.74silt\% \times OC\%] \times 0.06 \qquad (2)$$

Soil acidification risk is generally calculated using the rate of change of soil $pH_{Ca}$ from a current value to a set critical value, an acid addition rate and time. NLWRA (2001a) recommended the following equation, where the acid addition rate ( tonnes of lime per hectare per year) is the amount of lime needed to balance the input of acids:

$$\text{Time (years)} = [(\text{pH current} - \text{pH critical}) \times pH_{BC}] / \text{acid addition rate} \qquad (3)$$

In another variation, Noble *et al.* (2002) considered soil volume (V) and bulk density (BD) in the formulation of the following equation for Stylo (*Stylosanthes guyanensis*), a pasture legume, in tropical Queensland:

$$\text{Time (years)} = [(\text{pH initial} - 5.0) \times pH_{BC} \times BD \times V] / \text{net acid addition rate} \qquad (4)$$

Acid addition rates for Australian agricultural and pastoral systems are published (NLWRA 2001a), or can be calculated (Dolling *et al.* 2001):

$$\text{Acid Addition Rate} = (\text{pH initial} - \text{pH end}) \times pH_{BC} \times BD \times V \qquad (5)$$

Initial pH values can be obtained from undeveloped land of native vegetation preferably adjacent to a more developed site that can be used for pH end values. Soil pH values can also be obtained from studies undertaken over time. Equation 4 can be manipulated to predict soil pH at the end of a set number of years, although this is not common. Singh *et al.* (2003) used a similar equation to project current soil $pH_{Ca}$ and simulate soil $pH_{Ca}$ for 50 years in the future.

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[2] NLWRA (2001a) lists two $pH_{BC}$ pedotransfer functions and states that other functions in (Dolling *et al.* 2001) could be used depending on the availability of soil data. Dolling *et al.* (2001), in turn, refers back to Noble (2001) for more details of $pH_{BC}$ relationships. The comprehensive list of pedotransfer functions is available in Noble (2001).

## 2.3 Soil Acidification Processes

Soil acidifying processes in exotic, fertilized pastures are made up of a series of steps, which include the accumulation of organic acids from a buildup of soil organic matter; nitrification of ammonium fertilizers; loss of nitrate in leaching or runoff; and export of organic anions with removal of produce (Helyar and Porter 1989; Vimpany 1992). Acidifying processes include the following pathways:

- Leaching or runoff of nitrate fixed from atmospheric nitrogen and subsequently oxidized to nitrate (Vimpany 1992);
- The leaching or runoff of nitrate added to the soil as ammonium fertilizer; and
- Leaching or runoff of nitrate that has been mineralized from legume and other organic residues and subsequently oxidized to nitrate.

Soil acidification processes have been well researched in parts of southern NSW and northern Victoria. In the temperate climate of that area, winter rainfall prevails and agriculturally-induced soil acidification is widespread. A major factor of soil acidification in southern NSW is considered to be nitrate leaching (Helyar and Porter 1989). Here a nitrate buildup can occur during the dry summer season when conditions are ideal for mineralization of ammonium and plant uptake of nitrate is low. If seasonal winter rains leach nitrate before denitrification or plant uptake, then acidification may occur and soil pH may decline by up to 0.05 units per year (Helyar 1976).

The extent and severity of accelerated soil acidification on the tablelands of northern NSW are not as well understood. Here the climate is also temperate but with spring and summer-dominant rainfall. Less research has been completed in the north of the State and, because of this, acidification processes in this area are less understood. It might be expected that the processes will vary from those of the south because of differences in climate and pasture and grazing management and the scale of acidification could be affected. Specific research on Northern Tablelands soils has been undertaken (Friesen *et al.* 1985; Crocker and Holford 1991; Chen *et al.* 1999; Harris and Duncan 2002; Hutchinson *et al.* 2002) but these projects were either limited in the range of locations used, confined to one location, or did not exclusively apply to soil acidification.

Friesen *et al.* (1985) in a two-year monitoring trial on permanent pastures at *Chiswick*, a former CSIRO Pastoral Research Laboratory, south of Armidale, found soil $pH_W$ was negatively correlated with temperature and positively correlated to the soil moisture index. In a separate pasture experiment at *Chiswick*, Chen *et al.* (1999) labelled selected areas with $^{15}N$-enriched $NH_4Cl$ solution and observed found that ammonium-N was significantly higher in autumn and winter. They reasoned that, although pasture growth was synchronized with nitrogen mineralization and nitrification, ammonium domination of the soil nitrogen system prevented nitrate leaching in that environment.

In a paired-site exercise in the Walcha and Armidale areas, Crocker and Holford (1991) showed that soils of the Northern Tablelands were naturally more acidic than unfertilized, native pasture soils in the south, and that soil acidification in northern perennial pasture systems was slower and less frequent. It was claimed that perennial pastures persisted with summer rain and nitrate was recycled rather than leached down the profile (Crocker and Holford 1991). In another paired-site study, Harris and Duncan (2002) concluded that although granitic soils were at risk of acidification in the topsoil and subsoil, acidification under pasture on the NSW Northern Tablelands was less than in southern NSW. However, this study was limited to 18 sites within the Northern Tablelands, from Tenterfield to Walcha. Hutchinson *et al.* (2002) found substantial rates of acidification in sown pastures, but not in native pastures, in a long-term grazing experiment of more than 34 years at *Chiswick*. Changes in soil $pH_{Ca}$ of the surface soil in sown, fertilized pasture declined exponentially and were comparable to changes reported in southern NSW (Hutchinson *et al.* 2002).

### *2.3.1 The Nitrogen Cycle*

A key process in the nitrogen cycle that has the potential to affect soil acidification is nitrification by which ammonium, mineralized from legume and other organic residues, is oxidized to nitrate. A diagram of the nitrogen cycle in the soil system is given in Figure 2.2.

Atmospheric dinitrogen is biologically fixed by free-living *Prokaryotae* bacteria and *Protoctista* photosynthesis algae in the soil, and by legumes and clovers to form organic-N compounds represented here as amines ($R\text{-}NH_2$) within the plants (Equation 1, Table 2.1). No hydrogen ions are produced or consumed. Amines may be transformed to amino acids in proteins and other compounds. Nitrogen mineralization, by which organic nitrogen is converted to ammonium, is made up of two stages: aminization and ammonification (Tisdale *et al.* 1993). The term mineralization can also sometimes apply to the conversion of organic

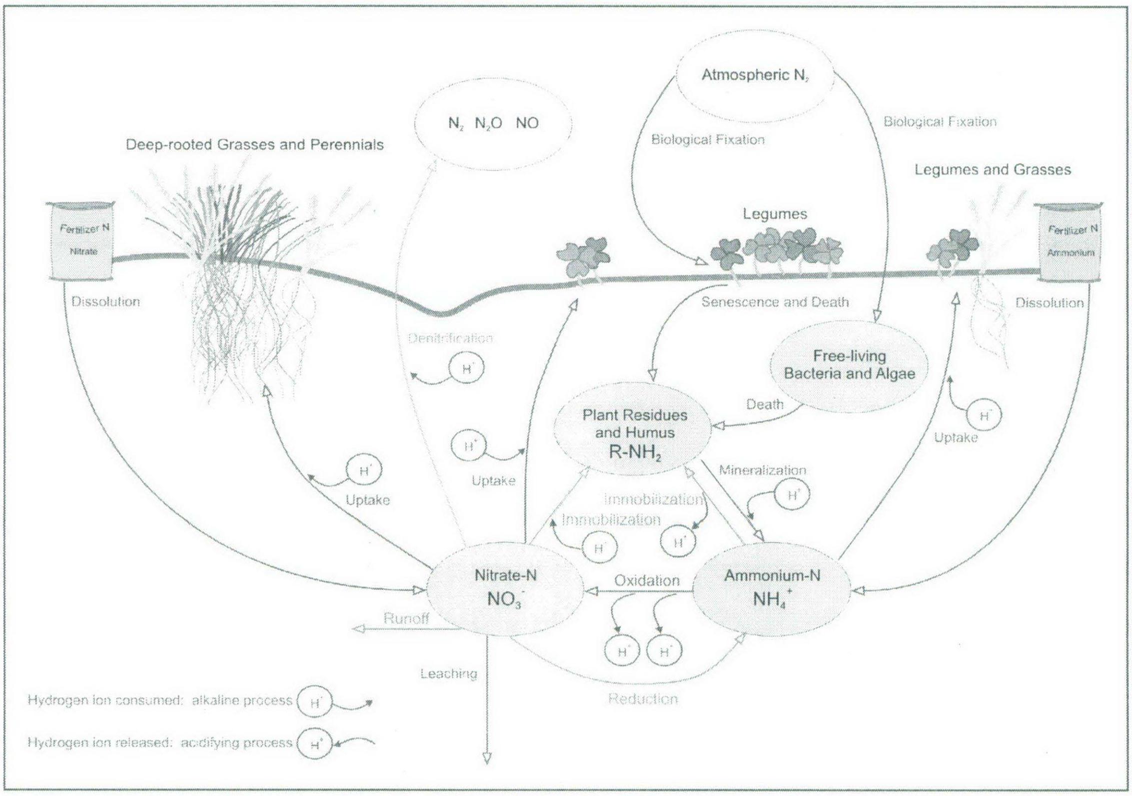

**Figure 2.2** **Nitrogen cycle as it relates to soil acidification in a pasture system. After White *et al*. (1984), Fenton *et al*. (1996) and MacLeod and Lockwood (1997)**

nitrogen to any inorganic form, which includes nitrification (Stevenson 1982). In this thesis, *mineralization* will refer to the process whereby organic nitrogen is converted to ammonium. As plant material decomposes, proteins are converted back to amines in the aminization process. Microbial decomposition breaks down the dead organic matter and amines are converted to form ammonium ions in the soil (Equation 2, Table 2.1); this is the ammonification process. With ammonification, one hydrogen ion is consumed per atom of nitrogen ammonified in this process. Ammonium ions are then available for uptake, or immobilization, by microorganisms or plants. In the autotrophic nitrification process, ammonium undergoes biological oxidation, by nitrite bacteria such as *Nitrosomonas* spp. to form nitrite (Equation 3, Table 2.1), before further oxidation (Equation 4, Table 2.1) by *Nitrobacter* spp. (nitrate bacteria) to form nitrate (Tisdale *et al.* 1993). Two hydrogen ions are produced per atom of nitrogen nitrified. Nitrate is available for direct uptake by plants. Alternatively, nitrate ions can be immobilized to soil organic matter, or lost from the system through leaching, runoff or reduced within the soil by denitrification. Plant uptake of nitrate (Equation 5, Table 2.1) and reduction to an amine consumes one hydrogen ion per nitrogen atom that is taken up.

**Table 2.1 Equations for nitrogen cycle reactions for a pasture system**

| | | | |
|---|---|---|---|
| $2N_2 + 4R\text{-}OH + 2H_2O$ | $\rightarrow$ | $4R\text{-}NH_2 + 3O_2$ | Biological fixation (1) |
| $R\text{-}NH_2 + H_2O + H^+$ | $\rightarrow$ | $R\text{-}OH + NH_4$ | Ammonia hydrolysis (ammonification) (2) |
| $2NH_4^+ + 3O_2$ | $\rightarrow$ | $2NO_2^- + 2H_2O + 4H^+$ | Biological oxidation by nitrite bacteria (3) |
| $2NO_2^- + O_2$ | $\rightarrow$ | $2NO_3^-$ | Oxidation by nitrate bacteria (4) |
| $NH_4^+ + 2O_2$ | $\rightarrow$ | $NO_3^- + H_2O + 2H^+$ | Equations (3) + (4) |
| $NO_3^- + R\text{-}OH + H^+$ | $\rightarrow$ | $R\text{-}NH_2 + 2O_2$ | Uptake and Reduction (5) |
| $NO_3^- + nH^+ + ne$ | $\rightarrow$ | $N_2, N_2O, NO, H_2O$ | Denitrification (6) |

Equation (2): Mineralization process
Equation (3) plus (4): Nitrification (or oxidation) process

Any process that produces an increase of hydrogen ions in the soil is acidifying. If a proton is consumed, the result is alkalizing; if a proton is released, the effect is acidifying (Helyar 1976). Mineralization uses one free hydrogen ion in the soil for every ammonium ion produced. Oxidation releases two hydrogen ions for every nitrate ion produced. One hydrogen ion is used for every nitrate ion taken up by plants or denitrified by *Pseudomonus* spp. (denitrifying bacteria). If the cycle of nitrogen mineralization, oxidation and uptake is complete, then no net loss or gain of hydrogen ions occurs and the process does not acidify the soil. Nitrogen cycling in a closed system is neutral (Helyar 1976).

Addition of ammonium fertilizer, such as ammonium sulfate, can also be acidifying. Here, the ammonium pool is directly supplemented because the hydrogen ions that would otherwise have been used during mineralization remain in the soil. The loss of nitrate in leaching, or runoff is also acidifying. For every nitrate ion lost this way, a hydrogen ion that is not taken up by plants or neutralized by as a result of alkali excretion during net anion uptake is left in the soil. In areas of high rainfall, an increase in moisture flow through the soil profile can promote nitrate leaching. During times of drought, moisture availability would be less and it could be expected that moisture flow through the soil would decrease.

Subsoil acidification is another problem that is widespread. The causes of acidification in this area are not as clear as those involved with surface soil acidification. Processes that could be involved are acid production by plant roots following excess cation uptake particularly by legumes (Tang 2004). It has been suggested that nitrate leaching can cause subsurface acidification but Tang *et al.* (2000) found that this process was unlikely to be a cause.

### *2.3.2 The Carbon Cycle*

Carbon cycle effects can also be acidifying. Processes that are acidifying include the buildup of humus and subsequent dissociation of humic acids that leave hydrogen ions in the soil (MacLeod and Lockwood 1997). Increased residues from pasture production can increase organic matter. Whilst organic matter can improve soil condition and promote soil biological activity, the humus component of soil organic matter is acidic (Lockwood *et al.* 2003). Organic acid production of carbon fixed by photosynthesis exported as anions in products or accumulated as anions in soil organic matter (Vimpany 1992) is acidifying. Plant materials contain organic anions, such as malate, that are produced when plant roots take up cations; as part of the process hydrogen ions are expelled into the soil (Lockwood *et al.* 2003). Acidification of the whole profile does not occur if the plant dies, but organic anions in the plant residues will tend to leave the surface more alkaline than the root. If the plant residues remain where it grew, organic anions within the residues will neutralise the expelled soil hydrogen ions and overall soil acidification in the profile will not occur (Lockwood et al. 2003). If the plant is harvested and the material taken off farm, organic anions are exported and net soil acidification results (Lockwood et al. 2003).

## 2.4 The Influence of Grazing Management on Soil Acidification

Agricultural management practices that can affect soil acidification processes include growing legume pasture species, applying ammonium fertilizer and removal of produce. Agriculturally-accelerated soil acidification can cause aluminium and manganese toxicity, molybdenum, calcium and magnesium deficiencies, reduced nitrogen fixation, a reduction of legume nodulation, low availability of plant nutrients such as phosphorus and molybdenum, and decreased nutrient cycling (NLWRA 2001a; Fenton *et al.* 1996). Symptoms of aluminium toxicity include poor root growth, shallow roots and stunted plants (Fenton *et al.* 1996). Pasture degradation and loss of productivity can occur as the availability of plant nutrients is reduced; microbial soil processes, nitrogen fixation and legume nodulation are affected and levels of aluminium increase (NLWRA 2001a; Fenton *et al.* 1996).

Soil acidification, induced by land use and land management practices, can result in production losses brought on by a reduction in soil productivity as plant growth is affected by soil acidity. Between a $pH_{Ca}$ of 4.8 and 5.5, the growth of legumes is depressed; plant yields are reduced when the pH falls below 4.8 and most species are affected when the pH falls below 4.3 units (NLWRA 2001a). AACM (1995) indicated that about 35 million hectares in Australia are considered highly acidic ($pH_{Ca} < 4.8$) and another 55 million hectares have the potential to become highly acidic. In NSW 13.5 million hectares of agricultural land is highly acidic, with another 10.8 million hectares moderately acidic and slightly acidic ($pH_{Ca}$ 4.9-6.0) (AACM 1995).

When trees and other native vegetative species are cleared and replaced with pasture that is fertilized and grazed, changes occur in the hydrological cycle and nitrogen and carbon cycles (Lockwood *et al.* 2003). Pasture management, which includes sowing legumes, increases nitrogen levels in paddock soils. Total soil organic nitrogen of around 30 kg N / ha / year can be found under temperate legume-based pastures (Peoples 2004). Legumes fix atmospheric nitrogen to form plant organic nitrogen that is mineralized to ammonium and oxidized to nitrate, thus increasing the nitrate pool. With tree clearing, water that percolates through the soil profile increases. This then increases the chance of accumulated nitrate to be leached from the soil, which is acidifying. Leaching under grazed pasture can be up to ten times more than leaching under pasture that is not grazed (Williams and Hook 1998). Shallow-rooted pasture plants, which are not as efficient in taking up nitrate that is leached through the soil profile, exacerbate the problem. In addition, grazing animals have an effect on nutrient movement in the soil and can redistribute more than 60% of ingested nutrients to the soil surface in concentrated urine and dung patches (Williams and Hook 1998).

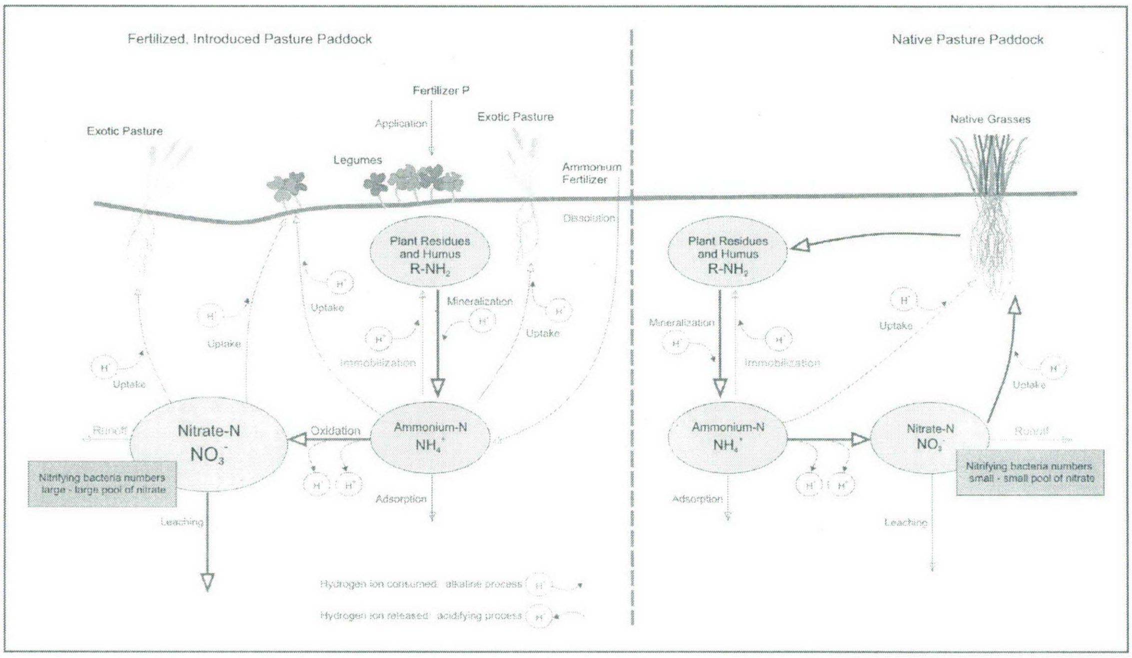

**Figure 2.3 Soil acidification pathways as a function of pasture management**

Figure 2.3 shows pathways of soil acidification processes as they relate to the nitrogen cycle for two management systems, a fertilized, introduced pasture paddock and an area of native grasses or pasture. Arrows that are bold denote the preferred pathways for each system. Oxidation of ammonium to nitrate is acidifying and two hydrogen ions are exported for every nitrate ion formed. However, if this is in conjunction with the mineralization of organic matter to ammonium and the uptake of nitrate, which each use one hydrogen ion, then the cycle is contained and no net acidification or alkalinization occurs. If ammonium fertilizer, such as ammonium sulfate, is applied, and the ammonium is oxidized to nitrate and taken up by a plant, then, in the absence of leaching, one hydrogen ion is released into the soil system for every ammonium ion added and the net result is acidifying. However, if ammonium fertilizer is applied and if nitrate leaching follows, then two hydrogen ions are released into the soil, and twice as much acidification occurs.

## 2.5 Managing Acid Soils and Soil Acidification

As stated earlier, soil acidification in pastures can cause soil degradation and production losses (Fenton *et al.* 1996), and aluminium and manganese toxicity, molybdenum, calcium and magnesium deficiencies, and decreased nitrogen fixation.

### *2.5.1 Symptoms and Diagnosis*

Soil acidity decreases plant available nutrients and can induce the dissolution and accumulation of aluminium in the soil (NLWRA 2001a). Chemical toxicity or nutrient deficiencies exhibited by plants can indicate a soil acidity problem. Impeded root growth, shallow roots and stunted plants are some of the symptoms that indicate aluminium and manganese toxicity (NLWRA 2001a; Fenton *et al.* 1996). A yellowing of leaves of clovers and other legumes can indicate molybdenum deficiency, while calcium deficiency can affect the nodulation of subterranean clover (Fenton *et al.* 1996). Emergence of acid-tolerant species such as Parramatta grass (*Sporobolus africanus*) or African lovegrass (*Eragrostis curvula*) can indicate a soil acidity problem. If left unchecked, such invasive species colonize and degrade a productive pasture. Parramatta grass and mature African lovegrass are low in nutritional value and unpalatable to stock (Land Protection 2006; Qld DPI&F 2005). Selective grazing by sheep and cattle changes the composition of the community: the more palatable species are grazed first encouraging the spread of the immigrant species until, in the worst possible case, a monoculture of the less desirable species results.

Diagnosis of an acidic soil can be made with soil testing. Tests can range from the simple field pH test that can be done in the field, to more complex laboratory analyses on soil samples taken from the affected area. Soil $pH_{Ca}$ and soil $pH_W$ are routine tests that are usually part of a suite of tests offered by a soil testing laboratory. If a soil is analysed for available phosphorus, the soil is normally tested for pH as well. For severely acidic soils, or if the soil $pH_{Ca}$ is below 4.5, aluminium is usually routinely tested (Hazelton and Murphy 1992). Soil testing of an exotic pasture paddock and an adjacent native grass paddock of the same soil type could provide information on whether the soil under the exotic pasture is slowly acidifying.

### *2.5.2 Treatment and Prevention*

A naturally acidic soil may not need amelioration if it supports a productive or palatable acid-tolerant pasture species. Treatment is advocated if a formerly productive pasture is becoming degraded and production losses are likely to occur. Acid additions should be minimized and controlled through better understanding and management of the nitrogen and carbon cycles, using plant tolerance to reduce acid effects, applying fertilizer nutrients such as molybdenum, or using liming amendments (Helyar 1991).

If a soil acidity problem is diagnosed, remedial steps could include using less-acidifying nitrogen fertilizers such as urea, anhydrous ammonia or nitrate-based fertilizers instead of ammonium fertilizers (Helyar 1991; Vimpany 1992) that are more acidifying. Nitrogen fertilizer application should coincide with, but not exceed, plant demand (Helyar 1991). Vimpany (1992) suggests that soil acidification could be reduced by minimizing water percolation and nitrate leaching below the root zone. This could be achieved by avoiding over irrigation, using deep-rooted perennial species, sowing plants to coincide with seasonal uptake of soil nitrate, minimizing inactive growth periods and incorporating stubble into fallow (Vimpany 1992). In addition, where appropriate, zero-tillage techniques should be used, and high stocking rates should be avoided (Helyar 1991).

Amelioration with lime could be useful in some circumstances. However, before the use of lime is recommended, its effectiveness in neutralizing acidification needs to be fully researched for each situation in a particular area. A full assessment of the degree and extent of acidification on a property, together with other factors such as soil buffering capacity, needs to be made. The cost of lime must also be considered and whether the benefit is worth the cost. Options such as growing more acid-tolerant perennial pasture species, planting deep-rooted perennials that will use nitrate, rotational grazing to avoid acidifying camp effects, or a combination of these options could prove more cost effective than liming and yet be just as productive.

Land-management extension techniques, such as that practised by Landcare and other agricultural and soil-management groups, can assist in improving the problem of soil acidification by communicating with land managers. Landcare is a national network of more than 4,000 community groups of people in Australia who are committed to a more sustainable use and management of natural resources (Landcare NSW 2006; LandcareOnline 2006). The

National Landcare Program in Australia has been instrumental in encouraging farmers to adopt sustainable management practices to improve productivity, profitability and the condition of natural resources (AFFA 2006). Farm managers on the NSW Northern Tablelands have been made aware of the possible problem of soil acidification through local land care groups.

Once an acid soil problem has been identified and treated, ongoing surveillance is needed to keep the problem under control. Surveillance would also be beneficial for a soil that is at risk of becoming acidic. Tools employed to assess an at-risk soil include response-surface calibration models that can be used in conjunction with lime-requirement predictions (Viscarra Rossel and McBratney 2001); models used to predict soil acidification by estimating nitrate leaching, nutrient transfer or removal and soil organic matter accumulation (de Klein *et al.* 1997) or computer models that work on proton budgets (Hochman *et al.* 1998; Verburg *et al.* 1998).

A soil acidification map is another tool that can help with awareness of a potential acidification problem, or the risk of worsening acidification. Fenton (2002) produced maps of surface and subsoil $pH_{Ca}$ and aluminium in conjunction with Landcare groups to inform farmers about their soil and educate them on better managing an acid soil. Predictive maps (Singh *et al.* 2003; Noble *et al.* 2002; Ahern *et al.* 1993; Helyar *et al.* 1990) used estimated, or actual, $pH_{BC}$ to predict the number of years it would take for a soil to reach a critical pH, for example $pH_{Ca}$ of 5.0. Singh *et al.* (2003) also produced a map that shows the predicted soil $pH_{Ca}$ for 50 years in the future.

## 2.6 Conclusion

Soil acidification is recognised as a land-degradation problem in Australia, yet the extent and distribution of acid soils in Australia is not fully understood. This lack of information includes the distribution of acid soils and severity of soil acidification on the Northern Tablelands. A general, Australia-wide, distribution was provided by the NLWRA (2001a) audit, but more specific detail at the local level is not available.

Although soil acidification processes have been well researched in parts of southern NSW and northern Victoria, the extent and severity of accelerated soil acidification on the tablelands of northern NSW are not as well understood. Differences in climate and pasture management in the north could affect the scale of acidification. Research on management-induced soil acidification on the Northern Tablelands had been undertaken (Harris and Duncan 2002; Hutchinson *et al.* 2002; Crocker and Holford 1991). However, Harris and Duncan (2002) assessed samples from only 18 paired sites over the tablelands from Tenterfield to Walcha. Although Crocker and Holford (1991) used more sites, the sites were limited to the Walcha and Armidale areas. Work by Hutchinson *et al.* (2002) was limited to one area south of Armidale.

Also on the Northern Tablelands, nitrogen and sulfur dynamics were assessed in a research project into seasonal variation on grazing land in the region (Chen *et al.* 1999). Temporal fluctuations in pH were included in a project on fluctuations in soil test phosphorus (Friesen *et al* 1985). However, a lack of knowledge still exists on the causes of soil acidification under Northern Tablelands pastures.

This review identified topics that needed research to fill the gap in knowledge on the NSW Northern Tablelands. Thus this research project was developed as a logical and important progressive step from earlier work in the region.

# 3. THE DISTRIBUTION OF ACID SOILS ON THE NORTHERN TABLELANDS OF NSW

## 3.1 The Northern Tablelands of NSW

Research for this project was undertaken on the Northern Tablelands of NSW. As part of this project, the extent and distribution of acid soils of the area were investigated. In this section, a brief description of the Northern Tablelands is presented as background information, and to provide a setting for this thesis. (See Figure 1.1 for a general map of the study area.) Geophysical features of the region and its agricultural industry are outlined, and bounds for the project are defined. In Section 3.3, a report is given on the production of a map of soil acidity on the Northern Tablelands.

### *3.1.1 Geophysical Features*

The NSW Northern Tablelands extend from Tenterfield (29°S, 151°50'E) in the north and south to Nundle (30°25'S, 151°10'E), and are bounded by an escarpment along the eastern boundary that passes through Dorrigo, and a steep erosion scarp to the west (Walker 1977). The tablelands have been described as typically gently, rolling country with shallow, open valleys and level skylines between 1 000 and 1 300 m (Walker 1977). Mountain ranges and associated peaks and gorges intersperse the plateau, increasing the altitude dimensions to between 600 m and 1 500 m. The Great Dividing Range bisects the tablelands in a north-south direction. Rivers to the west of the range form part of the Namoi, Gwydir and Macintyre river systems, which are tributaries of the Murray-Darling river system. Creeks to the east cascade over waterfalls and flow through gorges into four river systems: Richmond, Clarence, Bellinger and Macleay. In the southeast, creeks flow into the Hastings and Manning Rivers. Summers on the Northern Tablelands are usually moist and warm and winters are dry and cold. Table 3.1 provides long-term trends for rainfall and temperature for various centres in the region.

Soils of the tablelands are largely derived from basalts, granites and sedimentary rocks. Four main basalt fields are in the area: one is at the southern boundary of the region near Walcha, one runs diagonally across the centre of the tablelands from Armidale to Dorrigo, through Guyra and Glen Innes, one is in the northeast and one is in the southeast segment of the tablelands (Harrington 1977). Soils formed from basalt tend to be heavy textured with uniform to gradational profiles (McGarity 1977). Earths and texture-contrast soils derived from granite and metasediments are lighter in the surface texture. Northern Tableland soils categorized in the Australian Soil Classification system (Isbell 1996) include Dermosols, Vertosols, Ferrosols, and inter-grade Ferrosols/Dermosols derived from basalt; Kandosols, Sodosols, Chromosols, Kurosols, Tenosols and Tenosols/Kandosols/Kurosols from granite; and Yellow Kurosols, Yellow Kandosols and Yellow Chromosols from metasediments (pers.com. Dacre King 2004).

**Table 3.1 Temperature and rainfall averages for selected centres on the Northern Tablelands** (BoM 2005)

Mean Daily Maximum Temperature (°C)

| Centre/Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tenterfield | 27.2 | 26.1 | 24.7 | 21.8 | 18.0 | 14.9 | 14.4 | 15.9 | 19.4 | 22.3 | 24.8 | 26.7 | 21.4 |
| Glen Innes | 26.5 | 25.5 | 23.9 | 20.7 | 16.7 | 13.4 | 12.6 | 14.2 | 17.7 | 20.9 | 23.7 | 25.8 | 20.2 |
| Guyra | 24.6 | 23.4 | 21.8 | 18.3 | 14.1 | 11.2 | 10.3 | 12.0 | 15.5 | 18.8 | 21.5 | 24.0 | 18.0 |
| Armidale | 27.1 | 26.1 | 24.1 | 20.6 | 16.4 | 13.1 | 12.2 | 14.2 | 17.6 | 21.2 | 24.3 | 26.5 | 20.3 |
| Walcha | 25.3 | 25.2 | 23.1 | 20.2 | 15.5 | 12.8 | 11.9 | 12.7 | 16.1 | 19.9 | 22.6 | 24.6 | 19.2 |

Mean Daily Minimum Temperature (°C)

| Centre/Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tenterfield | 14.4 | 14.3 | 12.5 | 8.5 | 5.1 | 2.5 | 1.1 | 2.0 | 4.7 | 8.1 | 10.8 | 13.0 | 8.1 |
| Glen Innes | 13.2 | 13.1 | 11.5 | 7.8 | 4.5 | 1.9 | 0.5 | 1.3 | 3.9 | 7.1 | 9.7 | 12.0 | 7.2 |
| Guyra | 10.8 | 10.8 | 9.2 | 5.5 | 2.4 | 0.3 | -0.6 | 0.1 | 2.4 | 5.3 | 7.6 | 9.8 | 5.2 |
| Armidale | 13.4 | 13.3 | 11.3 | 7.5 | 3.9 | 1.6 | 0.3 | 1.1 | 3.7 | 7.0 | 9.8 | 12.2 | 7.1 |
| Walcha | 11.8 | 12.2 | 9.7 | 5.2 | 1.3 | -0.2 | -2.0 | -0.2 | 1.8 | 5.5 | 7.9 | 10.6 | 52.0 |

Mean Rainfall (mm)

| Centre/Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tenterfield | 113.7 | 95.5 | 80.4 | 47.5 | 48.6 | 50.5 | 55.4 | 43.3 | 50.9 | 77.6 | 83.2 | 104.7 | 851.4 |
| Glen Innes | 112.9 | 91.9 | 71.9 | 43.1 | 49.1 | 55.2 | 54.9 | 50.4 | 55.5 | 80.2 | 85.7 | 106.8 | 857.7 |
| Guyra | 113.0 | 92.7 | 72.3 | 48.6 | 51.7 | 61.0 | 60.0 | 54.9 | 57.2 | 81.8 | 88.1 | 99.5 | 880.9 |
| Armidale | 104.5 | 87.1 | 65.0 | 45.9 | 44.4 | 56.9 | 49.2 | 48.4 | 51.6 | 67.8 | 80.4 | 89.2 | 790.1 |
| Walcha | 103.9 | 86.3 | 63.1 | 44.8 | 46.0 | 58.6 | 54.4 | 53.4 | 56.1 | 70.7 | 80.8 | 90.0 | 808.0 |

| Centre Name | Centre No. | Latitude | Longitude | Elevation (m) | Last Record |
|---|---|---|---|---|---|
| Tenterfield | 056032 | 29.0479°S | 152.0172°E | 838 | 2004 |
| Glen Innes | 056011 | 29.7368°S | 151.7366°E | 1062 | 2004 |
| Guyra | 056016 | 30.2204°S | 151.6714°E | 1325 | 2004 |
| Armidale | 056002 | 30.5167°S | 151.6681°E | 980 | 1997 |
| Walcha | 056035 | 30.9853°S | 151.5942°E | 1050 | 1996 |

Vegetation on the Northern Tablelands is diverse and is made up of old-growth, temperate forest in protected areas such as national parks and reserves, regrowth forest, and cleared areas of both native grasses, introduced pasture grasses and intermittent crops. Land use across the region includes urban settlements, light industry and horticultural and agricultural enterprises. Horticulture includes vegetables, fruit, flowers, and more recently, vineyards. Sheep or cattle grazing are the main agricultural pursuits. This thesis focusses on soil acidity and soil acidification in grazing land of the Northern Tablelands.

### *3.1.2 Agriculture*

On the Northern Tablelands, sheep are grown for meat in areas of higher soil fertility. On low-fertile soils, superfine Merino wool production is a significant industry over the region. Beef cattle are also raised. Sheep and cattle grazing are often integrated on the same property either with sheep and cattle grazing together or in separate paddocks. The breakdown varies from 70 percent sheep and 30 percent cattle depending on commodity prices. Grazing management systems range from set stocking to intensive rotational grazing (pers.comm. Mick Duncan 2006).

Pasture improvement started in the 1940s when pastures were supplemented with legumes and amended with superphosphate. Legumes include white clover (*Trifolium repens*), red clover (*Trifolium pratense*) and subterranean clover (*Trifolium subterraneum*). Introduced grasses including ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerata*), phalaris (*Phalaris aquatica*), tall fescue (*Festuca arundinacea*), supplemented or replaced native grasses and pasture species.

### *3.1.3 Bounds of Project Defined*

The research area was contained within the Northern Tablelands area of NSW. Elevation above 700 m, longitudes of between 151.1°E and 152.6°E, latitudes between 28.9°S and 31.5°S, and an average annual rainfall of more than 600 mm were the criteria used to delimit the study area. The area was bounded in the north by Wallangarra on the NSW-Queensland border, Niangala in the south, by Dorrigo in the east and west to Inverell.

## 3.2 Mapping Acid Soils of the Northern Tablelands

The extent of soil acidity on the Northern Tablelands is poorly documented. Maps of surface soil pH for NSW (EPA 2003) and Australia (Dolling *et al.* 2001, CSIRO 2001) are available through electronic sources as detailed in Section 3.3.2. These maps are limited by scale and, as such, lack detail for the Northern Tablelands region. Small-scale soil pH maps of NSW published by Helyar *et al.* (1990) and Fenton *et al.* (1996) also lack detail. Detailed topsoil acidity maps have been produced for other regions of NSW, for example Canberra (McPherson and Jenkins 1999) or Katoomba (King 1994), but such a map has not been planned for the Northern Tablelands.

To provide a basis for this research project, the distribution and severity of acid soils across the Northern Tablelands were assessed. By defining the extent and distribution of acid soils of the region, management and extension could be more reliably informed.

### *3.2.1 Objectives*

- To estimate the extent and determine the severity of acid soils across the Northern Tablelands from available published data.
- To produce a soil pH map from these data.

### *3.2.2 Mapping Acid Soils in Australia*

Surveying the extent of soil acidification in Australia was given highest priority at a national workshop on soil acidity (Helyar 1988). Federal funding was provided for a national database, and as a result soil pH maps were produced by Helyar *et al.* (1990), Ahern *et al.* (1992) and Ahern *et al.* (1994). Other maps included those produced by Fenton *et al.* (1996), the Australian Agriculture Assessment 2001 (NLWRA 2001a), Chartres and Geeves (1992), Leech *et al.* (1998), Fenton (2002), and Singh *et al.* (2003). Summary Australia-wide maps of surface soil pH, for example Dolling *et al.* (2001), CSIRO (2001), and EPA (2003), are available through various electronic sources. Because each of these maps is limited by scale, detail at the regional level is lacking. For example, in the Australian Agricultural Assessment (NLWRA 2001a) for the Northern Tablelands area, only one soil pH category ($pH_{Ca}$ 4.8 - 5.5) or range is shown. This map was created using commercial soil test data and data from the Australian Soils Resources Information System (ASRIS). Commercial data were limited to postcode locations only; coordinates were not available because of privacy issues.

### 3.3 Soil pH Map Production

Commercial GIS software, MapInfo, was used to compile data on soil acidity of the region and to produce a general soil pH map to show the distribution of these soils. Soil pH data for the map were provided by DNR and CSIRO Land and Water. These data were supplemented by soil pH values generated from other components of this project.

#### *3.3.1 Software*

MapInfo Professional 6.5 (MapInfo Corporation 2001) GIS software was used for data entry, data storage and production of the maps.

#### *3.3.2 Data*

Digital data sets of soil properties from SALIS and NSB (CSIRO) were formatted and imported into MapInfo Professional. Data sets were in either Longitude/Latitude ADG66 or the Australian Map Grid ADG66, AMG Zone 56. These were transformed to a common grid, Longitude/Latitude ADG66, using built-in parameters within the software.

A table comprising 340 data points of the final combined data set used for the map is given in Appendix 3. The data sets were combined by transferring them to an EXCEL file. Attributes of the data points were surface soils, which ranged in depth from 0-5, 0-10 or 0-15 cm, and a soil pH value. The final data points were filtered and retrieved by sorting the data into attribute classes within EXCEL. Soil pH was listed as $pH_F$, $pH_W$ or $pH_{Ca}$. For this exercise, $pH_F$ was deemed to be equivalent to $pH_W$ (Hazelton and Murphy 1992). The following formula developed by Ahern *et al.* (1995) was used to convert $pH_F$ and $pH_W$ to $pH_{Ca}$:
$pH_{Ca} = 0.93pH_W - 0.373$ ($R_2 = 0.93$, $n = 7844$).
This method was used as it was the one prescribed by NLWRA (2001a). A later method using a spreadsheet look-up table developed by Henderson and Bui (2002) was also used and very similar results were obtained.

#### *3.3.3 Producing the Map*

Soil $pH_{Ca}$ data in digital form were overlaid against map points (latitude and longitude) on the base map within MapInfo Professional. To highlight soil pH unit value, these points were assigned a colour code according to the pH range. In each of the reviewed maps (Section 3.2.2), soil pH class subdivisions were colour coded but no uniformity was found between the maps. For the map in this report, the subdivisions and colours were based on those used by Helyar *et al.* (1990), Fenton *et al.* (1996) and Slattery *et al.* (1999) and emphasized plant growth problems that occur with soil acidity (Figure 2.1).

Point data were then interpolated and a thematic map, exhibiting shaded densities of pH ranges, was then generated within the GIS software. The interpolation method works on the principle that a point is interpolated, or "expanded", to the "boundary" of the expansion of neighbouring points. If the points are close together and uniform, the method can produce a map with high confidence levels of interpolation. However, for this map, data points were not evenly spaced so interpolation was kept to the minimum radius. Although the interpolation method does not consider soil landscape boundaries, it does show the extent and severity of acid soils on the Northern Tablelands.

## 3.4 Soil pH Map of the Northern Tablelands

A regional-scale map showing the extent and distribution of surface soil acidity of the Northern Tablelands was produced. The final map was limited by the small number of data points in the set, and this restricted the detail that could be shown. However, a visual qualitative assessment of the map does give an overview of the general location, extent and severity of acid soils in the region. Soils to the southeast tend to be more acidic than those to the west of the mapping area.

**Figure 3.1** **Soil pH$_{Ca}$ on the Northern Tablelands**
Shading effect around the edges of the mapped area was caused by an inherent software problem during image transfer and could not be resolved at the time of printing this document.

The map was produced at a scale that was appropriate to the low number of data points and lack of spatial regularity of these points. However, the map does show more detail than the published maps (CSIRO 2001; NLWRA 2001a) where only one soil pH class of 4.8-5.5 is depicted for the Northern Tablelands region.

## 3.5 Discussion

CSIRO (2001) and NLWRA (2001a) soil pH maps give the best perspective in a national context. As a subset of national and State data, the soil pH map produced here gives a better perspective for the Northern Tablelands and provides a foundation for further research. The map shows the general location, extent and severity of acid soils in the region with soils tending to be more acidic to the southeast. Approximately 72% of the mapped soils had a $pH_{Ca}$ of 5.5 or less and would be considered acidic. Of these 27% were strongly acid (4.51- 5.0 $pH_{Ca}$ units) and 35% were moderately acid (5.01-5.5 $pH_{Ca}$). Another 16% were slightly acid (5.51-6.0 $pH_{Ca}$) while only 6% were in the optimal range for plant growth ($pH_{Ca}$ 5.51-6.0). That more than 50% of soils are moderately or strongly acidic, and another 25% are at risk of becoming moderately acidic, is useful information for land mangers or extension officers. These data are considered unbiased and representative of the area as they were obtained from soil survey work as opposed to soil analyses for farmers. However, the data do not differentiate between land-management classes. To further assess the extent of soil acidification under pasture soils, a paired-site survey (Chapter 4) was undertaken.

Soil survey work on the Northern Tablelands has been an exiguous process. Many areas have not been surveyed, particularly in the National Parks. In addition, surveys have not been spatially regular or delineative of soil types or land-use. The map produced in this study was designed to be edited so that as new data points become available, they can be easily added. If data points from a survey become available, detailed, higher definition maps of surface and subsurface pH could be produced. These maps would be a valuable resource as information or decision-making tools for land managers or extension officers. With more data points, borders could be drawn subdividing 'themes' into bounded regions to create map polygons reflecting the pH for that area. The map could also be set up as an interactive tool so that information could easily be retrieved from the map window. Each polygon would be developed as a unique mapping attribute (UMA). A database could be established and, for each UMA, information such as soil type, pH range and rainfall would be recorded in the database. Hotlinks, where appropriate, would also be included so information about a specific area or UMA could be made available to anybody with access to a digital version of the map.

## 3.6 Conclusion

The soil pH map produced provides more detail than the soil pH maps of Australia (CSIRO 2001; NLWRA 2001a) and gives a better perspective for the Northern Tablelands region. The data set, and soil pH map, showed that acid soils did exist on the Northern Tablelands. Approximately 72% of the mapped soils had a $pH_{Ca}$ of 5.5 or less, with 27% strongly acid (4.51- 5.0 $pH_{Ca}$ units) and 35% were moderately acid (5.01-5.5 $pH_{Ca}$).

A question that was raised was whether these soils became acidic through natural or induced soil acidification processes. Alternatively, were the soils naturally acidic to begin with and made more acidic through land-management practices? In the next chapter (Chapter 4), the impact of pasture management on soil acidification and extent of acid soils under such improved pastures are examined. Here, a paired-site survey compares relatively natural areas with grazed, fertilized, sown pasture paddocks.