CSIRO Publishing

Australian *Journal* of Soil Research

VOLUME 40, 2002

An international journal for the publication of original research into all aspects of soil science

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Aust. J. Soil Res., 2002, **40**, 257–267

Risk mapping of soil acidification under *Stylosanthes* in northern Australian rangelands

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Abstract

The inclusion of *Stylosanthes* into pastures and cropping systems has proved to be a low cost method of improving product quality in Asia, Africa, South America, and northern Australia. However, there is recent evidence that accelerated soil acidification has occurred under these production systems, questioning their long-term sustainability. In an effort to assist producers and extension officers in identifying soils that are predisposed to accelerated acidification, an acidity risk map of the Dalrymple Shire in Queensland, Australia, was developed using information from a recently completed land resource survey. Validation of a previously derived pedotransfer function that predicts pH buffering capacity was undertaken using an independent set of soil samples collected from the Shire. Excellent agreement between measured and predicted pH buffering capacity was obtained. The pedotransfer function was used to estimate the pH buffering capacity of 44 soil associations in the Shire. These values were used to predict the number of years that it would take for soils to acidify from their current pH to 5.0 assuming a constant net acid addition rate of 2.1 kmol H^+/ha.year. Approximately 62% of the total area of the Shire is predisposed to accelerated acidification and would take between 10–20 years to acidify to pH 5.0. In contrast, a relatively minor proportion of the total area of the Shire (17%) had significant internal buffering capacity. However, the degree of uncertainty associated with these estimations on certain soil associations may be too high to be of relevance. In order to overcome this limitation a field test designed to assess the risk of accelerated acidification on a paddock basis is proposed and outlined in the paper.

Additional keywords: pH, buffer capacity, pedotransfer function.

Introduction

The inclusion of the *Stylosanthes* (stylos) has proved to be a low cost method of improving the quality of native pasture and legume-based cropping systems in Asia, Africa, South America, and northern Australia (Miller *et al.* 1988, 1991). This is due to the adaptability of the species to inherently infertile soils and climatic conditions ranging from the wet to the semi-arid tropics. Moreover, they have the potential to be more widely grown in the subtropics and tropics than those of any other genus currently being evaluated. Under the moderate to low rainfall regimes of northern Australia and south-east Asia, cultivars of *S. hamata* and *S. scabra* have been successfully established in agropastoral and seed production systems, as well as intercropped in plantations of rubber and coconuts and in some annual cropping systems. Indeed such has been the success of stylos that they form an integral component in the production of beef, poultry, and pig industries in Australia and south-east Asia and in the reclamation of 'wastelands' in India (Michalk *et al.* 1993; Pinstrup-Andersen and Pandya-Lorch 1994; Jayan 1995; Liu Goudoa *et al.* 1997).

Soil acidification is a naturally occurring phenomenon and is a result of long-term weathering and the leaching of exchangeable cations out of the soil horizon or profile. However, accelerated soil acidification in agricultural production systems is a consequence of increased product removal, the use of nitrogenous fertilisers, and changes in the carbon and nitrogen cycles associated with legume introduction (Helyar and Porter 1989). Whilst

 10.1071/SR01018 0004-9573/02/020257

use of leguminous plants to increase the fertility of farming systems is a fundamental practice in agricultural production systems throughout the world, the long-term negative impact of these production systems with respect to accelerated soil acidification has been well recognised (Haynes 1983; Helyar and Porter 1989; Moody and Aitken 1997). In many agricultural production systems the inclusion of legumes in crop rotations is a corner stone of arable-crop farming systems. In general, these production systems could be classified as sustainable if there are external inputs of fertiliser and liming materials at some phase in the rotation. However, there is considerable evidence to show that under permanent legume/pasture systems in south-east Asia and Australia there has been a gradual decline in soil pH (Chartres *et al.* 1990; Noble 1998; Noble *et al.* 1998).

Evidence from a series of surveys across northern Australia and south-east Asia (Noble *et al.* 1997, 1999) of legume-based pasture systems has shown that significant accelerated acidification has occurred on light-textured low fertility soils with a low inherent buffering capacity. Under these environments *Stylosanthes* becomes the dominant species in the sward resulting in a significant decline in the grass component. In these extensive low input production systems, applications of liming materials are not economically viable, and therefore alternative strategies are required (Middleton and Noble 1998). Thus the introduction of *Stylosanthes* in a pasture production system is a potential hazard, the consequence of which is acidification.

This study focuses on the role of soil survey information in the identification of areas at risk of accelerated soil acidification associated with *Stylosanthes* dominance. This would assist land and resource managers in the processes of decision-making associated with the establishment of *Stylosanthes* pasture systems on an extensive basis. The Dalrymple Shire in north Queensland was selected as the target area for the development of a surface soil acidity risk map. This selection was based on the existence of a recently completed comprehensive land resource assessment of the Shire (Rogers *et al.* 1999). In order to develop a risk map, an estimate of a soil's ability to resist shifts in soil pH had to be undertaken. In a previous survey of *Stylosanthes*-based pasture systems across northern Australia, Noble *et al.* (1997) developed several pedotransfer functions to predict soil pH buffering capacity. These functions were based on intrinsic characteristics of the soil, namely soil organic carbon, clay, and silt content. However, no validation of these functions was undertaken using an independent set of samples. Consequently, the first stage of this exercise was to validate the pedotransfer function developed for surface soils on a range of dominant soils in the Dalrymple Shire. The second stage was the production of a risk map for the Shire, and finally, the development of a field-based toolkit that could be used by producers and extension personnel to determine a soils predisposition to accelerated soil acidification.

Methodology

Study area

The Dalrymple Shire occupies 68 000 km^2 in north Queensland, roughly corresponding with the upper Burdekin River catchment. Average annual rainfall ranges from 500 to 1600 mm, with 80% occurring between November and April (De Corte *et al.* 1994). Although potential evoptranspiration is high (2000–2500 mm/year), the concentration of rain over a 5–6 month period leads to the filling of the soil profile and localised water logging every 3 years on average (Coventry and Williams 1984). The landscape over most of the Shire is characterised by level to undulating plains with long slopes and low gradients. Mesas, low range plateaus, and valleys constitute the major relief elements. Soils in the region exhibit a complex pattern, but generally, parent material and geomorphic history are the dominant factors controlling the character and distribution of soils (Isbell and Murtha 1970; Bui *et al.* 1996). The most common catena consists of red and yellow earths on uplands, sodic and related soils with abrupt textural contrast on the intermediate slopes, and cracking clay soils, often sodic in nature, with gilgai micro-relief in the lower portions (Bui *et al.* 1996). The proportions of broad soil groups have been reported by Rogers *et al.* (1999) as follows:

> Sandy surfaced soils (sands to sandy loams) cover 45% of the Shire, with uniform sandy soils covering 21%, gradational sandy soils 6%, and texture contrast soils occurring over 18% of the Shire. Loamy surface soil (sandy clay loams to clay loams) cover 44% of the Shire, with uniform loamy soils covering 1%, gradational loamy soils 22%, and texture contrast soils occurring on 21% of the Shire. Clay soils cover 9% of the Shire, with massive surface soils covering 1%, structured (blocky) 2.5%, and self-mulching clays occurring on 5.5% of the Shire. Rock outcrop (Basalt flow lines and sandstone outcrops) occupy 1% while <1% of the Shire is flooded by natural or man-made lakes.

More than 90% of the Shire is used for extensive beef production with most properties being between 10 000 and 50 000 ha (Rogers *et al.* 1999). The Dalrymple Shire land resource map, at a scale of 1 : 250 000, provides soil information at a higher resolution than previously available (i.e. pH of surface soils 1 : 5 000 000 Ahern *et al.* 1994). This map was used as the basis of the risk map.

Validation of pedotransfer function

Validation of the surface soil pedotransfer function of Noble *et al.* (1997) was undertaken on a independent set of 27 surface A horizon soils of variable depth collected from the Dalrymple Shire and archived at CSIRO Townsville laboratory (Table 1). The samples included the major soil series within the Shire as determined in the land resource survey of Rogers *et al.* (1999). The pedotransfer function for the 0–20 cm depth interval (Noble *et al.* 1997) is:

$$pH_{BC} = 6.28 - 0.11\times clay\% + 3.71\times OC\% - 0.16\times silt\% + 0.03\times silt\%\times clay\% \quad (n = 50) \qquad (1)$$

$$r^2 = 0.844$$

where pH_{BC} is the pH buffering capacity (mmol H^+/kg.pH unit); and clay, silt, and organic carbon (OC) are the percentage of each of these variables in the soil. The pH buffering capacity (pH_{BC}) measurements were made on each sample using the method of Aitken and Moody (1994). In brief, titration curves were established by adding incremental amounts of HCl to soil suspended (1 : 5) in water. For each titration 5 g of soil was weighed into each of 6 polyethylene tubes and appropriate amounts of deionised water were added such that the final volume was 25 mL. The acid solution was 0.04 M (standardised), and for each soil, additions of 0, 0.15, 0.25, 0.5, 1.0, and 2.0 mL were made. Additions of 1.0 mL of 0.05 M $CaCl_2$ were made to each tube to minimise variations in ionic strength as well as 0.25 mL of chloroform and the suspensions were equilibrated for 24 h at 25°C on an end-over-end shaker. The suspensions were then removed from the shaker and left to equilibrate for a further 6 days at 25°C. Re-suspension of the samples was undertaken on a daily basis by shaking for a 2-min period. After a total of 7 days the pH was measured and pH buffer capacity calculated from the inverse of the slope for the plot of pH versus acid added. Soil organic carbon was determined by the Walkley-Black method (Rayment and Higginson 1992) and particle size as described by Coventry and Fett (1979).

Development of acidity risk map

The rate at which a soil acidifies in a *Stylosanthes*-based pasture system is a function of the percentage of legume in the pasture. Previous measurements of accelerated acidification have shown significantly higher rates under *Stylosanthes*-dominant pasture when compared with those exhibiting an equal proportion of both grass and legume (Noble *et al.* 1997). There are numerous factors that influence species dominance in a sward. In the case of *Stylosanthes* it has been suggested that it is a function of management (intensity of grazing and fire), rainfall, inherent soil chemical properties (i.e. pH buffering capacity and soil P content), and the productivity of the pasture (Partridge *et al.* 1996).

In the development of an acidity risk map for the Dalrymple Shire, it was assumed that the establishment of *Stylosanthes*-based pastures was confined to areas within the Shire with an average annual precipitation of ≥500 mm. Using the aforementioned pedotransfer function, pH buffering capacities were assigned to selected soil associations that had been identified within the Dalrymple Shire resource assessment survey that is based on the 1 : 250 000 soil map of Rogers *et al.* (1999). A total of 44 soil associations out of 57 had laboratory data sets that allowed for the calculation of pH buffering capacity using Eqn 1 (Table 2). Using a modification of the model proposed by Helyar and Porter (1989) the following equation was used to calculate the time (T) in years for the pH of the surface soil to drop from its current pH to a pH of 5.0:

Table 1. Selected soil chemical and physical properties of surface soil samples (A horizon) used in the validation studies

T Series No.	Depth (cm)	% of Shire	Clay	Silt (%)	OC[A]	pH_w	pH buffer capacity Predicted (mmol H^+/kg.pH unit)	Measured
8	0–4	4.86	15	11	0.86	6.4	11.01	13.70
47	0–10	2.38	72	15	1.06	6.8	32.29	28.02
59	0–10	0.89	9	9	0.49	6.1	8.10	10.03
80	0–10	0.89	24	12	10.30	5.5	48.57	53.52
99	0–10	5.91	21	7	0.54	6.0	9.26	12.47
145	0–10	5.91	13	6	0.35	6.1	7.53	8.99
152	0–5	5.91	5	6	0.50	6.7	7.53	8.08
163	0–10	2.92	31	30	2.57	6.5	35.50	37.88
168	0–10	2.92	42	23	1.60	6.4	32.90	27.64
173	0–10	2.92	38	29	2.01	6.7	37.98	35.21
331	0–10	5.89	22	10	1.00	6.5	12.57	13.25
335	0–10	5.89	14	5	0.53	6.0	8.01	11.25
339	0–10	5.91	16	11	1.08	6.0	12.05	16.36
340	0–10	0.37	16	7	0.64	6.5	9.13	13.98
503	0–10	4.69	7	6	1.00	6.39	9.52	9.67
507	0–10	1.10	6	7	0.60	6.32	7.99	10.37
521	0–10	2.44	3	3	1.30	6.04	10.56	15.63
528	0–10	0.72	27	16	0.70	8.29	16.31	10.01
533	0–10	2.48	21	20	1.00	5.63	17.08	17.48
534	0–10	2.37	17	14	0.70	5.89	11.91	13.17
536	0–10	2.48	14	20	1.80	5.88	16.62	14.63
542	0–10	0.65	35	13	0.60	6.91	16.23	13.10
545	0–10	3.17	2	1	0.20	5.56	6.70	7.71
575	0–3	1.01	43	17	0.48	7.5	22.54	14.37
579	0–2	4.04	32	36	2.50	6.7	40.84	33.97
580	0–10	2.92	36	23	1.70	6.6	29.79	32.49
583	0–8	0.18	24	9	0.81	8.2	11.69	16.48

[A]Organic C content.

$$T = [(pH_i - 5.0) \times pHBC \times BD \times V]/NAAR \quad (2)$$

where T is time in years; pH_i is the current measured soil pH; pHBC is mean pH buffering capacity of the soil association (kmol H^+/kg.pH); BD is the mean soil bulk density calculated for each soil association using the method of Rawls (1983); V is volume of soil in the 0–15 cm depth interval; and NAAR is net acid addition rate (kmol H^+/ha.year), which was assumed to be 2.1 kmol H^+/ha.year based on pastures that are stylo-dominant (>80% stylo) (Noble *et al.* 1997).

Development of a field-based toolkit

In an effort to develop a simple method of determining the pH buffer capacity of soils in the Dalrymple Shire on a paddock point scale, pH buffer capacity was estimated using a 2-point pH method. Soils used in this study were the same as those previously described in the validation test. Soil (5 g) was weighed into each of 2 polyethylene tubes. Distilled water was added to the tubes: 24 mL to the first and 23.5 mL to the second. 0.5 mL of 0.04 M HCl was added to the second tube and 1.0 mL of 0.05 M $CaCl_2$ was added to both tubes. Each tube was shaken manually for approximately 30 s before being left to stand. pH measurements were undertaken at 1, 2, 4, 6, and 24 h. Prior to pH measurements, tubes were manually shaken for approximately 30 s. pH buffer capacity was calculated as follows:

$$\text{pH buffer capacity (mmol } H^+\text{/kg.pH unit)} = 1/\{(pH_c - pH_a)/C_a\} \quad (3)$$

where pH_c and pH_a are the pH values for the control and acid addition treatments respectively; C_a is the amount of acid added (mmol/kg) to the soil; this is a constant (40 mmol H^+/kg).

Table 2. Soil associations of the Dalrymple Shire used in the construction an acidity risk map for the region

Values represent the means of surface horizons ± s.e.

Soil association	Depth (cm)	pH_w	P^A (mg/kg)	OC	Silt (%)	Clay	Time to reach pH 5.0 (years)	pH buffer capacity^B (mmol H^+/kg.pH unit)
Amity	0–10	7.20 ± 0.68	24.9 ± 29.1	1.40 ± 0.26	19.0 ± 10.3	43.6 ± 18.0	59.6 ± 28.1	28.5 ± 21.4
Bluff	0–10	6.48 ± 0.50	5.31 ± 3.82	1.02 ± 0.64	12.6 ± 6.6	11.1 ± 4.6	16.6 ± 5.4	11.0 ± 4.8
Boston	0–4	6.02 ± 0.57	3.72 ± 2.61	0.57 ± 0.19	7.1 ± 2.5	14.0 ± 4.8	9.8 ± 4.8	8.7 ± 1.9
Burra	0–10	6.13 ±.0.65	2.47 ± 1.77	0.66 ± 0.20	6.2 ± 1.8	9.8 ± 3.5	10.1 ± 5.1	8.5 ± 1.2
Burdekin	0–10	6.46 ± 0.52	23.63 ± 16.46	0.60	7.0	6.0	12.7	7.9
Conjuboy	0–10	6.50 ± 0.44	80.02 ± 60.85	1.84 ± 0.34	24.3 ± 5.7	37.8 ± 3.9	44.0 ± 15.2	32.7 ± 9.3
Ceaser	0–8	6.59 ± 0.84	8.92 ± 6.74	0.83	12.0	8.0	15.5	9.4
Carse O'Gowrie	0–5	6.50 ± 0.72	4.78 ± 6.65	0.98 ± 0.96	6.0 ± 4.0	4.6 ± 1.5	13.9 ± 7.4	9.3 ± 3.6
Creek	0–25	6.42 ± 0.42	6.93 ± 7.57	0.16	2.0	3.0	9.6	6.4
Conolly	0–15	6.48 ± 0.65	8.66 ± 9.88	1.00	6.5 ± 0.7	6.5 ± 0.7	14.2	9.5
Cape	0–10	6.52 ± 0.61	15.35 ± 17.42	2.05 ± 0.35	29.5 ± 13.4	21.5 ± 10.6	34.4 ± 11.4	25.8 ± 16.2
Corea	0–8	6.24 ± 0.54	2.70 ± 2.59	0.61 ± 0.33	7.6 ± 3.3	11.3 ± 4.7	11.5 ± 4.5	8.6 ± 2.4
Charters Towers	0–10	6.81 ± 0.52	5.44 ± 3.74	1.07 ± 0.46	7.1 ± 2.1	16.0 ± 5.3	20.3 ± 6.5	10.7 ± 2.9
Dalrymple	0–10	6.63 ± 0.47	6.70 ± 3.24	0.95 ± 0.28	10.2 ± 2.8	15.7 ± 8.4	19.1 ± 5.4	11.2 ± 3.6
Dotswood	0–10	6.30 ± 0.44	11.93 ± 18.76	0.66 ± 0.35	20.0 ± 9.8	11.5 ± 0.7	15.3 ± 4.2	11.1 ± 3.4
Egera	0–17	8.01 ± 0.80	2.60 ± 1.18	0.86 ± 0.33	15.5 ± 0.7	49.0 ± 12.7	70.9 ± 23.2	24.3 ± 6.7
Fanning River	0–10	6.35 ± 0.70	19.36 ± 14.72	0.80 ± 0.14	7.6 ± 2.0	11.6 ± 4.7	13.3 ± 6.0	9.4 ± 1.4
Felspar	0–10	6.76 ± 0.27	85.77 ± 95.87	1.75 ± 0.44	25.8 ± 3.1	45.6 ± 7.8	58.6 ± 19.1	38.9 ± 10.6
Glencoe	0–11	6.66 ± 0.55	62.10 ± 55.01	1.80	34.0	46.0	69.0	49.3
Greenvale	0–10	6.35 ± 0.57	8.50 ± 13.24	0.76 ± 0.40	10.3 ± 1.1	9.0 ± 2.6	13.0 ± 4.9	9.2 ± 2.1
Hillgrove	0–10	6.65 ± 0.27	74.86 ± 90.10	1.49 ± 0.69	33.3 ± 3.0	40.0 ± 7.0	59.9 ± 14.8	42.0 ± 11.9
Lolworth	0–10	6.76 ± 0.41	10.64 ± 11.98	1.68 ± 0.87	17.0 ± 2.8	64.5 ± 10.6	53.2 ± 19.5	35.5 ± 12.5
Liontown	0–10	6.29 ± 0.51	3.54 ± 1.95	0.61 ± 0.31	8.0 ± 4.8	11.5 ± 7.6	12.0 ± 4.4	8.7 ± 3.1
Maryvale	0–10	7.94 ± 0.62	6.72 ± 4.72	0.49 ± 0.02	15.5 ± 2.1	55.5 ± 17.6	72.2 ± 27.2	25.3 ± 9.5
Mingela	0–10	6.53 ± 0.63	3.38 ± 1.07	0.36 ± 0.15	7.6 ± 2.5	10.3 ± 2.5	13.0 ± 4.8	7.6 ± 1.2
Manoa	0–10	5.89 ± 0.61	23.00 ± 14.14	1.43 ± 0.58	22.6 ± 2.5	41.3 ± 17.6	25.5 ± 16.1	31.5 ± 14.9
Mount Ravenswood	0–14	7.41 ± 0.69	4.44 ± 1.71	0.95 ± 0.20	10.0 ± 1.0	29.6 ± 8.9	34.8 ± 10.8	13.8 ± 3.1
Nosnillor	0–10	6.38 ± 0.70	4.27 ± 2.50	0.70 ± 0.62	4.0 ± 3.5	9.2 ± 5.6	12.4 ± 6.6	8.3 ± 2.8
Pandanus	0–12	6.75 ± 0.47	6.46 ± 4.38	0.45	4.0	7.0	13.5	7.3
Pentland	0–10	6.09 ± 0.55	4.45 ± 2.27	0.91 ± 0.45	7.5 ± 3.1	15.8 ± 6.8	11.8 ± 5.6	10.2 ± 3.4
Pallamana	0–10	6.09 ± 0.61	5.27 ± 7.21	0.54 ± 0.23	5.6 ± 2.3	9.4 ± 5.3	9.0 ± 4.7	7.9 ± 1.4
Paynes	0–5	5.99 ± 0.26	7.60 ± 8.35	1.80	5.0 ± 0.0	8.0 ± 2.8	11.0	12.4
Powlathanga	0–10	6.79 ± 0.83	5.32 ± 3.07	0.84 ± 0.29	17.0 ± 6.4	31.2 ± 4.3	35.1 ± 16.0	19.1 ± 7.8
Rangeview	0–4	6.29 ± 0.56	18.57 ± 20.01	2.30 ± 0.42	17.5 ± 2.1	22.0 ± 5.6	24.3 ± 9.6	21.1 ± 4.9
Rishton	0–10	6.51 ± 0.60	3.61 ± 2.23	0.20	1.0	2.0	10.8	6.7
Rangeside	0–9	6.08 ± 0.67	4.30 ± 3.58	1.11 ± 0.35	5.5 ± 3.0	14.5 ± 8.9	11.5 ± 6.6	10.3 ± 2.6
Scartwater	0–10	6.06 ± 0.45	6.86 ± 2.53	1.23 ± 0.62	11.0 ± 3.9	15.2 ± 4.7	13.2 ± 5.4	12.4 ± 4.5
Two Creek	0–14	6.43 ± 0.79	12.36 ± 11.66	1.05 ± 0.64	10.6 ± 5.5	10.0 ± 7.0	15.4 ± 7.9	10.5 ± 4.6
Tuckers	0–10	6.12 ± 0.94	8.10 ± 7.62	3.93 ± 3.49	11.2 ± 4.2	27.2 ± 4.9	21.4 ± 18.8	25.2 ± 16.8
Victoria Downs	0–5	7.11 ± 0.75	7.96 ± 6.36	1.36 ± 0.45	15.6 ± 1.1	43.0 ± 14.0	48.8 ± 19.9	24.2 ± 8.0
Wambiana	0–10	6.42 ± 0.61	3.30 ± 3.20	0.50	19.0	45.0	36.6	25.7
Wattle Vale	0–10	6.25 ± 0.60	4.08 ± 4.90	0.83 ± 0.83	7.1 ± 6.1	10.0 ± 5.6	12.0 ± 6.2	9.2 ± 4.5
Yarraman	0–10	7.09 ± 0.92	14.62 ± 7.48	1.36 ± 0.47	17.6 ± 4.0	48.3 ± 10.2	54.7 ± 28.2	28.8 ± 11.2

[A]Bicarbonate-extractable P (Colwell 1963).

[B]pH buffer capacity calculated using the following relationship: $pH_{BC} = 6.28 - 0.11\times clay\% + 3.71\times OC\% - 0.16\times silt\% + 0.03\times silt\%\times clay\%$.

Results

Validation of pedotransfer function

Selected soil properties of the archival soils used in the validation process are presented in Table 1. Within the set of samples, clay and organic carbon contents ranged from 2 to 72% and 0.2 to 10.3%, respectively, thereby giving an adequate range of these 2 parameters to test the pedotransfer function. The previously derived pedotransfer function uses clay, silt and organic carbon content to predict pH buffering capacity (see Eqn 1). A highly significant linear regression [predicted pH buffer capacity (mmol H^+/kg.pH unit) = 0.977(±0.034) measured pH; n = 27, r^2 = 0.885] was observed between measured and predicted pH buffering with no significant deviation of the slope from the 1 : 1 line (Fig. 1). This clearly indicates that the previously developed pedotransfer function is effective in predicting pH buffering capacity for the suite of surface soils used in this study.

Development of acidity risk map

In the initial conceptualisation of acidification risk, it was assumed that low soil P status is a factor contributing to *Stylosanthes* dominance in pastures systems. Consequently, soil P status could be used as a variable in differentiating between soils with respect to vulnerability *Stylosanthes* dominance. However, variability in soil P was so high (Table 2) at this scale it was not considered to be a meaningful parameter in delineating risk of *Stylosanthes* dominance. Using pH buffering capacity, a map of the Shire was produced at a 1 : 250 000 scale indicating the potential risk of acidification (Fig. 2). This map is based on the number of years required to reach a pH of 5.0 in water and a net annual input of

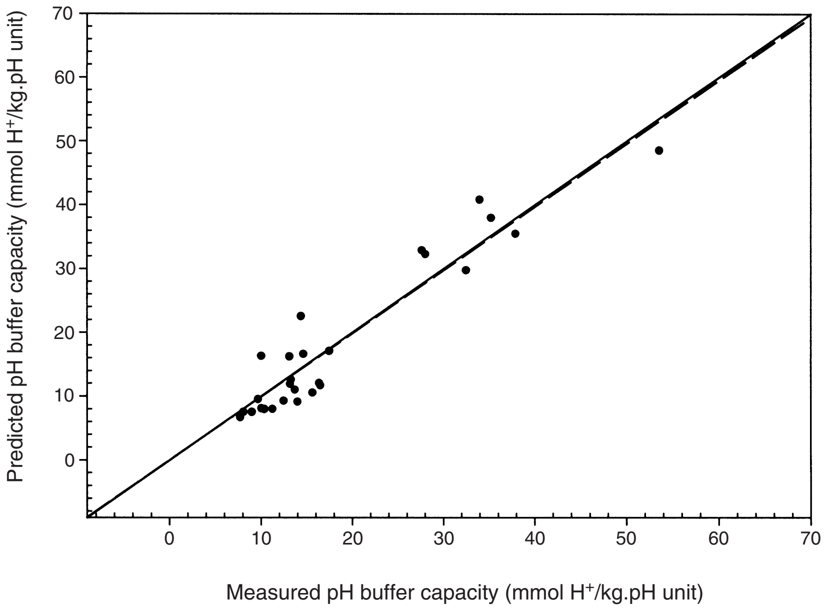

Fig. 1. Validation of predicted pH buffering capacity against measured values for 27 surface soil samples (A horizon) from the Dalrymple Shire. Equation for the solid line forcing the intercept through zero is: $y = 0.978(\pm 0.035)x$; $r^2 = 0.885$; $n = 27$. Dashed line is the 1 : 1 line.

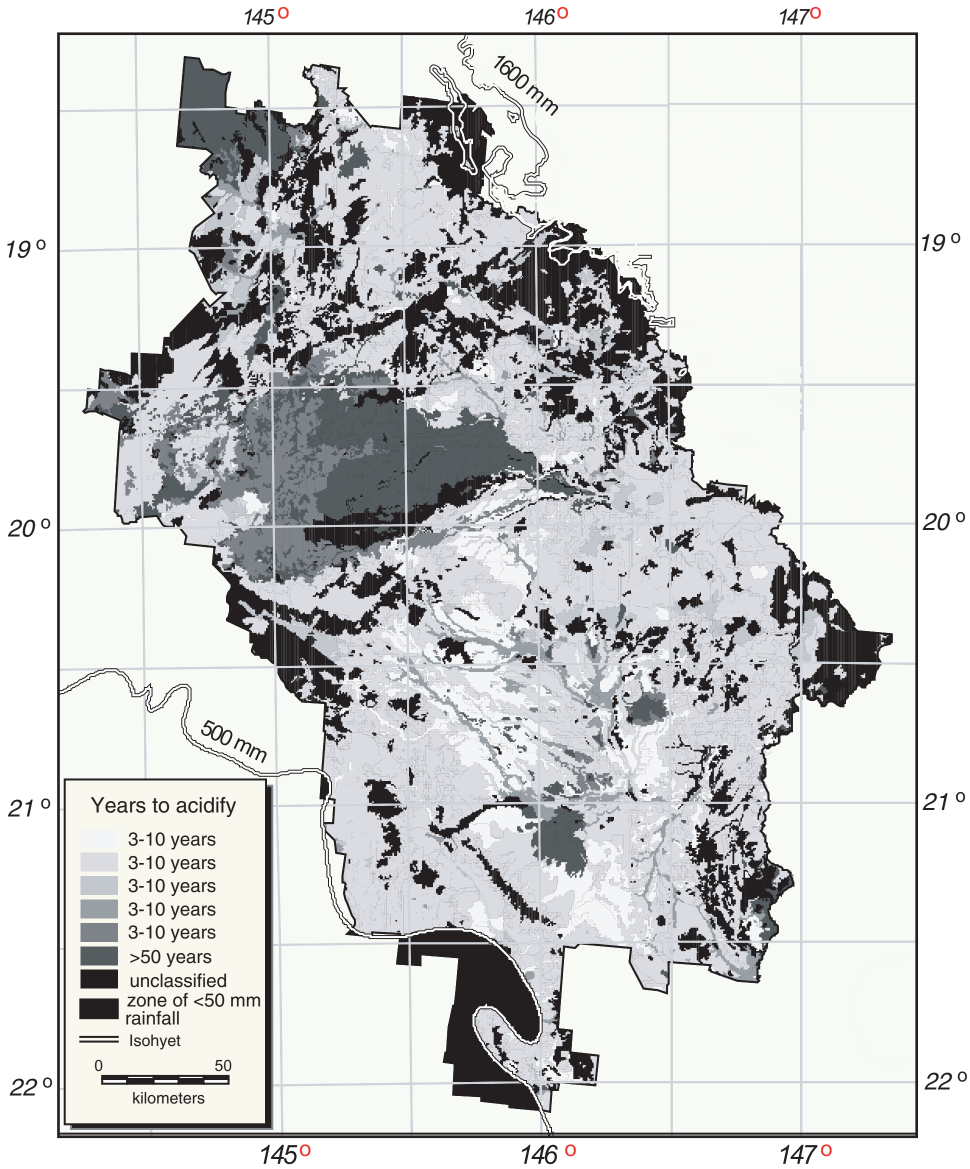

Fig. 2. Acidification risk map for the Dalrymple Shire based on the time required for the soil pH to decline to 5.0. The grids show latitude (°S) and longitude (°E).

2.1 kmol H^+/ha.year. It should be noted that time taken to reach this pH is dependent on the pH buffer capacity, NAAR, soil bulk density, and the initial pH. Therefore, alterations to any of these parameters will influence the time to reach some critical pH.

Development of a field assessment of risk

In order to use the previously discussed pedotransfer function, soil properties of clay, silt, and organic carbon content are required to predict pH buffering capacity. In general, these measured soil properties are not available at a paddock scale where the assessment of risk is most desirable from a management perspective. Therefore, a quick and simple method of estimating soil pH buffering capacity is required to be of relevance at a property/paddock scale.

The results of the different equilibration times associated with the determination of pH buffer capacity using 2 points are presented in Table 3. The estimated pH buffering capacity based on differing equilibration times (1–24 h) was regressed against values measured after a 7-day equilibration period. With increasing time the relationship between the aforementioned methods improved, with the slope of the regression curves decreasing from 4.031 after 1 h to 1.634 after 24 h. From a practical perspective an equilibration of time of 6 h or greater was deemed to be satisfactory in the estimation of pH buffering capacity. Substituting the estimated pH buffering capacity calculated for the (i.e. 6 or 24 h) equilibration period, the pH buffer capacity associated with a 7-day equilibration period could then be predicted and this value substituted along with the measured soil pH into Eqn 3.

Discussion

Based on the data of Gramshaw and Walker (1988) it is estimated that approximately 1 Mha of native pastures have been over-sown to *Stylosanthes* in Queensland. The effect of stylo in these native pastures has been to enhance animal performance and, in some cases, increase the carrying capacities of certain pastures. Based on the data of Miller *et al.* (1997) and current beef prices, this translates into a contribution of around $20–25 million annually to the beef industry (Noble *et al.* 2001). However, increased use of stylos with accompanying management practices, such as intensive seed/fodder production (with the associated export of plant material), has resulted in accelerated soil acidification and nutrient depletion (Noble *et al.* 1997, 1999). In addition, there is clear evidence to suggest that with declining soil pH, the productivity of both native and introduced grass species declines (Noble *et al.* 2001). Consequently, the long-term impact of accelerated acidification associated with stylos may be significant both from an economic and biological perspective. Due to the extensive nature of these production systems, remediation by liming is extremely costly and impractical (Noble *et al.* 1997, 1999; Moody and Aitken 1997).

The map in Fig. 2 clearly shows that a high percentage (62% to acidify to pH 5.0 in 10–20 years) of the Shire has soils that are predisposed to soil acidification. The reason is that a significant proportion of the southern region of the Shire is dominated by light-textured surface soils that have a low internal capacity to buffer acid additions. In contrast, the basalt-derived soils that predominate in the central northern region of the Shire and the

Table 3. Relationship between pH buffering capacity (mmol H^+/kg.pH unit) as estimated using a short-term equilibration period (x) with that measured after 7 days (y)

Equilibration time (h)	Equation	R^2
1	$y = 4.031(\pm 0.705)x - 5.423(\pm 5.495)$	0.671
2	$y = 3.459(\pm 0.417)x - 6.225(\pm 3.948)$	0.811
4	$y = 2.562(\pm 0.239)x - 3.463(\pm 2.561)$	0.814
6	$y = 2.203(\pm 0.196)x - 2.337(\pm 2.359)$	0.829
24	$y = 1.634(\pm 0.140)x + 0.159(\pm 2.109)$	0.841

scattered isolated pockets of Vertosols that occur throughout Shire have considerably higher internal buffering capacities and hence would take longer to acidify (>50 years). It should be borne in mind that the absolute values that are presented in the map and Table 2 should be treated with caution since we have assumed a constant rate of acid addition and have not taken into account management factors that may influence the rate of acidification. In addition, there is a high degree of uncertainty associated with some of the estimated values for particular soil associations (Table 2). It is quite feasible that rates of acidification will decline as decreases in soil pH reduce nitrogen fixation by the legume component. In addition, pasture species composition may change due to elevated nitrogen levels in the soil, thereby influencing rates of acid addition (Coates *et al.* 1997). All of these parameters would influence the time taken to reach some predetermined value. Notwithstanding this, the map clearly indicates areas within the Shire that are most sensitive to accelerated soil acidification and therefore could be used in broad decision-making by land managers. For example, by differentiating soils that are predisposed to accelerated acidification, a manager may strategically establish *Stylosanthes* in areas where the soils have the capacity to buffer acid inputs. In contrast, in areas of soils with low buffering capacity, managers, aware of the risk of accelerated acidification, can implement management strategies that minimise the risk of *Stylosanthes* dominance (Middleton and Noble 1998). These may include:

(1) Avoidance of excessive grazing pressure, particularly in summer, on native pasture that has been oversown with *Stylosanthes*. Selective and heavy grazing of palatable grasses like black speargrass (*Heteropogon contortus*) will weaken them and reduce their seed production. Over time this can lead to *Stylosanthes* dominance and the ingress of less palatable grasses. Rotational summer spelling is recommended for *Stylosanthes*-based pasture.
(2) Use of periodic early summer burning of native pasture with dense *Stylosanthes* so as to reduce *Stylosanthes* populations and promote grass.
(3) Including a 'grazing resilient' grass at the time of *Stylosanthes* planting. Grasses like *Urochloa mosambicensis* and *Bothriochloa pertusa* compete strongly with *Stylosanthes* and can tolerate a heavy grazing pressure when needed.
(4) Use of phosphorus fertiliser (or a high fertility soil) to promote greater grass competition and use of nitrate before leaching, a significant contributor to acidification.
(5) Intensive management of *Stylosanthes* as a fodder crop on small areas may assist in reducing the risk of widespread acidification on individual properties. This would result in maximum productivity being achieved and allow for prophylactic applications of lime to be applied. Such systems are being used in southern China (Liu Goudoa *et al.* 1997).

Whilst it may be argued that the mapping exercise is at a scale too coarse to be of value to the producer who manages a property at the paddock scale, the development of a simple test based on the development of a 2-point buffer curve may assist in assessing risk at this scale. All that is required is a pH meter and 2 reagents (namely, HCl and $CaCl_2$). A simple spreadsheet program has been developed that allows the operator to enter the 2 pH measurements and alter the bulk density of the soil and net acid addition rate, which is dependent on the degree of stylo dominance.

Conclusion

An acidification risk map was produced for the Dalrymple Shire in north Queensland. For the majority of regions throughout northern Australia, soil resource information is not at an appropriate scale for determining acidification risk. A simple equilibration test is proposed and a computer-spreadsheet program has been developed to estimate the time taken to reach some predetermined pH level. Whilst accelerated soil acidification under *Stylosanthes*-based pasture systems is a potential risk to long-term sustainability, knowledge of the risk, coupled with appropriate management strategies, could minimise acidification rates.

Acknowledgments

This study was generously supported by the Meat and Livestock Australia. We acknowledge the assistance of Mr M. Hodgen in the production of the risk map and Ms S. Berthelsen and Mr A. Davidson for laboratory analysis.

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Manuscript received 9 February 2001, accepted 13 July 2001