

MANAGING PHOSPHORUS IN INTENSIVE PASTURE SOILS TO IMPROVE THE LONG-TERM ENVIRONMENTAL SUSTAINABILITY OF THE DAIRY INDUSTRY

Jessica Rose Coad (BAgrSc Hons)

School of Agricultural Science



**UNIVERSITY
OF TASMANIA**

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THESIS COMMITTEE

Primary supervisor:

Dr Leigh Sparrow

Senior Research Fellow in Soil Science

Tasmanian Institute of Agriculture, University of Tasmania

Co-supervisors

Dr Lucy Burkitt

Senior Research Officer

Fertilizer and Lime Research Centre – Soil and Earth Sciences

Institute of Agriculture and Environment, Massey University

Dr Warwick Dougherty

Leader – Soils (South) and Research Scientist

NSW Department of Primary Industries – Agricultural Resources

Other members

Dr Ross Corkrey

Senior Biometrician

Tasmanian Institute of Agriculture, University of Tasmania

DECLARATION OF ORIGINALITY

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DEDICATION

In loving memory of my Father, who was always proud, and encouraged me to do my best; *“Good on you kid, do all you can do, get all the knowledge you can get”*. It was after his passing that I decided to undertake my PhD.

I also dedicate this thesis to my Mother, whom I greatly respect and love. I look forward to writing your entertaining and diverse life story with you.

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PREAMBLE

Throughout this thesis, the term phosphorus, or its chemical symbol 'P', will be used. With respect to P fertiliser, it is acknowledged that the correct term is phosphate fertilisers, however, the term phosphate will only be used where specific definition is required. However, before we get too bogged down with the details concerning P in pasture soils, let's get to know the element a little.

The word phosphorus is derived from the Greek words *phos* and *phorus*, which mean 'light' and 'bringing', respectively. Phosphate was the thirteenth element to be discovered – and interestingly it hasn't had a completely pleasant impact on the world. Ironically, during the Battle of Hamburg in World War II, thousands of P laden fire bombs engulfed the city, where P was first discovered by an alchemist in 1669. Phosphate was first sold as a medical treatment in the seventeenth century to increase intelligence, and was still available over the counter in the 1950s; however, this perceived benefit encouraged overdosing and in some cases led to death (Emsley, 2000). Perhaps the agriculture industry of today can learn from experiences of the past.

ABSTRACT

By definition, there is little or no pasture production benefit of plant available soil phosphorus (P) concentrations above agronomic optimum. Soil P concentrations above the agronomic optimum can result in unnecessarily elevated P concentrations in runoff that can adversely impact on water bodies. I hypothesised that a reduction in these excessive P concentrations in pasture soils may be achieved through applying fertiliser P at rates that are less than those required to maintain soil P concentrations. This thesis considered this hypothesis by utilising six established field sites which represented the broad range of soils used for pasture production in south eastern Australia (Burkitt *et al.*, 2001; Burkitt *et al.*, 2006). The soils at the sites encompassed a wide range of P buffering indices (PBI) (from 6–519) and textures (sand to clay loam). At each site a replicated trial consisting of four initial soil P (P_{init}) concentrations combined with four on-going P fertiliser rates (P_{fert}) had been previously established, and soil samples taken from these trials formed the basis for much of the work presented in this thesis.

The first experimental chapter (Chapter 2) reports on the changes in extractable P of these field soils which were sampled (0-10 cm) once every six months (biannually) for up to four and a half years. Phosphorus extractable in calcium chloride ($CaCl_2$ -P) was monitored using annual samples of the two lowest and the highest P_{init} concentrations receiving the two lowest and the highest on-going P_{fert} rates. Olsen- and Colwell-extractable P concentrations were monitored biannually for all sixteen treatments. Excluding a soil with an extremely low PBI where soil P concentrations could not be increased, the study revealed decreases to be larger the greater the P_{init} concentration, and the smaller the on-going rate of P_{fert} . The influence of P_{fert} on decreases in extractable soil P was not as large as that of P_{init} concentration. The relative decrease in the more readily available $CaCl_2$ -P (-57%) was greater than relative decreases in the agronomic measures, Olsen-P (-25%) and Colwell-P (-12%). When P_{fert} was withheld, soil P concentrations initially well above agronomic optimum remained above this level. This study advances the knowledge of P decline characteristics and will aid land managers in understanding likely changes in soil P concentrations when P fertiliser inputs are reduced.

The second experimental chapter (Chapter 3) reports the development of a model to assist policy makers and land managers in setting realistic timeframes to return soils with excessive P to agronomic and/or environmental optimum. The model utilised the original field study's (Chapter 2) $CaCl_2$ -P, Olsen-P and Colwell-P dataset. The model assumed and confirmed the suitability of an exponential decay function and predicted the final P concentration for $CaCl_2$ -P, Olsen-P or Colwell-P as: Final P concentration = (previously measured P concentration + $e \times P$ fertiliser applied) $\exp(-d \times \text{years since P applied})$; where e is the increase in soil P for each unit of applied P and d is the decay constant representing how quickly the soil P moved from the labile to unavailable P pools. Using parameters derived across all the soils, where P exports ranged from 2.9 and 12.3 kg P/ha.yr, the model predicts it would take approximately 14 years (ranging from 11 to 20 years) for Olsen-P concentrations of between 34 and 44 mg/kg to decrease to an agronomic optimum of 17 mg/kg. An initial Olsen-P concentration of between 55 and 96 mg/kg would take approximately 32 years (ranging from 26 to 49 years). Using soil specific parameters, the model also identified that some soils, i.e. those with high PBI, could

be maintained at agronomic optimum P concentrations without the risk of environmental loss being above the specified $\text{CaCl}_2\text{-P}$ threshold of 0.25 mg/kg (0.05 mg/L). In contrast, soils with low P sorption capacity exceeded the environmental threshold even when soil P concentrations were below agronomic optimum i.e. Olsen-P 14-17 mg/kg. Despite soil P decreases varying according to soil, a soil term was not incorporated into the model as there were only six soils studied. Further work incorporating more soils and various P exports is required to examine the influence of soil properties such as P sorption, and P export, on decreases in soil P.

Chapter 4 reports on an investigation of the changes in further soil P pools as extractable P concentrations of selected treatments of Chapter 2 decreased. These treatments included the two lowest and the highest P_{init} concentrations which received no on-going P_{fert} treatment. This research revealed that the majority of the P was not being exported or sorbed, but inorganic P (P_i) was being converted to organic P (P_o). A longer period of monitoring is required to examine if the P_o concentration will stabilise once a maximum P_o concentration is approached. Relationships between the various P measures allowed us to calculate a degree of P sorption saturation (DPSS) for these soils. Degree of P sorption saturation was relatively low for the two lowest PBI soils when compared to higher PBI soils, despite $\text{CaCl}_2\text{-P}$ concentrations being some of the largest reported in the literature. Further correlation of DPSS with P losses from Australian soils is required as we suggest that the thresholds will vary for soils with extreme P sorption capacities. Alternative methods of calculating DPSS, using Australian measures such as P sorbed after the addition of 1000 mg P/kg, as measured as part of the PBI method, and Colwell-P, without the requirement of an alpha value, were proposed.

Chapter 5 reports the findings of an incubation study and the longer-term effect of drying and rewetting soils. It was found that extremely low PBI soils with high organic matter (OM) contents may be at high risk of P loss to the surrounding environment. Chapter 5 showed that drying and rewetting the soils with the lowest PBI produced large increases in $\text{CaCl}_2\text{-P}$ and Olsen-P, hypothesised to be of microbial and OM origin. Thus, irrespective of fertiliser management, there are large risks of P loss from such soils, even when Olsen-P concentrations are below agronomic optimum. In comparison, P released from soils of higher PBI did not result in large increases in $\text{CaCl}_2\text{-P}$, which remained below the threshold of environmental concern, probably due to chemical sorption.

The large potential for P loss from soils of extremely low PBI was further highlighted in the final experimental chapter (Chapter 6). Chapter 6 compared extractable soil P concentrations of the lowest and highest PBI soils to a depth of 100 cm. It was revealed that soil with an extremely low PBI was susceptible to large P losses, with the majority of applied fertiliser P i.e. 81% (406 kg P/ha) not recovered in this deep sampling zone. Such a large potential loss of applied P brings into question whether such soils should be used for agricultural purposes, especially if soluble P fertiliser is applied, unless the soil's ability to sorb P is firstly increased through the application of a suitable amendment.

Until preferred soil P extractions and thresholds have been accepted for determining the risk of P loss according to soil P concentration and buffering capacity, the depletion of soil P concentrations of intensively

grazed pastures to agronomic optimum must be encouraged. Only once agronomic optimum soil P concentrations are reached should the appropriate maintenance P fertiliser application, to account for soil sorption and P exported in produce, be supplied. However, the currently defined agronomic optimum i.e. Colwell-P of 23 mg/kg for PBI <15, may be too high for extremely low PBI soils. Phosphorus fertiliser management for low PBI soils requires more precision than higher PBI soils to limit environmental loss of P. Indeed, intensive grazing of extremely low PBI soils is questionable until their PBI's are increased through application of amendments.

GENERAL INTRODUCTION

Pasture-based Australasian dairy production places great emphasis on soil P concentration. Since pasture is the cheapest feed source, fertiliser P is typically used to achieve and maintain soil P concentrations at or above that required for optimum pasture production. However, soil P concentrations above agronomic optimum (excessive soil P concentrations) are common in Australasian intensively grazed pasture soils. These excessive soil P concentrations are the result of P imports in fertilisers, effluent, and livestock fodder, exceeding removal in farm produce, runoff, and leaching. An Australia-wide study by Gourley *et al.*, (2010) found that 80% of 1773 pasture paddocks sampled from 37 conventional dairy farms had Olsen-P concentrations above agronomic optimum (14-17 mg/kg), with 50% of these paddocks having concentrations one and a half times, and 20% at least three times the agronomic optimum.

Excessive soil P concentrations are not only an unnecessary economic expense and use of a finite resource of raw P (Cordell *et al.*, 2009); they also pose a risk to the surrounding waters. Indeed, surface P runoff from intensively managed Australian dairy pasture soils has been reported to contain total-P concentrations in the range of 0.9–35.0 mg/L (Nash *et al.*, 2000; Dougherty *et al.*, 2008; Burkitt *et al.*, 2010b). It has generally been accepted that the more P there is in a soil, the greater is the risk of environmental loss (Sharples and Rekolainen, 1997; Burkitt *et al.*, 2010b).

Reducing excessive soil P concentrations through reducing or withholding P fertiliser could potentially reduce P losses to the environment. However, little is known of the decrease in so-called environmental and agronomic P concentrations when P fertiliser is reduced or withheld, especially for a range of initial P concentrations (P_{init}), and soil P sorption properties, representative of intensive pasture grazing systems.

It was the objective of this thesis to;

- 1) describe the decrease in soil P concentrations of a range of PBI pasture soils, which each contained a range of P_{init} concentrations, and received a range of on-going P fertiliser (P_{fert}) rates,
- 2) develop a model to predict the final environmental and agronomic soil P concentrations according to P_{init} concentration, rate of on-going P fertiliser, if supplied, and time since P fertiliser application had occurred,
- 3) quantify the processes influencing the changes in environmental and agronomic P concentrations when P fertiliser is withheld, particularly the degree of P sorption saturation (DPSS),
- 4) assess the magnitude and duration of changes in P pools after drying and rewetting (DRW) soils in order to understand how PBI affects the potential of DRW cycles to supply bio-available P pools, and
- 5) assess the influence of soil texture and PBI on downward P movement by comparing P recovery from the surface 100 cm of two contrasting soils.

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