



Department of  
Primary Industries and  
Regional Development

Digital Library

---

Resource management technical reports

Natural resources research

---

5-2020

## Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative

Robert Summers

Peta Richards

David Weaver

David Rowe

Follow this and additional works at: <https://library.dpird.wa.gov.au/rmtr>

 Part of the [Agriculture Commons](#), [Environmental Monitoring Commons](#), [Natural Resources Management and Policy Commons](#), and the [Soil Science Commons](#)

---

### Recommended Citation

Summers, R, Richards, P, Weaver, D & Rowe, D 2020, 'Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative', Resource management technical report 416, Department of Primary Industries and Regional Development, Perth.

This report is brought to you for free and open access by the Natural resources research at Digital Library. It has been accepted for inclusion in Resource management technical reports by an authorized administrator of Digital Library. For more information, please contact [library@dpird.wa.gov.au](mailto:library@dpird.wa.gov.au).

# Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative



Resource management technical report 416



# **Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative**

**Resource management technical report 416**

**Rob Summers, Peta Richards, David Weaver and David Rowe**

© State of Western Australia (Department of Primary Industries and Regional Development), 2020

ISSN 1039-7205

Cover: Annual horticulture on Bassendean sand in Nambeelup.



Unless otherwise indicated, 'Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative' by Department of Primary Industries and Regional Development is licensed under a [Creative Commons Attribution 3.0 Australian Licence](https://creativecommons.org/licenses/by/3.0/au/). This report is available at [dpird.wa.gov.au](https://dpird.wa.gov.au).

The Creative Commons licence does not apply to the State Crest or logos of organisations.

### **Recommended reference**

Summers, R, Richards, P, Weaver, D & Rowe, D 2020, 'Soil amendment and soil testing as nutrient reduction strategies for the Peel Integrated Water Initiative', *Resource management technical report 416*, Department of Primary Industries and Regional Development, Perth.

### **Disclaimer**

The Chief Executive Officer of the Department of Primary Industries and Regional Development, and the State of Western Australia accept no liability whatsoever, by reason of negligence or otherwise, arising from the use or release of this information or any part of it.

Copies of this document are available in alternative formats upon request.

Department of Primary Industries and Regional Development

3 Baron-Hay Court, South Perth, WA, 6151

Telephone: +61 (0)8 9368 3333

Email: [enquiries@dpird.wa.gov.au](mailto:enquiries@dpird.wa.gov.au)

Website: [dpird.wa.gov.au](https://dpird.wa.gov.au)

# Contents

<b>Acknowledgements .....</b>	<b>iv</b>
<b>Summary .....</b>	<b>v</b>
<b>1 Introduction .....</b>	<b>1</b>
<b>2 Using clay from mineral sands mining to rehabilitate farmland .....</b>	<b>3</b>
2.1 Rehabilitation of mineral sands mines to farmland outside WA .....	3
2.2 Case studies of mineral sand rehabilitation in WA.....	4
<b>3 MZI mineral sands in Keysbrook .....</b>	<b>7</b>
3.1 Soil sampling .....	7
3.2 Surface and internal drainage.....	13
3.3 Effect of MZI mine site on water quality .....	17
3.4 New process of pre-mixed sand and clay .....	21
<b>4 Glasshouse trials of soil amendment with MZI clay and sand.....</b>	<b>23</b>
4.1 Preliminary glasshouse trial .....	23
4.2 Main glasshouse trial .....	27
<b>5 Impact of MZI mine operations on water quality .....</b>	<b>36</b>
5.1 Widespread soil amendment in the Peel–Harvey Catchment.....	37
<b>6 Soil amendment of a nearby market garden .....</b>	<b>38</b>
<b>7 Intensification of land use from grazing to horticulture .....</b>	<b>46</b>
<b>8 Soil amendment elsewhere in the Peel–Harvey Catchment .....</b>	<b>47</b>
<b>9 Effects of soil testing .....</b>	<b>50</b>
<b>Shortened forms .....</b>	<b>55</b>
<b>References .....</b>	<b>56</b>

## Acknowledgements

This project is part of the Transform Peel initiative for the Peel region, supported by the Western Australian Government and Royalties for Regions.

We gratefully acknowledge the collaborative nature and cooperation of Piers Goodman and Tara Read from MZI Resources Pty Ltd — a mineral sands producer on Hopelands Road in Keysbrook that provided the information and resources to assess their mine site's effect on the water quality of the area and the potential for using the clay they separate in their mining process. Since completing this study, the mine was purchased by Doral Mineral Sands.

We acknowledge access to the Supafresh horticulture operation on Corio Road in Ravenswood and assistance from Troy Cukrov of Trodan Produce (WA) Pty Ltd, which enabled us to collect information on the effect of horticulture on sandy soils and the commercial perspective on using soil amendments in the region.

Thanks to Tim Pope (DPIRD) for his drilling expertise for collecting samples from the MZI and Supafresh sites; Matt Giraudo and the Peel–Harvey Catchment Council for providing the MZI tenement and mine site mapping; Rob Deyl for installing and monitoring soil moisture equipment at the Supafresh horticultural site; and Angela Rogerson for editing this report.

## Summary

The Transform Peel program focuses on 42 000 hectares (ha) due east of Mandurah called the Peel Food Zone, 75 kilometres (km) south of Perth in the shires of Murray and Serpentine Jarrahdale and includes an assessment of intensified and enclosed agriculture and a business park. The Peel Integrated Water Initiative was developed through Transform Peel to identify water sources and minimise the effect of these projects on water quality by reducing the nutrient loads discharged into the Peel–Harvey Estuarine System, which has been suffering from poor water quality for this reason.

The mineral sand miner MZI Resources Pty Ltd (MZI) is located within the Peel Food Zone and works to rehabilitate farmland they have mined that previously contributed to nutrient losses and water quality issues in the Peel–Harvey Estuary. Rehabilitation has potential to improve this landscape by reshaping the mined area and increasing the soil's capacity for nutrients by mixing subsoil clay into the soil surface. Preliminary monitoring of run-off across the mine site and associated farmlands indicates a reduction of phosphorus (P) and nitrogen (N) of up to 87%. If the rehabilitation is sustained, when mining is complete the MZI mine site has the potential to reduce the P loss in Nambeelup Brook by up to 16%.

Using the clay from mining as a soil amendment on the predominantly sandy Nambeelup Catchment located outside the mine site could reduce P loss by over 68% (4.6t of P per year based on 2006–15 data (Hennig et al. in prep)). Glasshouse studies during this project supported this 68% reduction at a catchment scale, with a 75% reduction in P leaching and no decrease in pasture productivity.

Bentonite clay reduced P leaching from nearby intensive annual horticulture and improved agronomic soil properties. However, using the local MZI clay instead of bentonite as a soil amendment for horticulture is, potentially, a cheaper option. Notably, using MZI clay reduced P leaching, but not enough to reach the environmental target reduction of 50% to allow horticulture land use approval, and N leaching was extreme and not reduced by bentonite or MZI clay.

A soil testing program to improve fertiliser management in the Peel–Harvey Catchment has been carried out since 2009. Analysis of the results has shown most paddocks in the Peel–Harvey Catchment do not need P. Analysis of P fertiliser sales indicated that P use has declined in localities where soil testing and farmer training has been focused. Modelling showed that combining soil amendment and soil testing reduced P loss by 79% (5.3t of P based on 2006–15 data (Hennig et al. in prep)) in the Nambeelup Catchment.

The widespread use of clay for controlling P loss from pasture requires field assessment and demonstration at the farm scale. Switching the mine site's land use to horticulture may reduce P loss normally occurring from these sands, but it would require substantial changes to the landform to reduce inundation and water retention, and minimise N loss downstream. Modifying the landscape would require testing to confirm its effectiveness, as well as changes to mining approval and rehabilitation requirements from several agencies.





# 1 Introduction

In 2017, 136 850 people lived in the Peel region. From 2011 to 2016, the region's population increased by 5.4%, more than double the state's overall growth rate (2%) for the same period. Further growth will occur as Perth's urban footprint shifts south. A long-term strategy to attract new industries and businesses to the Peel region is needed to deal with this rapid population increase and the corresponding need for local employment.

The Peel region is located 75km south of Perth and its major regional centre is Mandurah. For regional development, the Peel region covers five local government areas of Boddington, Murray, Serpentine Jarrahdale, Waroona shires and the City of Mandurah. The Peel planning region is smaller and covers the City of Mandurah and the shires of Murray and Waroona. The Shire of Serpentine Jarrahdale is in the Metropolitan planning region and the Shire of Boddington is in the Wheatbelt planning region. Figure 1.1 shows the location of the Peel region, for regional development purposes and its five local governments.

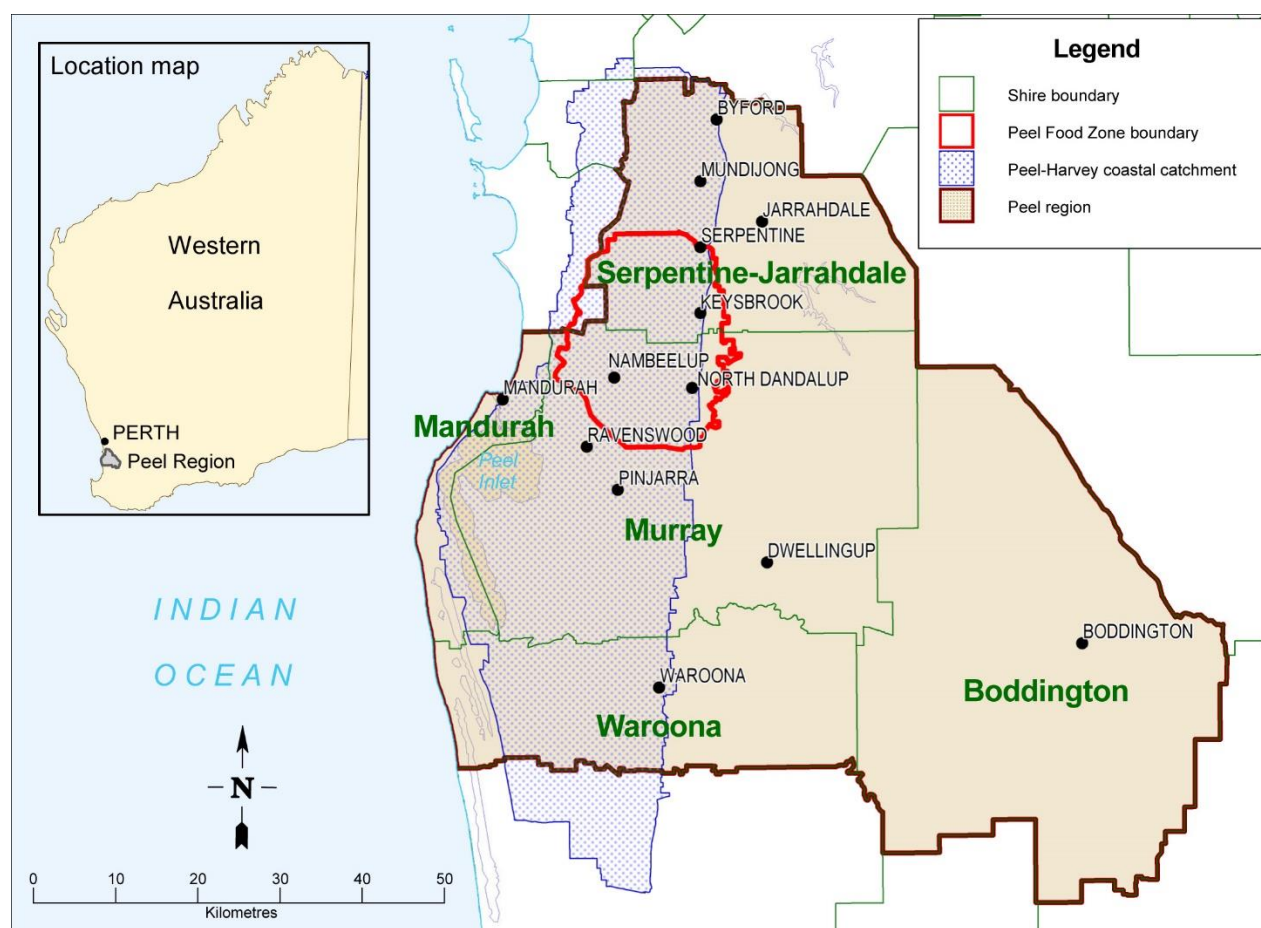


Figure 1.1 The Peel region, Peel Food Zone investigation area and the Peel–Harvey coastal catchment

The Peel Development Commission worked with local stakeholders to develop the Transform Peel initiative — a transformative 35-year economic development program for the region. Transform Peel includes an assessment of intensified and enclosed agriculture and a business park. The Peel Integrated Water Initiative (PIWI) was

developed to minimise the effect of these projects on water quality by reducing the nutrient loads discharged into the Peel–Harvey Estuarine System (Peel–Harvey Estuary), which has been suffering from poor water quality for this reason.

The aims of the PIWI were to:

- identify a range of technically viable water supply options to support the development of the Peel Food Zone (PFZ) and the Peel Business Park, as well as maintaining the water balance for the region
- reduce the nutrient load from the Nambeelup Catchment to the Peel–Harvey Estuary by 50%.

To achieve these aims, the PIWI explored greater retention of nutrients in the region's predominantly sandy soils using soil amendments and improved fertiliser management through soil testing and farmer training.

The Department of Primary Industries and Regional Development's expertise on nutrient management was employed to assess techniques to reduce nutrient loss from the landscape to the waterways. Interventions, such as soil amendment and improved nutrient management, in pasture and horticulture were examined to understand the possible effects on pasture and horticulture in the region.

We developed several opportunistic activities to assess the viability and efficacy of these interventions. Most activities were based on short-term studies and are only indicative of their potential. The activities included:

- assessing the rehabilitation of other mineral sands mines overseas and elsewhere in Western Australia (WA)
- sampling and testing soil on existing rehabilitated sites on the MZI mine
- assessing water quality measurements of drains traversing the mine site, which were taken by MZI as part of their operating procedure
- undertaking glasshouse trials to determine the effects of the mined clay on pasture growth, P retention and uptake of contaminants
- assessing the existing soil amendment on a horticultural property near the MZI mine, including the irrigation system
- assessing the potential of soil amendment and nutrient management interventions on a regional scale
- assessing the potential effect on nutrient impacts from intensification of land use from pasture to in-ground horticulture
- evaluating the soil testing to date and reviewing available data on the effects of farmer behaviour when adopting improvements in fertiliser management.

## 2 Using clay from mineral sands mining to rehabilitate farmland

There is limited information, research and case studies concerning mineral sands mines being rehabilitated to farmland in WA; much of the literature relates to rehabilitation of mine sites to native vegetation. So we reviewed literature from outside WA and compiled local farmers' experiences into case studies.

### 2.1 Rehabilitation of mineral sands mines to farmland outside WA

Research in countries other than Australia found:

- productivity can be returned to pre-mining levels, but it does vary
- compaction is a common problem
- returning organic matter, such as compost or topsoil, aids in returning to pre-mine production
- P retention can be elevated by mixing the soil components during rehabilitation.

In Virginia, United States, Daniels et al. (2003) tested how composting and topsoiling affected the production of a range of row crops after rehabilitation. The study used 25 centimetres (cm) of topsoil or the addition of 110 tonnes per hectare (t/ha) of compost over a range of sand and slimes (clay) mixtures. Depending on the crop, productivity was estimated to be reduced by 3–27% when compared to undisturbed soils; there was no difference in productivity between the topsoil and compost.

The limitation on agricultural productivity at rehabilitated sites was attributed to the variability in surface texture and compaction. Barnhisel, Gray and Skousen (1990) and Schroeder (1997) made similar observations of reduced yield due to compaction. Meredith (2007) also found yields were limited by compaction after mining, but considered that the sites could be returned to near pre-mine yields after extensive organic soil amendment using biosolids and remedial tillage.

Adding organic soil amendment (composts) does increase yield. Stolt et al. (2001) supported compost use in the rehabilitation of mineral sands tailings; however, these improvements in soil structure may have occurred in soils with substantially higher clay content than those generated by the shallow mining of MZI.

Of particular interest to the PIWI is an assessment of P retention and leaching in sand from a mineral sands mine at Amity Point in North Stradbroke Island, Queensland. Diggie and Bell (1984) found that the iron and aluminium content of tailings were enough to retain P applied in the top 20cm of the soil surface. While the mineral composition and content greatly differ from those in the Keysbrook region, the low levels of P-adsorbing material substantially reduced leaching, which enabled the application of water-soluble P during rehabilitation without concern for leaching.

## **2.2 Case studies of mineral sand rehabilitation in WA**

Farms from Harvey to Capel in south-west WA were visited during this project to ascertain the effects of the rehabilitation of mineral sand mining on productivity and other aspects of farm management. Farmers were opportunistically surveyed about their experience and should not be considered representative of all mining operations or current procedures.

The surveyed farmers reported the following:

- Lime and fertiliser had been applied to all properties visited to correct the acidity and low nutrient levels after mining.
- Adequate mixing of the subsoil clay and sand was one of the most important factors affecting production.
- The desirable amount of clay added to the sandy soil was quite small, at 5–10%.
- Mixing a small amount of clay — only 1–5 millimetres (mm) depth of clay or about 10–50t/ha — into the reserved sandy topsoil that was being returned to the mined landscape during rehabilitation appeared to improve productivity.
- Excessive clay in reconstructed subsoils caused perched watertables that hindered downward drainage, which was a major problem.
- Barriers of clay within the soil profile were inadvertently constructed when the shallow mined voids were filled, causing limited horizontal water movement and drainage.
- The separation of the clay into a single, narrow particle size reduced permeability, created poor soil structure and often resulted in hardsetting soil.
- Re-use of topsoil, preferably within one year, was essential for re-establishment of healthy pasture; the topsoil removed during mining was re-used for rehabilitation more than five years later and resulted in poor plant growth.
- Buried haul roads, clay berms and the bases of stockpiles were visibly affecting pasture production many years after rehabilitation.

### **2.2.1 Case study 1**

The rehabilitation of a farm after mineral sand mining in the foothills of the Darling Scarp resulted in several issues with the texture and drainage of the subsoil and near topsoil more than 20 years after mining.

The initial placement of stockpiles resulted in deep profiles of sandy soil uphill and upstream of clay soils derived from the slimes separation. Consequently, the location of the stockpiles drove the composition of the deeper subsoil, which has impaired the drainage of the subsoil. Watertables were diverted to the surface as the water moved downhill from the large sandy subsoil profile. The water then encountered massive formations of clay at depth and brought that clay to the surface, creating subsoil dyke structures from the clay stockpiles.

Subsurface drainage was installed on the waterlogged site with limited effectiveness because the drainage pipes were installed too far apart and the high clay content of the topsoil and upper soil that was being drained impaired the movement of the drainage water into the drainage pipes.

The rehabilitated paddocks have high clay contents and, after more than 20 years, are producing much less pasture than adjacent untouched paddocks. Symptoms of salinity

in rehabilitated paddocks that were irrigated with Wellington dam water appear greater than in the paddocks that were not mined.

Tillage and deep-ripping have been used to alleviate some of these issues, though limited improvement and productivity persist in about a third of adjacent paddocks.

Soil tests showed that the Colwell P (Colwell 1965), Colwell K and pH indicate satisfactory soil nutrition; however, salinity measured as electrical conductivity showed a major difference between sites that have been mined and those that have not. The site's history of fertilisation with superphosphate and potash, as well as the application of lime, has maintained measures of fertility. Despite this, poor internal drainage of the soil caused by high clay content and poor structure has resulted in reduced species establishment and limited productivity of the pasture.

Irrigation of the rehabilitated sites has been withdrawn because the return on the cost and effort is questionable. In summer and without irrigation, the soil becomes hardsetting.

This site was one of the first to be mined in the area and better management of the subsoil was developed during the years that followed.

### **2.2.2 Case study 2**

To the west of Bunbury and adjacent to Boyanup, the farmer described soil that was originally sandy, poor and unproductive to have improved after slimes (separated clay) were applied to the surface and cultivated to achieve a well-mixed layer of sand and clay. The slimes were applied 2–5mm thick as a liquid from a tanker onto the topsoil, which was spread back onto the site from stockpiles. The slimes were then mixed into the topsoil.

Adding clay to the topsoil on sloping sites caused unexpected water erosion and necessitated changes to grazing management and pasture species planted. However, the overall experience on the rehabilitated sandy soil was positive.

Rehabilitated areas of the farm containing soils that were originally highly productive deep loams were described as having too much segregated clay of one texture. This resulted in fast, early growth and, as winter progressed, livestock needed to be removed to avoid pugging or pulverising the soil surface, which was not a problem before. Farmers have adapted their management and good hay crops can be grown from the areas that livestock are excluded from over winter.

During summer, the paddocks were described as requiring a hammer to crack, while, in winter, temporary electric fencing pegs could be pushed into the ground with a boot.

In retrospect, some of the paddocks were believed to be grazed too soon after rehabilitation; the re-incorporation of pasture or cover crop as green manure back into the topsoil for 1–2 years would have increased the carbon content of the soil, improved soil structure and reduced the subsequent effects of livestock.

Farmers also described large, deep stockpiles of topsoil that sat for five years, which resulted in poor topsoil that needs decades to increase the organic matter content. It should be noted that current mineral sand mining practice aims to return topsoil in one year to minimise this effect.

The haul roads covered with fill and topsoil could be visible after 20–30 years and the need to break up and rip these barriers to infiltration and roots was made clear by the farmers.

Farmers also described their experiences with making compost from excess organic matter. The addition of clay to compost is common elsewhere and an agronomist recommended adding pulverised clay to the compost; however, this resulted in hardsetting compost that was not suitable to be spread onto the paddocks.

### **2.2.3 Case study 3**

The mineral sand mining on this farm took place on poor deep sand along the slopes of the foothills of the southern edge of the Darling Scarp. The rehabilitation resulted in 10cm of sandy topsoil over a layer of red clay up to a metre thick on top of poor deep sand. The paddocks were sloping and the water perching over the clay resulted in unexpected erosion because the site was previously well-draining. Grazing and groundcover had to be managed to maintain enough vegetation at the beginning of winter and avoid recurrence of erosion.

There was minimal mixing when returning the clay to the deep sandy soil creating a barrier to infiltration. Also, there was no attempt to add a small amount of clay to the sandy topsoil.

Although the site produced better pasture than the unproductive landscape before, the farmer believed that better mixing throughout the profile would have produced a substantially better outcome.

### 3 MZI mineral sands in Keysbrook

#### Summary of findings:

- P from fertiliser application had accumulated in the topsoil, but was spatially variable.
- Clay integration after mixing on-site varied considerably down the soil profile and across the site.
- Increases in P retention were high enough to retain 70% more P on-site than the previous sandy soil.
- Other indicators of soil fertility improved with the addition of clay.
- Improvement in pasture growth from the earlier conventional mixing of clay in the field could be made with minor changes to the slope of the paddocks and small spoon drains.
- Preliminary measurements indicate water quality may be improved by the passage of water across the disturbed landscape of the mine site and contact with clay.
- The new process of mixing the clay before being returned was better mixed than mixing on-site and the resulting clay content was sufficient for P retention without being a hindrance to soil drainage.
- Retaining some mine voids and elevating some parts of the landscape may result in an improved landscape for agriculture which needs investigation.
- Analysis of the existing site, which used the earlier method of mixing on-site, showed that the soil rapidly accumulated P and grew good quality pasture. Additionally, other measures of soil fertility rapidly increased to levels better than the original soil, which will likely improve the retention of P and K, improving the agronomic performance of the soil and minimising costs.

#### 3.1 Soil sampling

The MZI Keysbrook mineral sands mine is located 25km north-east of the Mandurah and 65km south of Perth (Figure 3.1). The current mining envelope is 1380ha and about 430ha has been mined to date, with at least twice that area potentially available for future use. The orebody is shallow and mining is generally only 2–4 metres (m) deep. The shallow operation rapidly generates and fills mined voids, then caps them with topsoil that has been reserved in stockpiles for as little as 18 months.



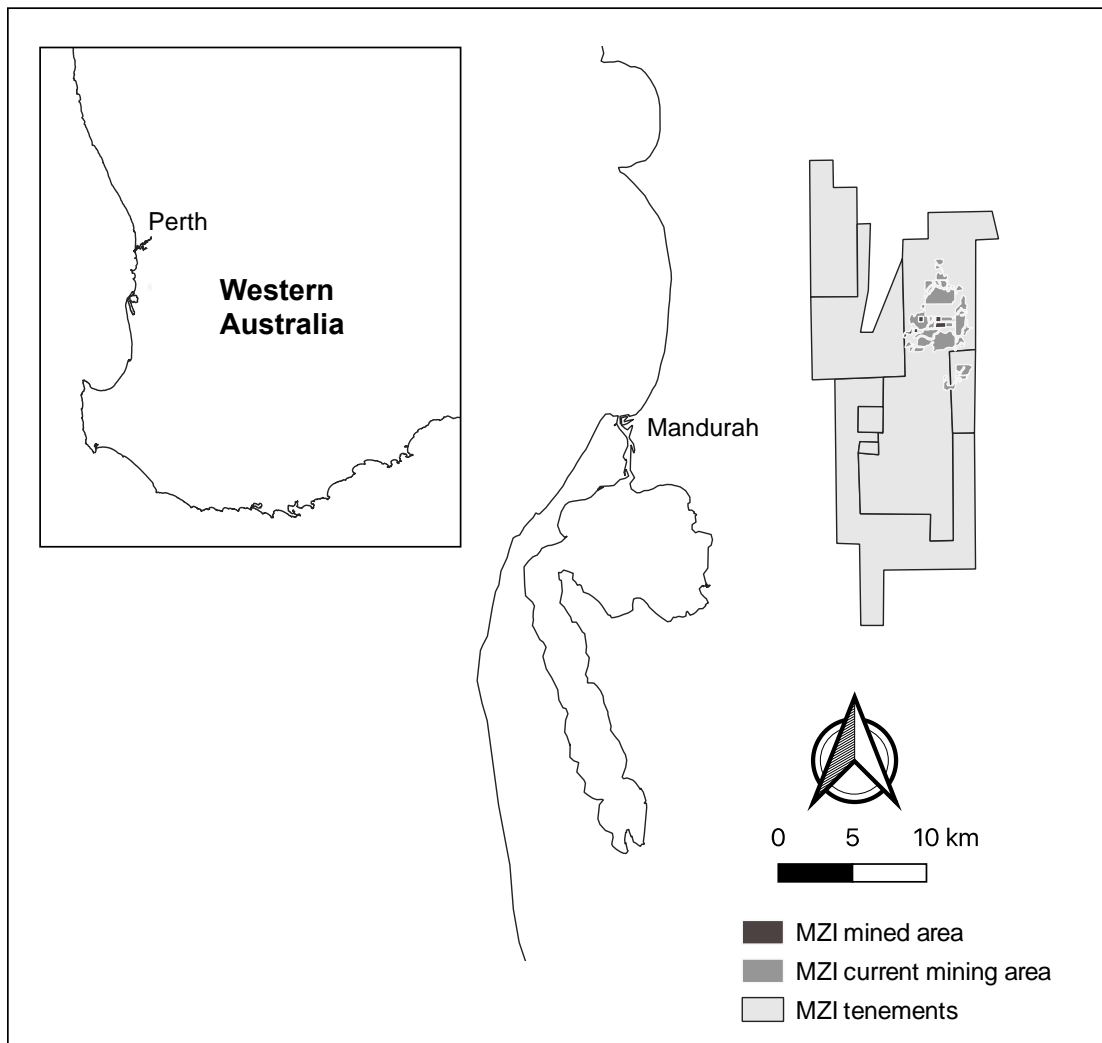


Figure 3.1 The extent of the MZI operation and tenement

During the mining operation, the clay is separated from the sand to extract the titanium-rich ore, which is transported to enrichment facilities. The clay and sand are then pumped back to the mine voids prior to rehabilitation. In the earliest phase of the mining, some clay was stockpiled and still remains. The first rehabilitation started with transporting the sand and clay in separate slurries back to the mine voids. After filling the voids, the slurries were solar dried then mixed using a range of mining and agricultural equipment to develop a more homogenous profile. Now, rehabilitation is carried out by mixing a sand and clay slurry before filling the mine voids.

The native sand in the area has very poor nutrient retention and P can easily leach through the soil because of the high permeability and low P-buffering capacity. These issues are exacerbated by high watertables that limit the interaction of rainwater with the soil, causing surface run-off. The addition of P-retentive materials, such as clays, can greatly increase the P retention of these soils and has been shown to reduce P loss by at least half (Summers, O'Connor & Fox 1993; Ward & Summers 1993). The addition of excessive clay can also lead to increased run-off if landform is not considered.

Incorporating clay into the upper soil profile during rehabilitation from mineral sands mining has the potential to greatly reduce P loss into the Peel–Harvey Estuarine

System. This soil amendment process also has the potential to increase the agricultural productivity of the rehabilitated soil through reduced nonwetting and increased P and moisture retention. Additionally, there is the opportunity to reduce the constraint of waterlogging by using raised beds, enabling investigation of changes from the existing cattle grazing system to another land use and greatly increase the longevity of P retention. However, alterations to the landscape are limited by the current approval conditions of the mine.

Case studies showed that effective mixing was important for returning the site to productive pasture. The existing mine rehabilitation at MZI Keysbrook was sampled to assess how well the clay had been mixed into the soil profile and the effect the incorporation of clay had on the soil's properties.

### 3.1.1 Methods

Core samples of soil up to 1m deep were taken using a direct push hydraulic sampler (Geoprobe) and supplemented with three 0–10cm composite soil samples (>40 cores) taken manually to represent the surface of the entire site. Shallow sampling was required to enable enough bulk for a full particle size analysis and extensive sampling of the soil surface. The 0–10cm sample is consistent with the standard sampling technique for agronomic purposes. The 1m cores were separated at 0–5cm, 5–10cm, 10–20cm, 20–50cm and 50–100cm. As part of the rehabilitation program, the site received 7t/ha of crushed limestone, 50 kilograms per hectare (kg/ha) of monoammonium phosphate and 20kg/ha of potassium sulfate. Compost was applied to the site at up to 100 cubic metres per hectare (m<sup>3</sup>/ha).

The soil samples were analysed for Colwell P and K (Colwell 1965), phosphorus buffering index (PBI; Burkitt et al. 2002), phosphorus retention index (PRI; Allen & Jeffery 1990), and organic carbon (OC; Walkley & Black 1934).

Notched box and whisker plots were used to graphically represent the data (Figure 3.2). These plots show the distribution of analyte concentrations. Box and whisker plots represent percentiles — the lower whisker shows the 5th percentile, indicating that 5% of the data is less than this value and 95% of the data is greater than this value. This same logic applies to various locations on the boxplot; for example, the 50th percentile has 50% of the data points above and 50% of the data points below this point. Shaded sections of the plot show 'notches'. In the absence of a formal statistical test, a visual assessment of significant differences can be approximated when the notches of box and whisker plots that are being compared do not overlap. Plots i and ii and plots i and iii are significantly different, while plots ii and iii are not.

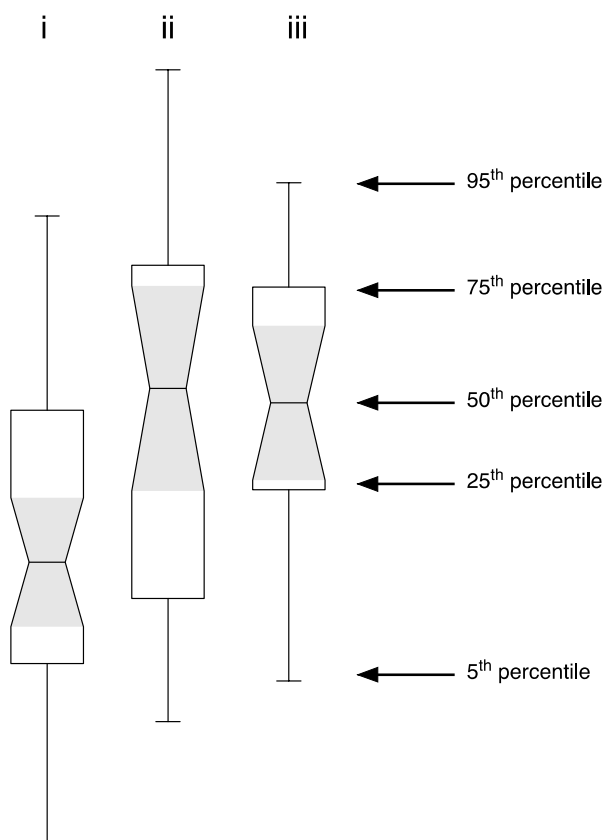


Figure 3.2 Anatomy of notched box and whisker plots

### 3.1.2 Results

Colwell P mainly accumulated in the surface and varied considerably across the rehabilitated paddock — 14–65mg P/kg in the top 5cm of soil. This variability is likely during the establishment of the site when P application is uneven and multiple applications have not accumulated over years or have not been redistributed by livestock. More P was applied in the form of inorganic fertiliser and compost than was required for optimal pasture growth. Consequently, when the soil was sampled more extensively by combining multiple cores, a Colwell P of 51–64mg P/kg was found (Figure 3.3a). A soil with a PBI of 26–36 (Figure 3.3b) requires 15–20mg P/kg (80–95% of maximum production) (Gourley et al. 2019; Summers & Weaver 2011). As such, the soil contained 2–3 times the P needed for agronomic requirements for beef pasture after one fertiliser application.

The amount of clay carried up through the sand varied; the top 10cm of returned topsoil contained 5–7% clay, the 10–20cm layer contained 5–35% clay and the 20–50cm layer contained 2–42% clay (Figure 3.3c). The varying amounts of clay in these mid-layers may contribute to localised issues with perched watertables. However, the highly variable nature of this layer throughout the paddock may result in permeable layers allowing drainage down to the sandier 50–100cm depth.

Clay in the 10–50cm layer corresponded with elevated PBI levels, which is likely to affect P retention when water drains through the soil profile (Figure 3.3b). The PBI of the topsoil was enough to prevent P run-off during winter when the watertable was at the surface, except when the soil was completely saturated. If the soil is not saturated

with P from prudent fertiliser application, it is likely that most of the P will be retained and that the amount retained would be far greater than the amount retained in the original sandy soil before mining. It is also worth mentioning that the PBI increased with increasing clay content (Figure 3.3d).

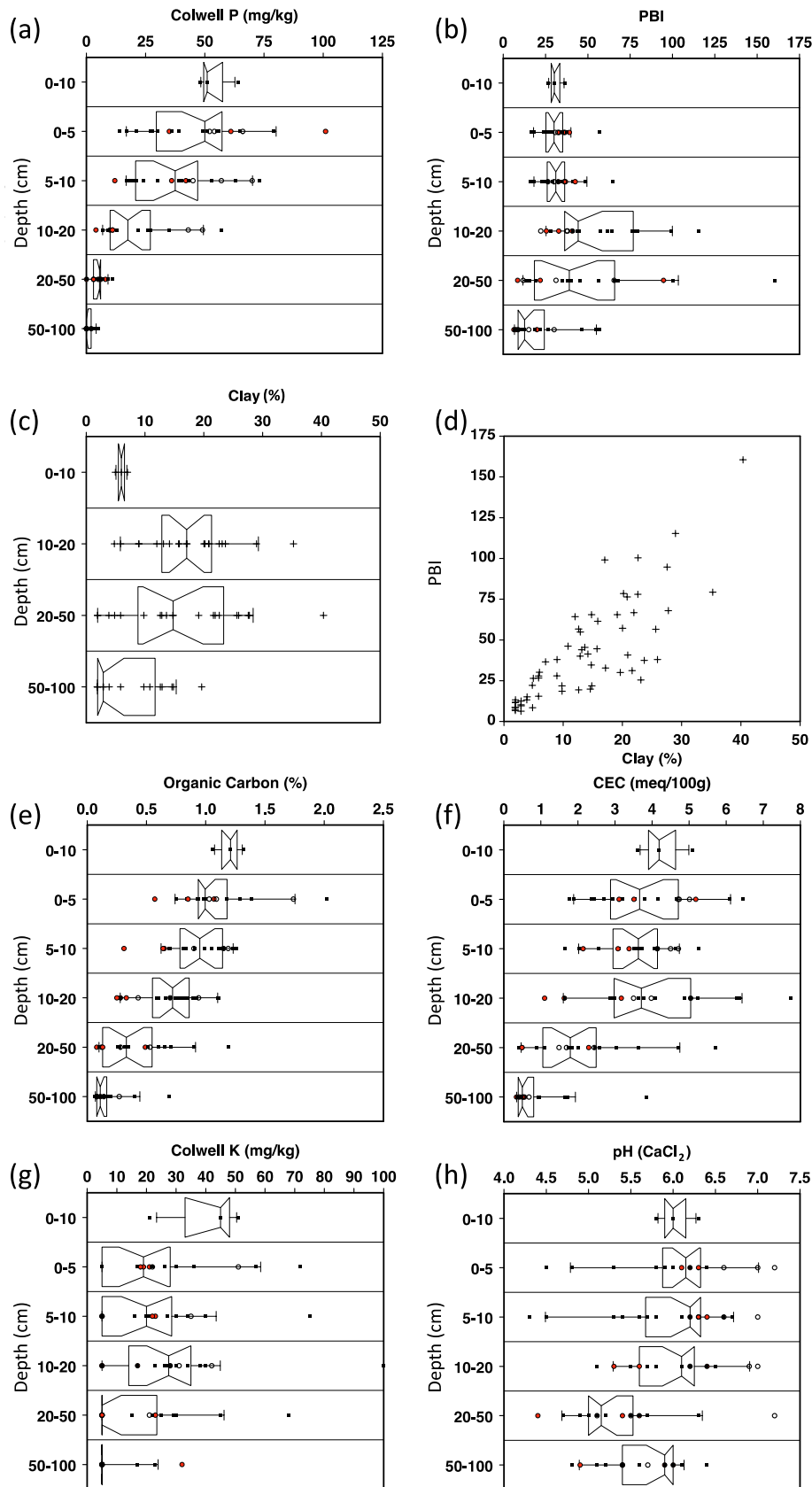
Earlier soil amendment field trials suggested that increasing the PBI to more than 35 (PRI approximately 8) will reduce P run-off by 70% (Summers, Guise & Smirk 1993; Summers, Smirk & Karafilis 1996).

The OC, cation exchange capacity (CEC) and potassium (K) were highest in the topsoil (Figure 3.3e, f, g) where the liming successfully raised the  $\text{pH}_{\text{CaCl}_2}$  to about 6 (see Figure 3h). The presence of clay or organic matter contributes to the CEC of the soil, the addition of clay to sandy soil increases OC in the soil (Churchman et al. 2014; Harper et al. 2012) and the application of lime further increases the CEC. The connection between these effects is visible in samples taken from the MZI site after one season of pasture growth (Figure 3.4a, b). The samples indicated a link between the OC increase and the clay content and CEC.

The CEC has an important role in retaining K from leaching. The addition of clay and the increase in OC resulted in an increase in CEC (Figure 3.4a, b, e). While loss of K is not linked to water quality problems, it is an expensive addition to farming systems and soil testing has shown K deficiency is common in coastal leaching soils (see Section 9). Additionally, provision of sufficient K will further increase plant uptake of P, reducing P losses. Having a low CEC makes it difficult to manage K applications and small amounts must be added frequently. If the soil is treated with more K than it can retain, the K will leach and run-off the property. On most coastal sandy soils in the region, the difficulty in accessing the wet paddocks and the short growing season usually affords only one or two opportunities to apply fertiliser.

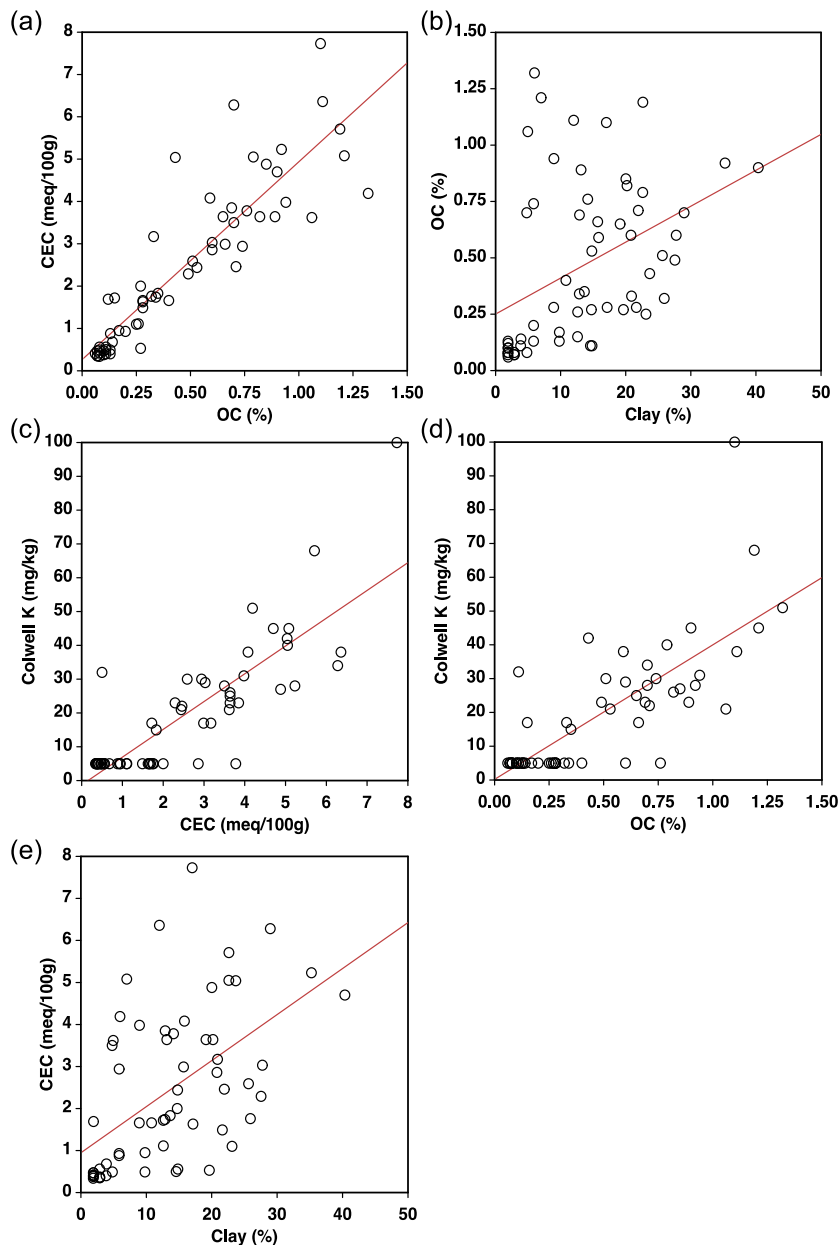
Excluding liming or applying organic matter, there are few options for improving the CEC for K retention; however, this application of clay appears to improve the cation exchange to an extent that affects economics. An important finding for plant nutrition and productivity is the magnitude of the link between the K content (Colwell K) of the soil and the OC and clay content (Figure 3.4b, c). Increasing the OC content by 1% increased the ability to retain cations like K (measured as CEC) by up to 4 milliequivalents per 100 grams (meq/100g). Similarly, increasing the clay content up to 8% can increase the CEC by up to 4meq/100g. Moreover, increasing the CEC by 4meq/100g can increase the Colwell K by up to 45 milligrams per kilogram (mg/kg). This is the equivalent of storing about 45kg of K or about 90kg of muriate of potash (at \$600/t ex-depot in September 2018), which is about \$54/ha more than the soil can store. This change is likely to be permanent because the clay will help maintain the OC content, perpetually saving the farmer \$54/ha.

The residues from the pasture grown on the site will increase each year, which increases the amount of organic matter in the soil. The increase in residues will also increase the CEC, which will improve the amount of K the soil is able to retain.



Note: Regression of PBI and clay percentage is described by  $Y = 2.72X + 4.78$   $r^2 = 0.66$ .

Figure 3.3 Soil chemical and physical analyses sampled down the soil profile



Note: Regressions are a)  $Y = 4.67X + 0.26$ ,  $r^2 = 0.80$ ; b)  $Y = 0.016X + 0.25$ ,  $r^2 = 0.17$ ; c)  $Y = 8.22X - 1.28$ ,  $r^2 = 0.71$ ; d)  $Y = 39.8X + 0.19$ ,  $r^2 = 0.60$ ; e)  $Y = 0.109X + 0.95Y$ ,  $r^2 = 0.29$ .

Figure 3.4 The relationships between the organic carbon (OC), clay content, the cation exchange capacity (CEC), and the potassium content (Colwell K)

### 3.2 Surface and internal drainage

The drainage through the subsoil profile may be influenced by the use of sand berms as discrete embayments to prevent the clay slurry from draining. These can be seen, alongside the sampling locations, to be running mainly north–south, which may act to channel soil water to the drainage lines that run east–west (Figure 3.5). The sand banks of the embayment create subsoil drainage across the site, which may contribute to the overall drainage of the site and reduce inundation that would limit production when the site is returned to its pre-mine state.

a) 11/06/2015



b) 02/04/2016



c) 09/01/2017



d) 25/08/2017



Figure 3.5 Samples taken on 17/11/2017 (circles with dot) overlain on images from Google Earth that were taken: a) before the site was mined; b) during the mining; c) during rehabilitation; d) after the site was rehabilitated



The low grade or slope of the site and, to some extent, the decreased permeability of the rehabilitated soil profile exposes the site to some inundation. This is common in the native soils of the region and is usually managed using spoon drains. This site was previously a bay from a linear travelling irrigator and is likely to have been graded for the trafficability of the irrigator during summer.

The minor inundation caused by limited surface drainage and the grade of the site affected germination in the newly established site (Figure 3.6). Grasses performed better with the heavy breaking rain and inundation than the chicory, which generally thrives in drained soil.

By summer the ryegrass dominated the pasture area which was newly seeded; however, some patchiness persisted (Figure 3.7). These patches were likely the areas hindered by inundation or the effects of high clay content near to the surface.

In the following year, earlier germination minimised the effects of inundation and high clay content, resulting in spectacular growth of clover (Figure 3.8). Addition of organic matter from the pasture improved soil structure and retained nutrients, which increased plant growth in subsequent years.



Figure 3.6 Shallow puddles and inundation reducing germination and persistence of seedlings. Grasses persisted, while chicory (large yellow leaves in the left foreground of both images) did not germinate or failed to thrive





Figure 3.7 Strong growth of ryegrass pasture was dominant by the first spring (a), but varied establishment of the pasture persisted (b)



Figure 3.8 In the second season, pasture growth improved substantially and balansa clover was dominant

The inundation is relatively minor, but could be reduced by slightly increasing the grade to the drain alongside the paddock. However, some settling would be inevitable and the site would require spoon drains for beef grazing or regrading several years after construction.

Alternatively, using a raised bed will increase the effective drainage for greater longevity of P retention and increased pasture growth. This could be achieved by increasing the width and depth of the main drainage system or by retaining ponds to supply fill for raised beds, but these methods require further study to confirm their effectiveness.

### **3.3 Effect of MZI mine site on water quality**

The effect of the mine on water quality was assessed because P travelling across relatively flat paddocks and in the shallow drainage system may interact with clay from disturbed soil surfaces or the mining operation. These effects were examined through testing water quality in the drainage lines that travel across the site, generally from east to west. A nearby example of this effect occurred when a drain of vegetation was scraped during drain maintenance in Coolup, exposing the clay subsoil and causing a reduction in P concentration through run-off. This effect lasted for several years and has since been replicated by adding cracked lateritic gravel to the drain base, showing that the reduction in P was due to the clay's sorption of P or the water's exposure to lateritic surfaces (Summers et al. 2014).

#### **3.3.1 Methods**

Water flowing across the MZI mineral sands site was measured as part of the licence conditions of the mine. The results were analysed to identify the effects of the disturbance of the landscape and the exposure of clay on the quality of the water flowing across the mine site.

The location of surface water sampling sites can be seen with a surface water (SW) prefix in the map of the sampling sites (Figure 3.9). Watercourses that traverse the mine site were sampled upstream of the mine site (SW3), immediately downstream (SW4) and further downstream at the exit of the mine site (SW6) in 2016 and 2017.

The catchment upstream of the mine site is about twice the size of the catchment portion in the mine site that contributes to the downstream monitoring point (SW4). The upstream catchment extends into the scarp, where the slope and the higher run-off coefficient of soils derived from laterite cause the proportion of the flow to likely be greater than the coastal section.

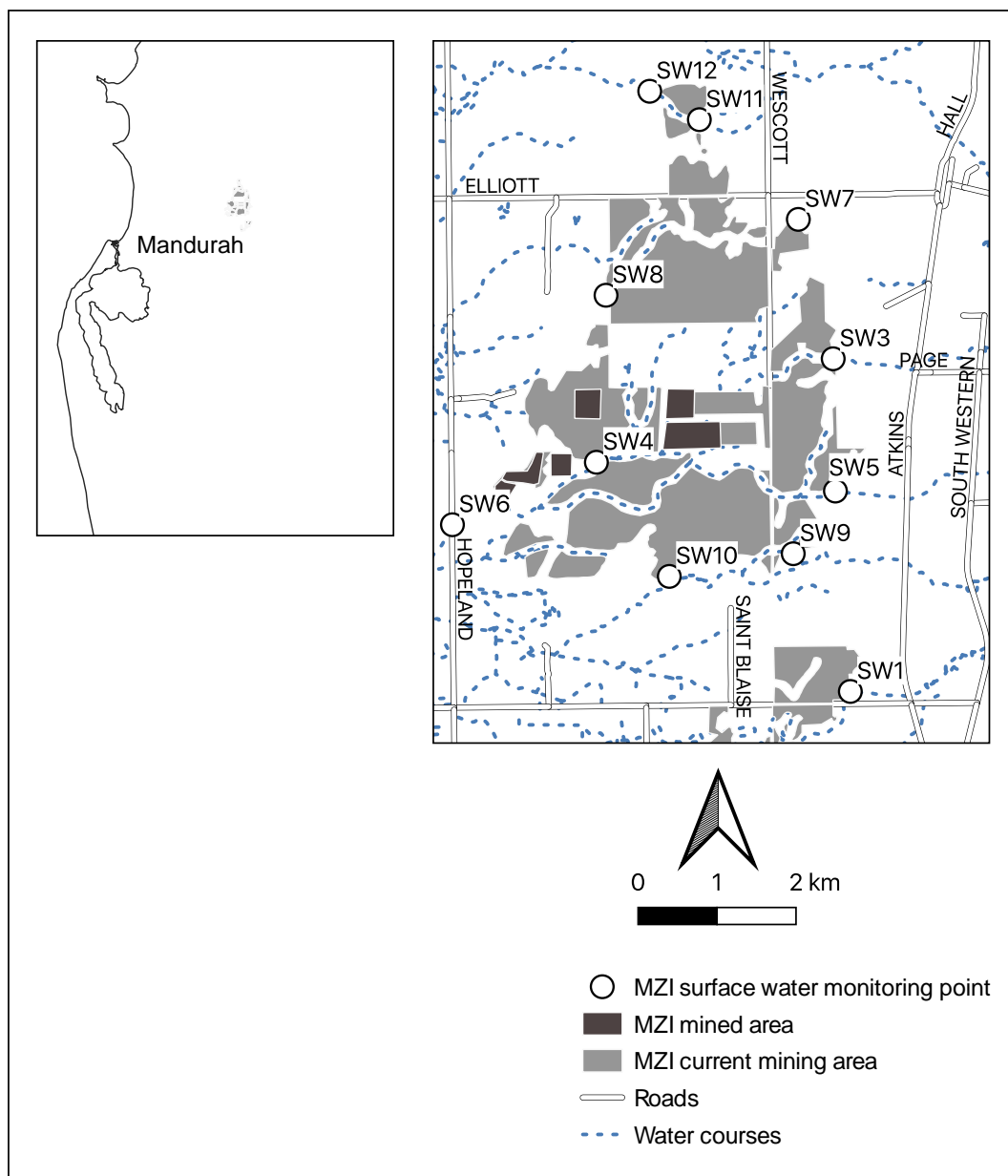


Figure 3.9 Sampling sites and watercourses traversing the mine area

### 3.3.2 Results and discussion

In general, the concentration of total phosphorus (TP; Figure 3.10), total nitrogen (TN; Figure 3.11) and, to a lesser extent, total suspended solids (TSS; Figure 3.12) progressively falls as the water travels across the actively mined site. In July, September and October 2017 the upstream sampling site (SW3) was moved away from an area draining an upstream dairy because there was different sampling staff and a change of protocol. This resulted in measuring a less contaminated section of catchment during these periods with much lower concentration of contaminants. The reduction in P may have been caused by no P being applied in the catchment during mining, which contributed to some dilution. Although the flows were not measured at these points, it is unlikely that an 800% dilution could have been responsible for the difference in concentration. Sorption of P onto clay exposed in the mining operation is likely to have been responsible for most of the P reduction.

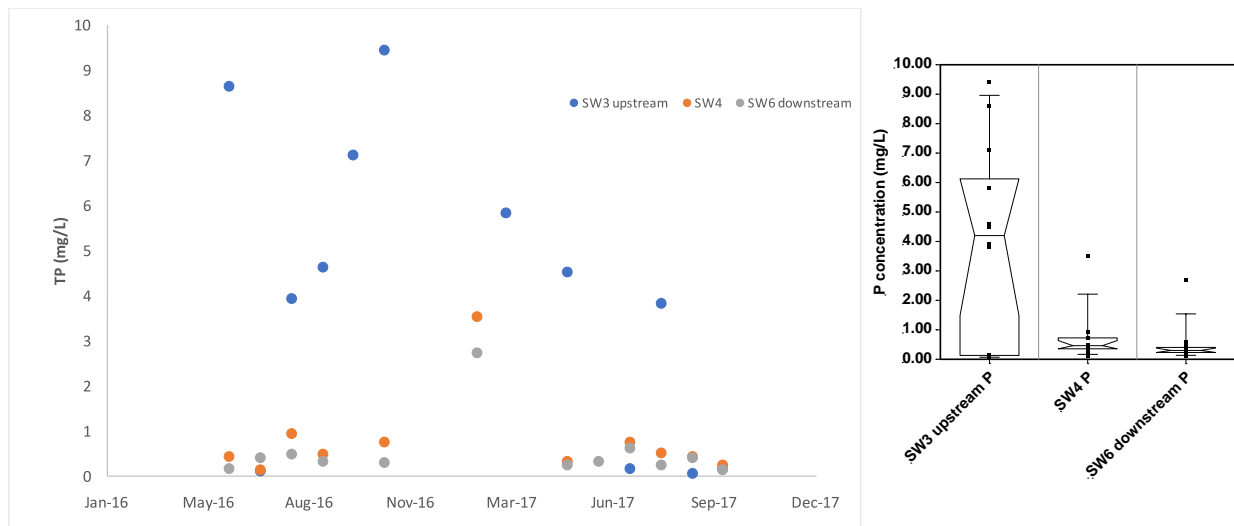


Figure 3.10 Concentration of total phosphorus (TP) in surface water (SW) from a watercourse that traverses the mine site from SW3 upstream of the mine site, through SW4 immediately downstream of the mine site and SW6 on the downstream exit from the mining area (inset shows a box and whisker summary)

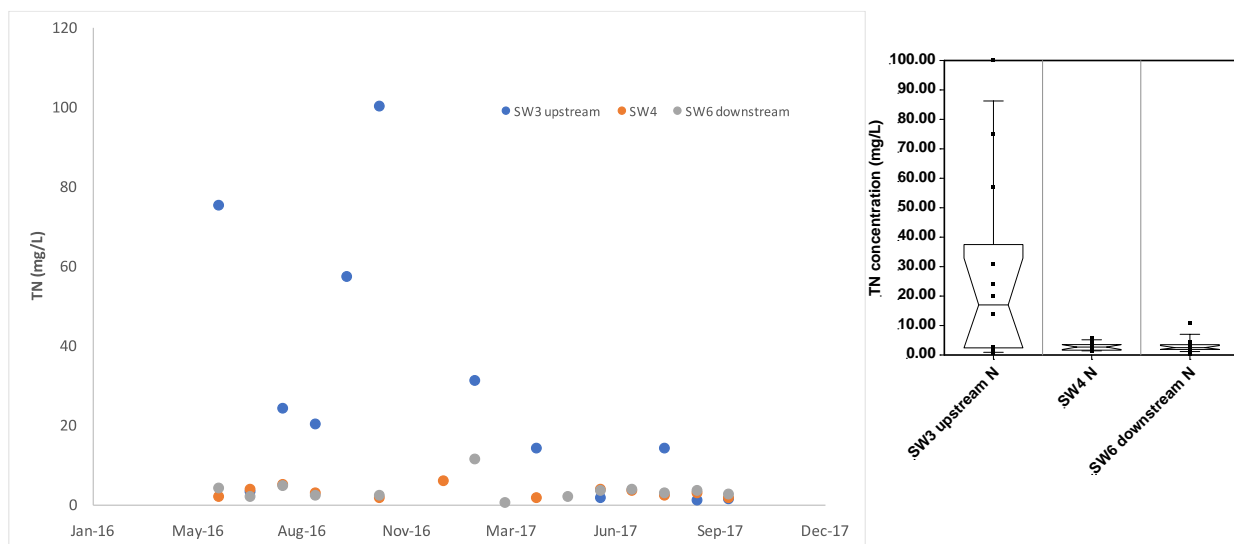


Figure 3.11 Concentration of total nitrogen (TN) in surface water (SW) from a watercourse that traverses the mine site from SW3 upstream of the mine site, through SW4 immediately downstream of the mine site and SW6 on the downstream exit from the mining area (inset showing a box and whisker summary)



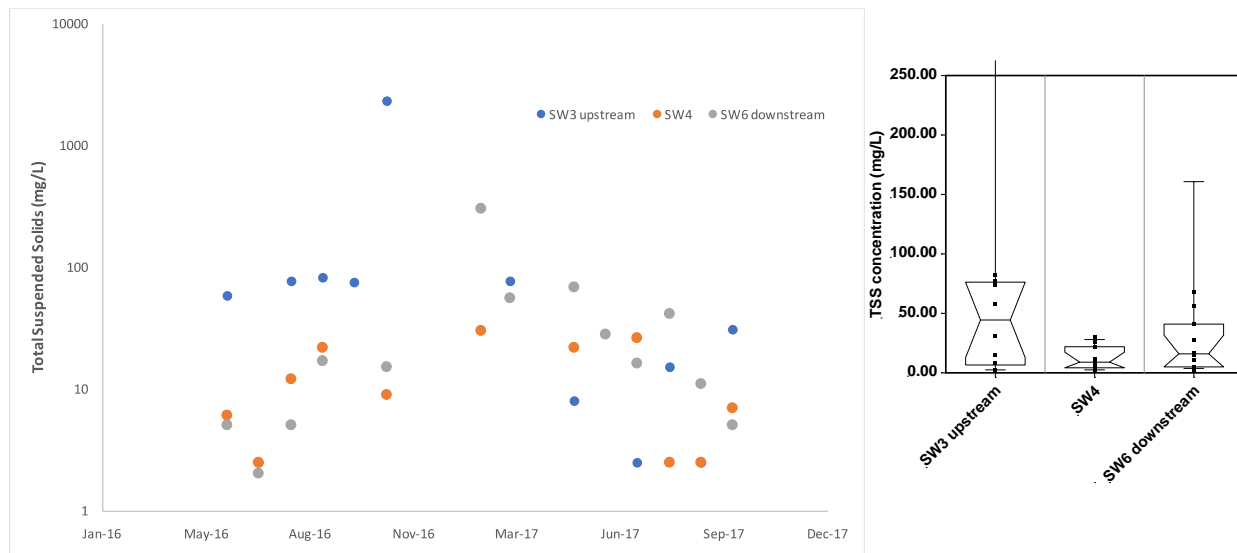


Figure 3.12 Concentration of total suspended solids (TSS) in surface water (SW) from a watercourse that traverses the mine site from SW3 upstream of the mine site, through SW4 immediately downstream of the mine site and SW6 on the downstream exit from the mining area (inset showing a box and whisker summary)

Reasons for the reduction of N concentration is unclear without further analysis of the fraction of nutrients in the run-off.

The reduction of P concentration across the site should continue beyond the mining operation through the rehabilitation of the entire mine site by mixing nutrient-retentive clay into the soil surface. The longevity of this reduction will depend on how well drained the site is after rehabilitation. If the landscape is returned to a flat landform that continues to become inundated in winter, then only the P retention of the shallow topsoil will retain surface-applied P fertiliser because the relatively static groundwater will act as a barrier to downward movement. Monitoring of other soil amendment sites used for beef grazing has shown that the capacity to retain P may be about 20 years (see Section 9). This would be assuming P fertiliser continues to be applied at the low rates associated with beef grazing. If the landscape is altered to include elevated sections that drain into excavated sections, the water will drain through a larger soil profile and P saturation of the topsoil will become less problematic. Moreover, the P retention should last longer with a larger P-sorbing profile. This affords the opportunity to explore potentially higher rates of P application.

The main finding is that P and N concentrations in the water decreased by over 85% after travelling across the site.

### 3.4 New process of pre-mixed sand and clay

MZI altered their method for filling the mine voids during this study. Mixing the clay and the sand on-site in the mine rehabilitation area was replaced with pumping a slurry of pre-mixed sand and clay into the void, removing the need for mechanical mixing in the paddock. If clay was to be used outside of the mine site, a different procedure would be required, such as spreading the clay through an agricultural lime spreader.

#### 3.4.1 Methods

The new mixture of sand and clay was sampled from one bulk sample and analysed to examine the chemical and physical properties.

#### 3.4.2 Results and discussion

The new soil profile is internally draining because the clay content is only 8.8% and the P retention is high enough (PRI 5.0–9.9) to control P leaching (Table 3.1 and Table 3.2). These qualities are similar to a Spearwood sand, which is ideal for annual and perennial horticulture. Soils with similar nutrient contents and many years of annual horticulture retain the P applied in the top 1m of soil (McPharlin et al. 1990). Note that the analysis of the new sand and clay mixture was from one bulk sample and varying clay content could occur depending on the clay in the profile and the depth of the excavation. MZI have reported that on occasions, mining depth increased with the express purpose of increasing the clay content of the ore. This facilitates more efficient pumping of the slurry back to the mine voids.

The fertility of the soil is very close to a virgin soil with low P, K, OC, pH and CEC (Table 3.2). In the samples taken from 12-month-old rehabilitation (Figure 3.3), these parameters rapidly improved after P, K and lime were added.

Table 3.1 Physical composition of two samples of the pre-mixed slurry of sand and clay that is now being returned to the rehabilitation sites

Electrical conductivity (dS/m)	pH		Clay (%)	Coarse sand (%)	Fine sand (%)	Sand (%)	Silt (%)
	CaCl <sub>2</sub>	H <sub>2</sub> O					
0.064	6.5	7.6	8.83	88.82	2.34	91.17	<0.01
0.064	6.1	7.3	8.80	87.24	2.97	90.22	0.98

dS/m = decisiemens per metre; CaCl<sub>2</sub> = calcium chloride; H<sub>2</sub>O = water

Table 3.2 Chemical composition of two samples of the pre-mixed slurry of sand and clay that is now being returned to the rehabilitation sites

P Colwell (mg/kg)	K Colwell (mg/kg)	Organic carbon (%)	CEC (meq/100g)	Exchangeable cations					PRI	PBI	Total P (mg/kg)
				Al (meq/100g)	Ca (meq/100g)	Mg (meq/100g)	K (meq/100g)	Na (meq/100g)			
3	25	0.10	1.28	0.22	0.52	0.32	0.04	0.17	9.9	29	8.0
2	21	0.09	0.99	0.22	0.29	0.22	0.03	0.22	5.0	22	2.5

Al = aluminium; Ca = calcium; Mg = magnesium; Na = sodium

An evenly mixed soil profile with only 8.8% clay is likely to improve the variable drainage and mixing issues in the earlier technique which caused some surface ponding of water (Figure 3.6) and some variation in plant establishment (Figure 3.7). Despite having better permeability, this ponding is likely to persist if the paddock does not have a steady grade to the drainage line or spoon drains to remove heavy rainfall. In its current form, the site would only be suitable for grazing livestock, as it was before.

Alternatively, the risk of inundation could be reduced by redistributing some of the soil from the excavation to increase the height of the soil profile (Figure 3.13). This would leave ponds in the paddock which could serve as stock watering points or as a superficial water source for irrigation. Increasing the width and depth of drainage would improve drainage, generate more soil for elevation and allow for crops that cannot tolerate waterlogging. Ponds and broader watercourses would increase the opportunity to retain nutrients on-site for longer and with greater interaction with a larger sediment surface.

The new clay and sand mixing technique produces a superior mix with consistent P retention that is high enough to retain annual horticultural P applications if the landscape is modified for water to drain through the soil rather than over it.

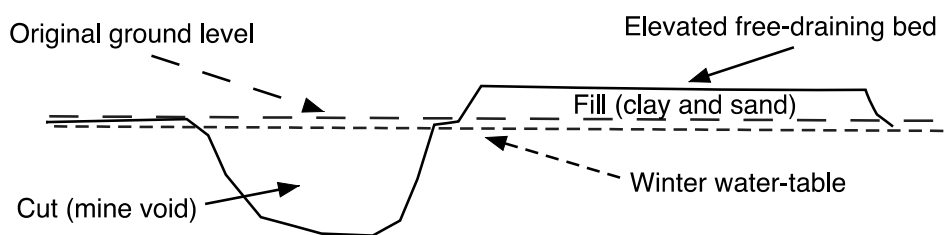


Figure 3.13 Cross-section of an alternative rehabilitation profile that encourages water to drain through the soil rather than over the soil

## 4 Glasshouse trials of soil amendment with MZI clay and sand

Mixing clay sourced from deep in the mine's soil profile will affect how much P is required for adequate growth because the clay has a much greater capacity to retain P. A trial was needed to define the ideal clay content for a range of applications after rehabilitation or off-site. The subsoil clay which has not been exposed to P will compete with plants for the P applied in fertiliser; therefore, the effect of clay on P requirements must be defined.

To assess this effect, varying proportions of clay were mixed and clover (*Trifolium subterraneum*) was grown using varying rates of P. Changing rates of P were used to define the response of the plant to applied P for the new soil type and to determine whether the clay was different to natural soils of similar P-sorption capacity. Agronomists will be able to use this information when recommending applications of fertiliser to these new soils.

Knowing the soil's capacity to retain P enables the P fertiliser requirements from the Colwell soil P test (plant available P) to be accurately interpreted, and also provides information about the risks of P leaching. To enable a consistent mix of clay and sand in the mining rehabilitation program, a measure of the clay content or, preferably, the soil P-retention capacity is required. Both the clay content and conventional measures of P-retention capacity are slow and expensive, limiting their value for the frequent and timely decisions concerning the clay content of the material returned to the mined areas.

There are no simple methods for measuring the P-sorption capacity of soil. Therefore, a technique that used a pH soil test in a sodium fluoride (NaF) solution to determine the clay content and PBI in the field or in a rudimentary mine laboratory with simple pH testing equipment was explored.

### 4.1 Preliminary glasshouse trial

A preliminary trial using 8.8% clay mix was developed to determine the range of rates of P to apply during the full trial that would include a range of rates of clay.

#### 4.1.1 Methods

Ten rates of P were used, one rate of clay (8.8%) and two replicates in 4.5kg pots. Rhizon sampling tubes ([www.rhizosphere.com](http://www.rhizosphere.com)) were inserted in the lower third of each pot. The plants were grown for 10 weeks.



#### 4.1.2 Results and discussion

##### *Plant growth*

The plant growth continued to rise and did not reach a maximum (Figure 4.1), showing the application rate of fertiliser P needed to be higher to meet the maximum requirements in the 8.8% clay and higher again for the next trial of mixes with a greater proportion of clay (10.7% and 13.6%). The increase in plant growth alongside the increase in P is apparent in Figure 4.2.

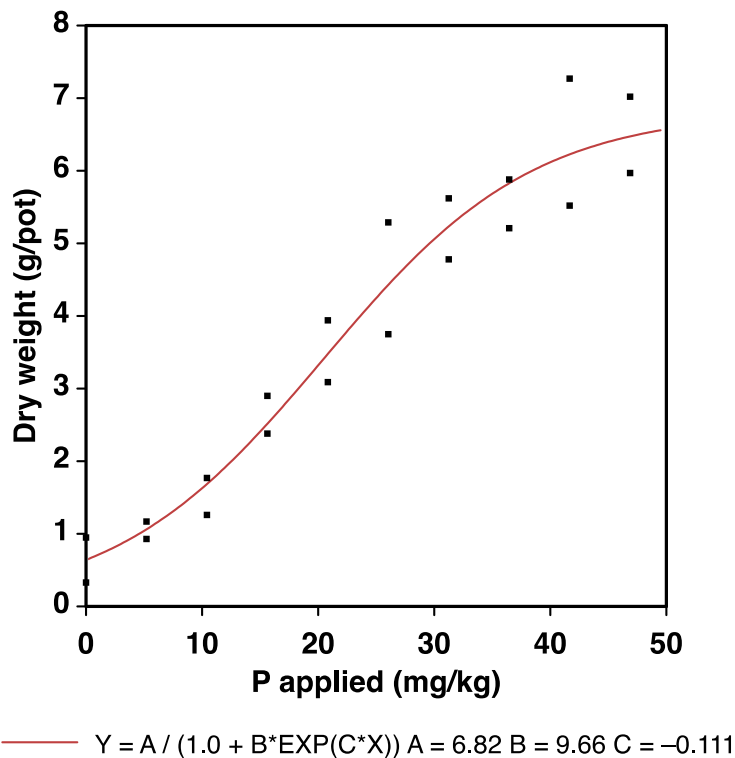


Figure 4.1 The plant growth in response to applied P on the initial trial with 8.8% clay



Note: The white Rhizon sampling tubes can be seen inserted in the lower third of the pots.

Figure 4.2 Clover growth in pots with varying rates of P applied: a) 0kg/ha; b) 17kg/ha; c) 42kg/ha; d) 75kg/ha

#### *Plant tissue analysis*

Analysis of the harvested plant tops indicated no nutrient deficiencies, except the expected P deficiency in the lowest application rates of P (Table 4.1). Additionally, there were no toxicities found in the tissue analysis.

Table 4.1 Tissue analysis of whole plant tops compared with the agronomic range (Reuter & Robinson 1997) and the maximum levels of minerals in feed from (National Research Council 2005)

P applied	P applied	Arsenic	Boron*	Cadmium	Calcium*	Chloride	Chromium	Copper*	Iron*	Lead	Magnesium*	Manganese*	Nickel	NO <sub>3</sub> *	Phosphorus*	Potassium	Sodium	Sulfur	Total nitrogen	Zinc
mg/kg	kg/ha equiv.	µg/kg	mg/kg	µg/kg	%	%	µg/kg	mg/kg	mg/kg	µg/kg	%	mg/kg	µg/kg	mg/kg	%	%	%	%	%	mg/kg
46.9	75	256	33.8	91.0	1.38	1.36	1883	33.6	307	338	0.43	205	446	3038	0.52	2.83	1.08	0.40	3.55	60.2
41.7	67	217	33.7	76.0	1.27	1.46	984	36.1	338	285	0.43	199	526	2732	0.44	2.88	1.09	0.39	3.22	57.0
36.5	58		36.8		1.27	1.64		41.3	138		0.46	203		5599	0.48	3.42	1.38	0.41	4.08	65.3
31.3	50		35.4		1.44	1.54		35.6	191		0.49	226		3718	0.36	3.17	1.17	0.43	3.89	61.9
26.0	42		31.7		1.33	1.45		33.3	318		0.45	246		4193	0.33	2.75	0.95	0.38	3.81	65.6
20.8	33		32.8		1.33	1.45		34.8	326		0.49	255		4037	0.27	3.00	0.96	0.40	3.94	68.7
15.6	25		31.1		1.5	1.50		34.8	234		0.58	276		4046	0.21	0.22	0.23	0.24	0.25	75.1
10.4	17		28.2		1.3	1.70		34.5	191		0.52	215		3275	0.19	2.07	1.01	0.34	3.85	61.8
5.2	8		25.4		1.1	1.80		46.9	212		0.41	150		3537	0.24	2.20	0.96	0.34	4.28	55.0
0.0	0		23.2		1.1	1.50		29.8	200		0.43	137		528	0.09	1.42	1.11	0.22	3.08	74.9
Plant nutrient range																				
Target range			15–25		0.7–0.8			4.6–6.5	30–40		0.2–0.3	30–35		41–150	0.28–0.32	1.5–2.0		0.22–0.25	2.5–4.0	16–22
Toxic			10 000		20			>1000	100 000		10	10 000		>5000	>10	>10	>10	>0.45		>2000
Livestock range																				
Maximum tolerable level		30 000	150	10 000	1.5		100 000	40	500	100 000	0.6	2000	100 000							500

\* Elements applied in the application of basal nutrients.

## 4.2 Main glasshouse trial

Another glasshouse trial was designed to assess the ideal range for rates of clay to improve the nutrient and water retention for land uses after the mine site's rehabilitation. This identifies the possible specifications required for soil mixtures to fulfil the different nutrient application rates of these land uses.

### Summary of findings:

- Clover grown on a sand mixed with 8.8% clay showed no deficiencies or toxicities.
- No more P than expected is required, as P requirements are similar to those derived from national recommendations based on the clay content or PBI.
- P fertiliser must be applied to the rehabilitated soil and soil testing is required to determine the rate of P applied (standard soil testing guidelines apply).
- The extra P retention from the clay will greatly reduce the P leaving the site, if P is applied only where needed.
- Although P in solution is reduced by clay, it is not reduced enough to meet water quality targets for the waterways.
- Addition of clay increased the requirement of P through the effect of increasing P-retention capacity.
- The pH test using a sodium fluoride solution was found to be a quick and effective test to determine the P-retention capacity (PRI or PBI) and clay content.

### 4.2.1 Methods

Permeable tubes for soil water sampling ([Rhizons www.rhizosphere.com](http://Rhizons.com)) were inserted into the pots for the main glasshouse trial. The samples were analysed to assess the P concentration of the soil solution as a surrogate for the effects of fertilisation on P leaching. The soil was also analysed to assess the clay's effect on the soil's properties.

The 10-week trial had five rates of P and three replicates at five rates of clay — 2.9%, 5.5%, 8.8%, 10.7% and 13.6% — in 4 litre (L) pots with about 6kg of soil (Table 4.2). A basal application of nutrients, excluding P (all solutions in Table 4.3), was applied prior to seeding and a solution of  $\text{NH}_4\text{O}_3$  and  $\text{K}_2\text{SO}_4$  was applied weekly after the third week (single solutions 4 and 5 in Table 4.3). The soil was watered to minimise losses from the free-draining pots so that most of the P concentration could be attributed to plant uptake and clay sorption rather than leaching.

The different soil mixtures of clay and sand used in the glasshouse trial were tested for  $\text{pH}_{(\text{NaF})}$  and for measures of P sorption and clay content to gain a simple indication of P retention without laboratory access. The literature describes some minor differences in the  $\text{pH}_{(\text{NaF})}$  technique. Here, a 1 molar NaF solution was used in a 1:40 ratio of soil to solution with a contact time of one hour. The solution was then measured using a standard pH meter.

This method relies on adding a NaF solution to the soil, which results in the fluoride ion displacing hydroxyl ions from the clay, as well as organic fractions that cause increased pH. The more hydroxyl ions removed from the clay, the stronger the P-retention capacity. This  $\text{pH}_{(\text{NaF})}$  test has previously been used to indirectly test P-sorption capacity

(Alves & Lavoretti 2004; Fieldes & Perrott 1966; Gilkes & Hughes 1994; Singh & Gilkes 1991).

Table 4.2 Treatments of P applied to pots with differing clay contents

Increase in clay content relative to base sand – 2.9% clay (t/ha)	0	35	75	100	140
Clay content (%)	2.9	5.5	8.8	10.7	13.6
P applied to pots (kg/ha equivalent)	0.0	0.0	0.0	0.0	0.0
	7.9	9.8	11.7	12.1	12.6
	15.9	19.6	23.3	24.3	25.2
	31.7	39.2	46.7	48.5	50.4
	55.5	68.6	81.7	84.9	88.2
	71.4	88.2	105.0	109.2	113.4

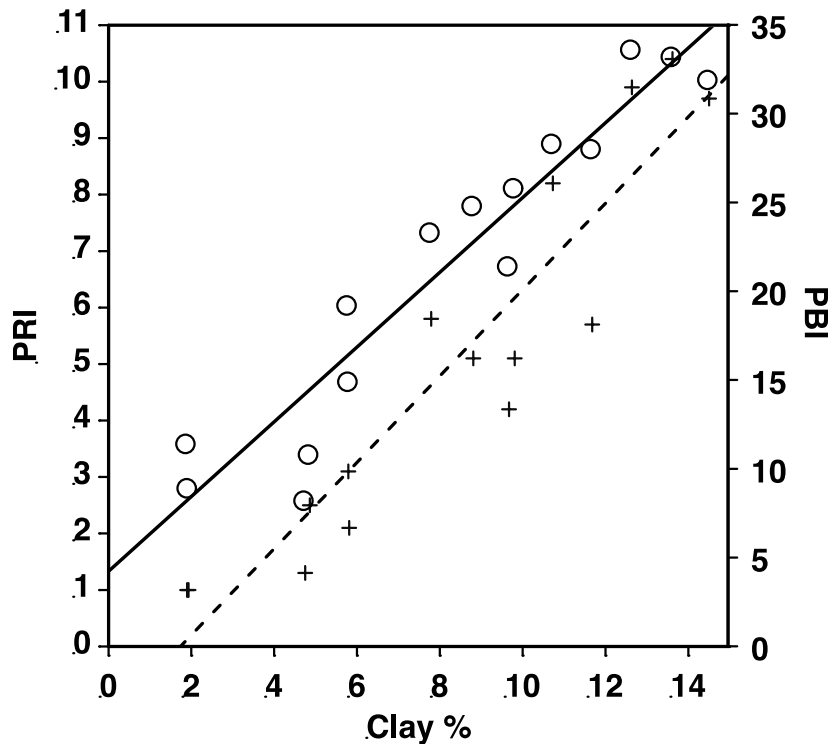
Table 4.3 Complete basal solutions (without P) applied at the start of the trial (all solutions) and the weekly maintenance basal (solutions 4 and 5)

Nutrient	Concentration (g/L)	Volume per pot (mL)	
Na <sub>2</sub> MoO <sub>4</sub>	1.60	3	Combined solution 1
H <sub>3</sub> BO <sub>3</sub>	0.08	3	Combined solution 1
ZnSO <sub>4</sub>	2.80	3	Combined solution 2
CuSO <sub>4</sub>	3.20	3	Combined solution 2
MnSO <sub>4</sub>	11.40	3	Combined solution 2
MgSO <sub>4</sub>	120.00	3	Combined solution 2
CoSO <sub>4</sub>	0.20	3	Combined solution 2
CaCl <sub>2</sub>	50.00	3	Single solution 3
NH <sub>4</sub> NO <sub>3</sub>	60.00	3	Single solution 4
K <sub>2</sub> SO <sub>4</sub>	64.80	3	Single solution 5

### 4.2.2 Results and discussion

#### *Sodium fluoride pH*

The slimes fraction from the MZI mine site had 79% clay which had a PRI of 1331 and a PBI of 298 ( $n=3$ ) and the relationship between clay content and PRI or PBI was linear up to the highest level of clay used in the pots (Figure 4.3).



Notes:

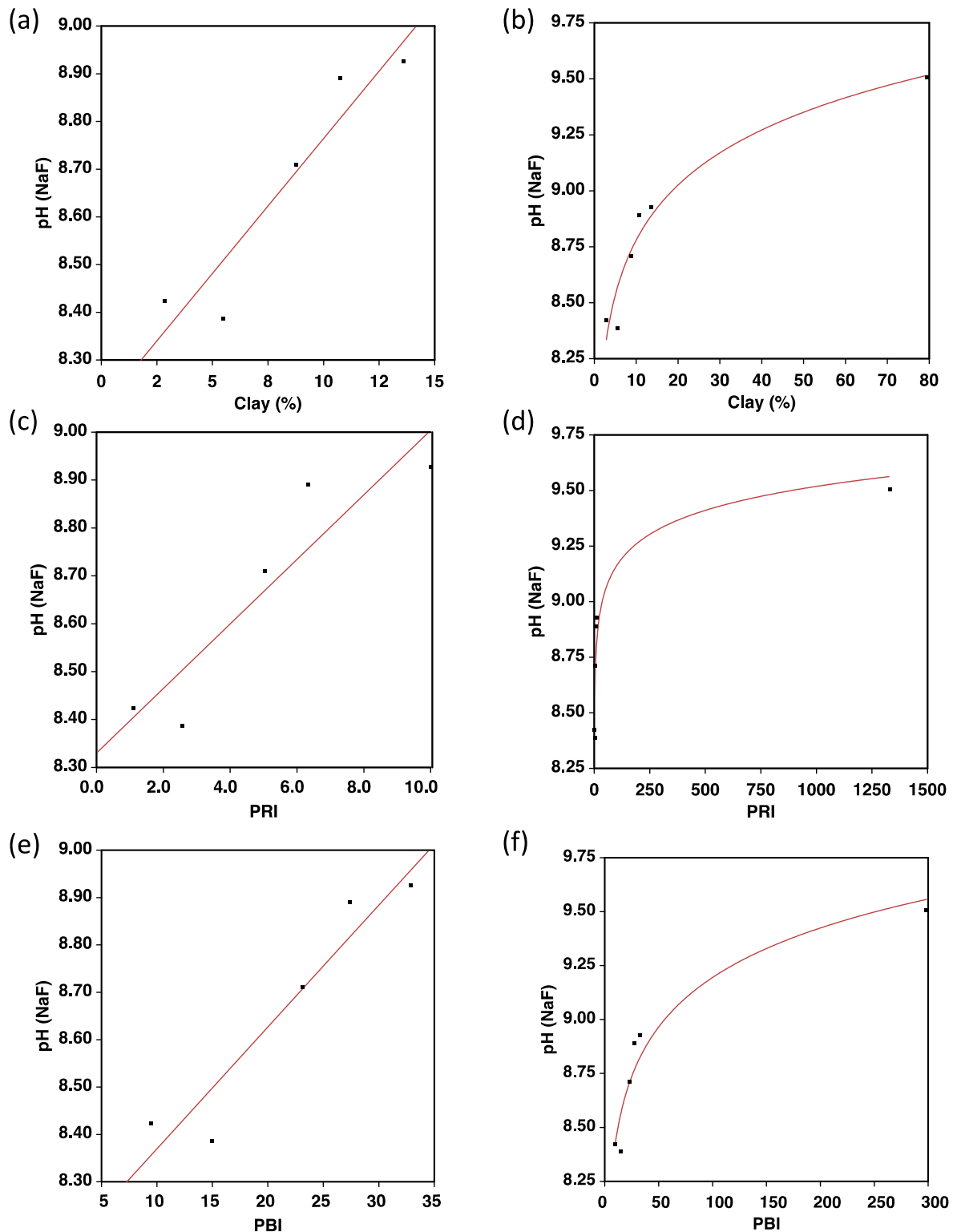
1. PRI is the dashed line and crosses, and PBI is the black circles and solid line.
2. Regression of PRI is  $Y = 0.76X - 1.32$  ( $r^2 = 0.87$ ); regression of PBI is  $Y = 2.11X + 4.13$  ( $r^2 = 0.90$ ).

Figure 4.3 Phosphorus retention index (PRI) and phosphorus buffering index (PBI) of the MZI sand and clay mixes

The relationships between the  $\text{pH}_{(\text{NaF})}$  and the clay content, and PRI and PBI are logarithmic up to 79% clay (Figure 4.4a, b, c, d). These relationships also highlighted a linear relationship in the range that indicated where most of the clay content will likely be generated on the mine site.

The results show that this test can be used as an accurate measure of clay content in the mine site and, more generally, to determine the PBI of soil in a simple, cheap and quick test. The  $\text{pH}_{(\text{NaF})}$  test can monitor the quality of the soil returning to the mine void and replace more-expensive tests for the agronomic assessment of a soil's P-buffering capacity.





Note:

Clay (%) by  $\text{pH}_{(\text{NaF})}$ : linear  $Y = 0.0566X + 8.20$ ,  $r^2 = 0.89$ ; log curve  $Y = 7.96 + 0.355 * \ln(X)$ ;

PRI by  $\text{pH}_{(\text{NaF})}$ : linear  $Y = 0.0674 + 8.33$ ,  $r^2 = 0.847$ ;  $Y = 8.44 + 0.155 * \ln(X)$ ;

PBI by  $\text{pH}_{(\text{NaF})}$ : linear  $Y = 0.0257X + 8.11$ ,  $r^2 = 0.91$ ;  $Y = 7.67 + 0.33 * \ln(X)$

Figure 4.4 The relationship between the proportion of clay and the  $\text{pH}_{(\text{NaF})}$  shown as the linear section (left) and log curve (right) for the expected clay content range and for clay contents up to 79%

### Plant growth

The design of the glasshouse trial enabled an assessment of the plant growth, plant tissue content and P in solution for a range of rates of clay incorporated into the soil.

More clay requires more P to be applied for the same growth. The increase of clay in the soil steadily increased the amount of P required, as shown by the decreasing slope of the fitted curves (Figure 4.5), which is represented by the 'c' coefficient in the equations below decreasing from 0.59 in the lowest clay content to 0.11 in the highest. More P was needed because the increasing clay content was competing against and buffering the applied P. At the highest clay content of 13.6%, the full range of the response curve was not explored and the curve may not be fully representative without higher applications of P being applied.

The clay content had little effect on the maximum yield. The pots were watered to achieve the best growth and the improvements in growth from the addition of clay will likely become more apparent in the field. Increases in water-holding capacity, and season length are favoured by soils with higher clay content between rainfall events.

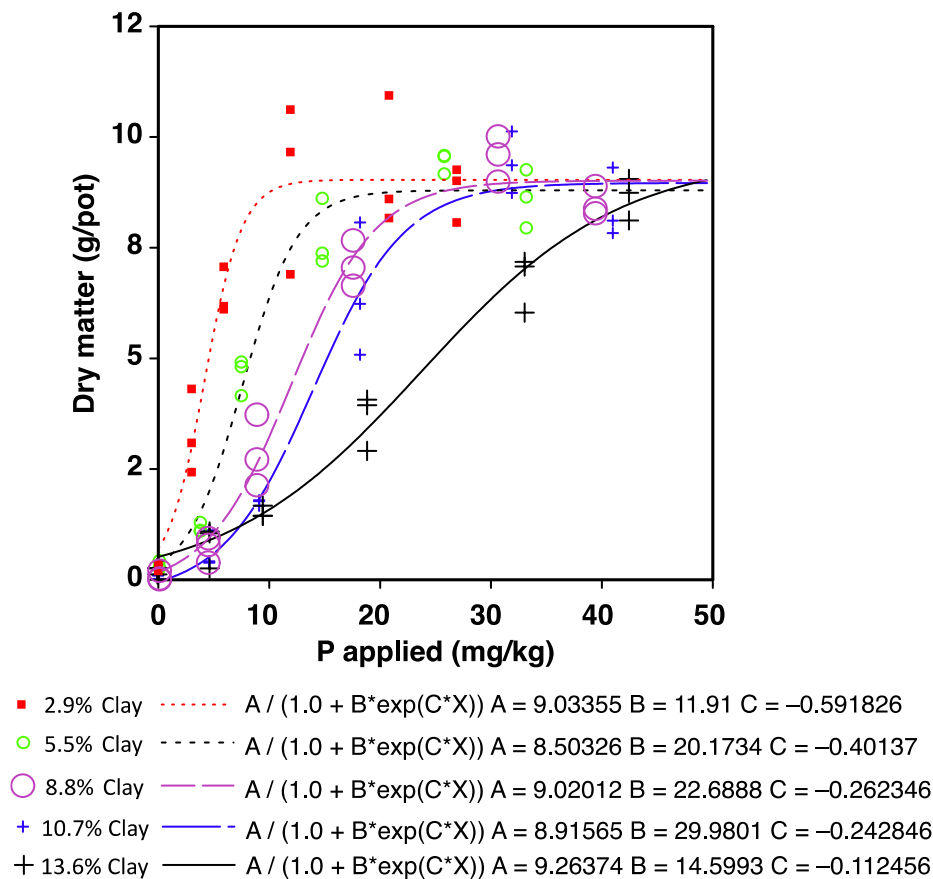


Figure 4.5 Plant yield as influenced by P applied and clay content



The estimations of P requirements from the glasshouse trials are lower than published field requirements. Less P was required in the glasshouse trials than those of the recommendations (Table 4.4) probably because leaching losses were minimised, and fertiliser recommendations in Summers and Weaver (2011) are based on field trials.

Note that the fit of the dry matter production curve for the 13.6% clay treatment was limited by not having enough P applied to fully explore the curve to a plateau (Figure 4.5).

Table 4.4 The fitting of the response curve from the pot trial and P requirement based on recommended values from the tables of (Gourley et al. 2019; Summers & Weaver 2011)

Clay (%)	PBI	Target Colwell P 95	P for 95% of maximum* yield (kg/ha)	P required based on continuous function (mg/kg)	P required based on continuous function (kg/ha)
2.9	9.5	17	33 (32)	9	14
5.5	15.0	21	44 (41)	15	24
8.8	23.2	25	58 (50)	23	37
10.7	27.4	26	58 (53)	25	40
13.6	32.9	27	58 (55)	50	80

\* Values from the tables used in Gourley et al. (2019); (Summers & Weaver 2011) have been converted to a continuous function and are shown in brackets.

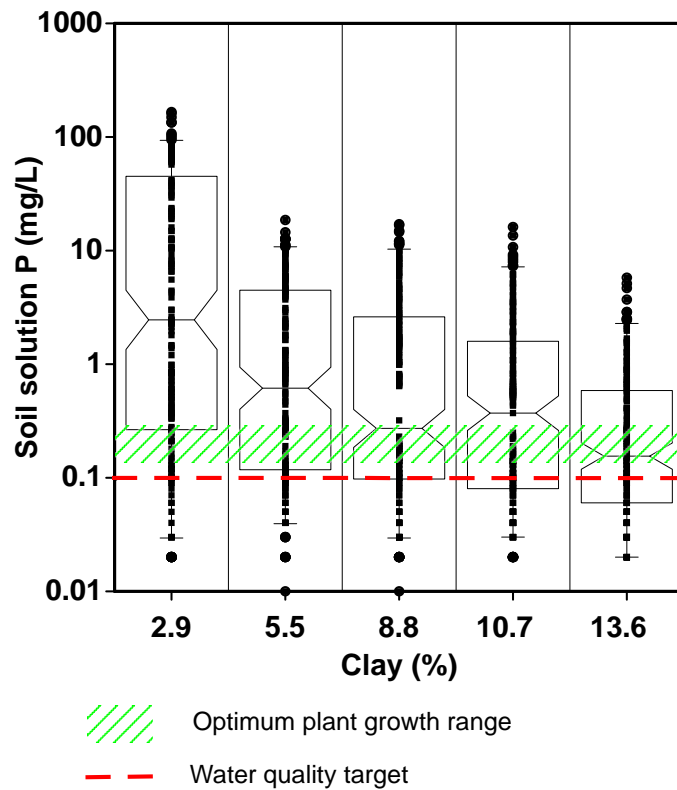
Note: The response curve was solved by [www.symbolab.com/solver/](http://www.symbolab.com/solver/).

### *Phosphorus concentration in soil solution*

The P concentration in sand without added clay had several times more P in solution than those with added clay. Even at high rates of P fertiliser, clay reduced the P concentration in the soil solution. More clay resulted in considerably less P in the soil solution (Figure 4.6) — the 2.86% clay soil had a median P concentration of 2.45mg/L and the 5.5% clay soil had a median P concentration of 0.61mg/L. The P concentration in solution of each pot gradually declined over the weeks of the experiment (Figure 4.7).

The P concentration in soil solution fell with the increasing clay content despite increased application of P necessary to achieve the P concentration for optimum plant growth (Figure 4.7).

Even with clay and optimum P application, the P in the soil solution was well above soil solution concentrations for optimum plant growth and environmental targets for most of the growing season. The target for P concentration in water running into the Peel–Harvey Estuary is 0.1mg/L (Environmental Protection Authority 2007), which is difficult to achieve with even the highest clay content demonstrated here. Consequently, the P concentration in the soil solution will always be higher than is acceptable at the Peel–Harvey Estuary, if optimum agronomic yields are desired. The P concentration in soil solution is higher than in run-off; however, relative comparisons should be made because plant uptake, dilution and sorption occurs enroute from the paddock and the waterbodies.



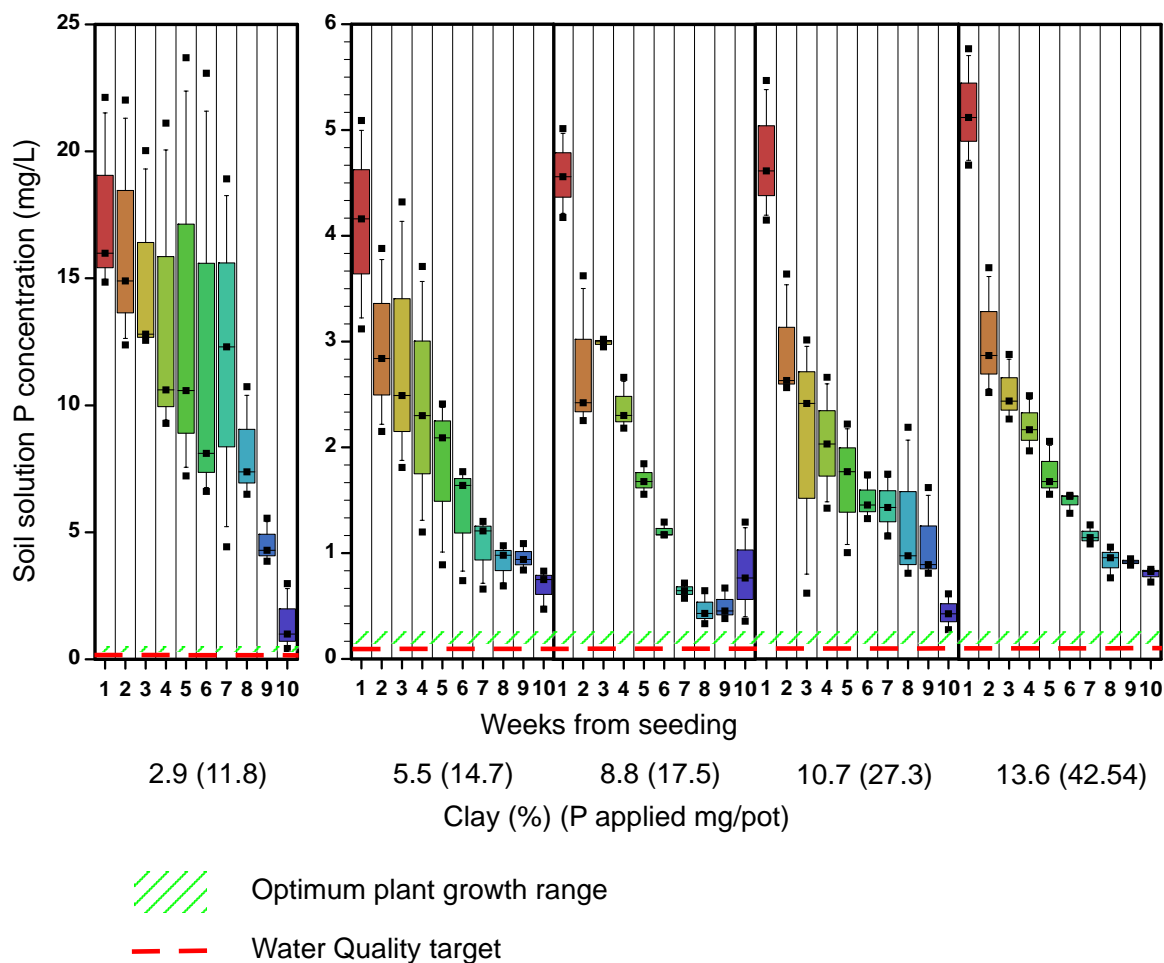
Note: The dashed red line is the target for water flowing into the Peel–Harvey Estuary and the diagonal green stripes show the range for P concentration for optimum plant growth.

Figure 4.6 The soil solution's P concentrations, aggregated for each of the clay contents and each of the P applications

Currently the P concentration and load entering the Peel–Harvey Estuary needs to be reduced by 50% to meet the environmental targets. A 75% reduction in P concentration in soil solution is achievable when the clay content is increased in a sand with no added clay, which has 2.9% clay, to a sand with 5.5% clay which would require 35t/ha of clay added (0–10cm).

Maintaining an optimum P concentration in the soil solution of 0.15–0.3mg/L for optimum plant growth (Asher & Loneragan 1967; Russell & Russell 1973) requires considerably more P in the soil solution than optimum for most of the growing season because of the progressive reduction of P concentration (Figure 4.7). The excess at the start of the season represents an increased risk of leaching and contaminated run-off. Moreover, the optimum P concentration for plant growth is above the target for the water running into the Peel–Harvey Estuarine System.

The aim of soil amendment is to proportionally reduce the P losses from paddocks and to combine the approach with other measures to meet the catchment targets. These results show it is possible to meet targeted proportional reductions by adding clay to the soil. Later discussions show how using soil amendment at the paddock scale effects translate to catchment scale reductions and contributes to catchment targets.



## Notes:

1. The red dashed line is the target for water flowing into the Peel–Harvey Estuary and the diagonal green stripes show the range for P concentration for optimum plant growth.
2. The P applied (in brackets) is that required to reach 95% of maximum production.

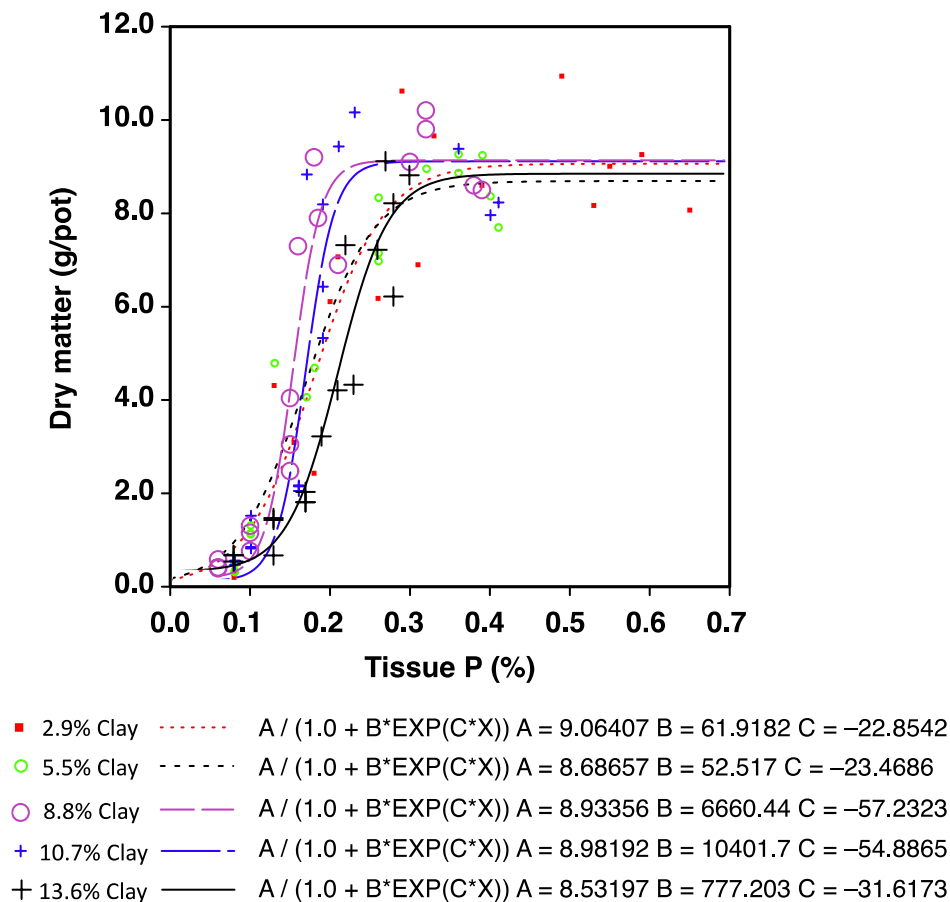
Figure 4.7 The continuous decline in P concentration in the soil solution for each of the clay contents

### Plant tissue analysis

The addition of clay did not reduce the yield response to P. The slope of the dry matter response curve (Figure 4.8) indicates that the 8.8% and 10.7% clay content may have had minor relative benefits for yield response to P, which may increase the efficiency of uptake and use of the applied P, potentially also reducing P loss yield response was (in order) 8.8% ≥ 10.7% > 13.6% > 5.5% > 2.9%, but none of these were significantly different ( $P < 0.05$ ).

The tissue concentration of clover plants grown in the glasshouse compared well with data from the literature. A variation on the Mitscherlich curve was fitted to the combined data of Figure 4.8 (curve not shown), resulting in a plant tissue P concentration for 95% of maximum production equalling 0.27%; for 90% of maximum production, P concentration was 0.25%; for 85%, P concentration was 0.23%; for 80%, P concentration was 0.22% ( $Y = 8.69 / (1.0 + 0.014 * \text{EXP}(-0.287X))$ , sum squared absolute error = 0.0195). This corresponds with published marginal range of 0.22–

0.23% and adequate range of 0.25–0.50% for clover (*Trifolium subterraneum*) at pre-flowering, although the P levels here at 63 days after emergence were slightly higher than at the start of flowering (Weir & Cresswell 1993).



Note: Relationships are combined for all clay treatments.

Figure 4.8 The relationship between the clover plant tissue and the dry matter yield at 63 days after emergence

## 5 Impact of MZI mine operations on water quality

### Summary of findings:

- P loads from Nambeelup could be reduced by as much as 16% in the long term by the current mixing clay to rehabilitate the Keysbrook mine site.
- Soil amendment of the predominantly sandy Nambeelup Catchment with MZI clay could reduce P loss by more than 68% or 7.1t of P.
- Widespread soil amendment of sandy soils in the Peel–Harvey Catchment could reduce P loads by 27% or 48.5t of P.

The current area mined is about 430ha and the approximate rate of mining is 150ha/y. The approved footprint is currently 1380ha. Adjacent areas with a reasonable prospect of being mined (subject to approvals and farmer consents) could add 700ha. There may be a further 2000ha available, if it is economically feasible in the longer term. The total potential area in the longer term, subject to approvals, is 4080ha.

Soil amendment on a similar scale (4300ha) at the Meredith Catchment near Harvey increased P sorption by a fraction of the amount created by the mine rehabilitation at Nambeelup. P losses were reduced by about 50% at the Meredith Catchment (Summers, Guise & Smirk 1993) and by as much as 97% at 200t/ha of soil amendment (Ward & Summers 1993). Based on the monitoring of the Meredith Catchment by the Department of Water and Environmental Regulation (DWER), the P load was reduced by about 2t/y.

Soil amendment with another mining by-product in the Nambeelup Catchment on Lakes Road resulted in a 70% reduction of P loss (Summers, Vlahos & Bell 1989; Summers 2001). Moreover, the soil disturbance and exposure of subsoil clay to the passing water makes the mine site effectively a large area of amended soil which is already having a positive effect on the water quality of the area with the P concentration being reduced from 4mg/L to 0.5mg/L (87% reduction above) for water traversing the site.

If the soil amendment is restricted to the potential MZI area, the P reduction would be 87% from 4080ha. Because the water traversing the mine site drains east from the Darling Scarp across farmland that is discharging nutrients into the water, the mine site is processing this upstream water as well as run-off derived from the mine site, effectively improving water quality from about twice the area of the mine site.

The Nambeelup Catchment has an area of 14 300ha and discharges 10.5t of P per year and 43.8t of N per year (Table 5.1). The potential MZI area with consent is about 2080ha, which is 14% of the Nambeelup Catchment and could be double with longer term approvals. Assuming 87% P reduction from the potential area with longer term approvals, P reduction of 16% of the 10.5t of P per year or a reduction of 1.7t of P per year is possible (Table 5.1). This compares to findings obtained from field results of the Meredith Catchment site, which had substantially less increase in P retention of the soil.

At the current rate, it would take over 20 years to mine the potential resource area, so any P reduction effect would be phased and lagged because the mine site is upstream of most of the catchment, which would continue to discharge P into the run-off water.

Please note that this is a simple estimate, not modelled data. Also, the effect on N is not considered here because the mechanism of N retention is not known and cannot be extrapolated to a larger area of catchment.

Table 5.1 Nutrient load of the Nambeelup Catchment

Nutrient	Load (t/y)	Load (kg/ha)
Total nitrogen	43.8	3.6
Total phosphorus	10.5	0.86

Source: (Kelsey et al. 2011)

Table 5.2 Potential effects of the MZI mine site on water quality in the Nambeelup Catchment, if the 87% P reduction from rehabilitated land is maintained

	Time frame (years)	Cumulative area of effect (ha)	Potential P load reduction (kg)
Current area	Now	430	179
Current approved area	6	1380	576
Potential area with consent	11	2080	868
Long-term potential area with approvals	24	4080	1703

## 5.1 Widespread soil amendment in the Peel–Harvey Catchment

There is excess clay available from the mine site to enable soil amendment elsewhere in the catchment. The rehabilitation process at MZI now mixes the clay with the sand and pumps the mixture directly into the mine voids. The P-retention capacity indicates that this process generates much more clay than necessary for the entire soil profile to reduce P loss by 50% and only soil amendment of the top 10cm would be required for the application rates of P normally associated with beef grazing. If the deeper subsoil was filled with sand and some of the clay was reserved and used elsewhere, the applicable area for soil amendment would represent up to 65% of the Peel–Harvey Catchment.

Widespread soil amendment of sandy soils in the Peel–Harvey Catchment has been modelled and could reduce P loads by 27% or 48.5t of P (Kelsey et al. 2011).

Please note that using clay from the mine site for soil amendment elsewhere is a substantial intervention to the mineral sands operation and would require a strong economic driver. There may also be regulatory issues associated with the mining of clay and potential conflicts with existing requirements for rehabilitation.

## 6 Soil amendment of a nearby market garden

The soil and groundwater from a market garden on Corio Road in Ravenswood were analysed to assess the effects of the pre-existing bentonite clay soil amendment on the groundwater. The analysis also provided an understanding of the area's potential for increased intensity of land use by applying various types of local clay to the site. Notably, this information may be applied to soil amendment using clay from the MZI site in the future.

### Summary of findings:

- P leaching at the Corio Road horticultural site appears to be minimised by lowering the watertable below and through the pre-existing, naturally occurring clay that is deep in the soil through pumping groundwater from bores and a soak. This clay is likely to be similar to the MZI clay nearby.
- N leaching is extremely high throughout the groundwater within the property, showing that it is difficult to meet environmental guidelines with intensified land uses, such as in-ground horticulture.
- The majority of N may be being recycled after capture by the irrigation bore field, thereby minimising the off-site effects.
- Bentonite clay appeared to reduce P leaching by about 50% in the shallow soil layer.
- Some P appears to escape to the untreated west side of the property, and less so to the east where the site was treated with bentonite clay.
- Soil moisture monitoring showed that irrigation was well scheduled with very little leaching beyond 30cm when there was no rain.
- During periods of rain, water flow into the soil cannot be controlled, and rainfall may occur during irrigation in summer and nutrients can leach beyond the root zone.
- Applying 20t/ha of bentonite clay appeared to reduce the P concentration leaching into groundwater, but the reduction is insufficient for horticulture operations to avoid polluting nearby watercourses. A higher application rate may help to meet the guidelines, but may increase the clay content too much which may cause problems with plant growth. The bentonite clay used here did not have any effect on N leaching so managing N remains an issue.
- These results are preliminary and are based on a single opportunistic assessment of an existing case of soil amendment with a different clay to that from MZI. Clay from MZI has a stronger affinity for P than the bentonite clay used here so an investigation into its effectiveness to reduce P losses is warranted.

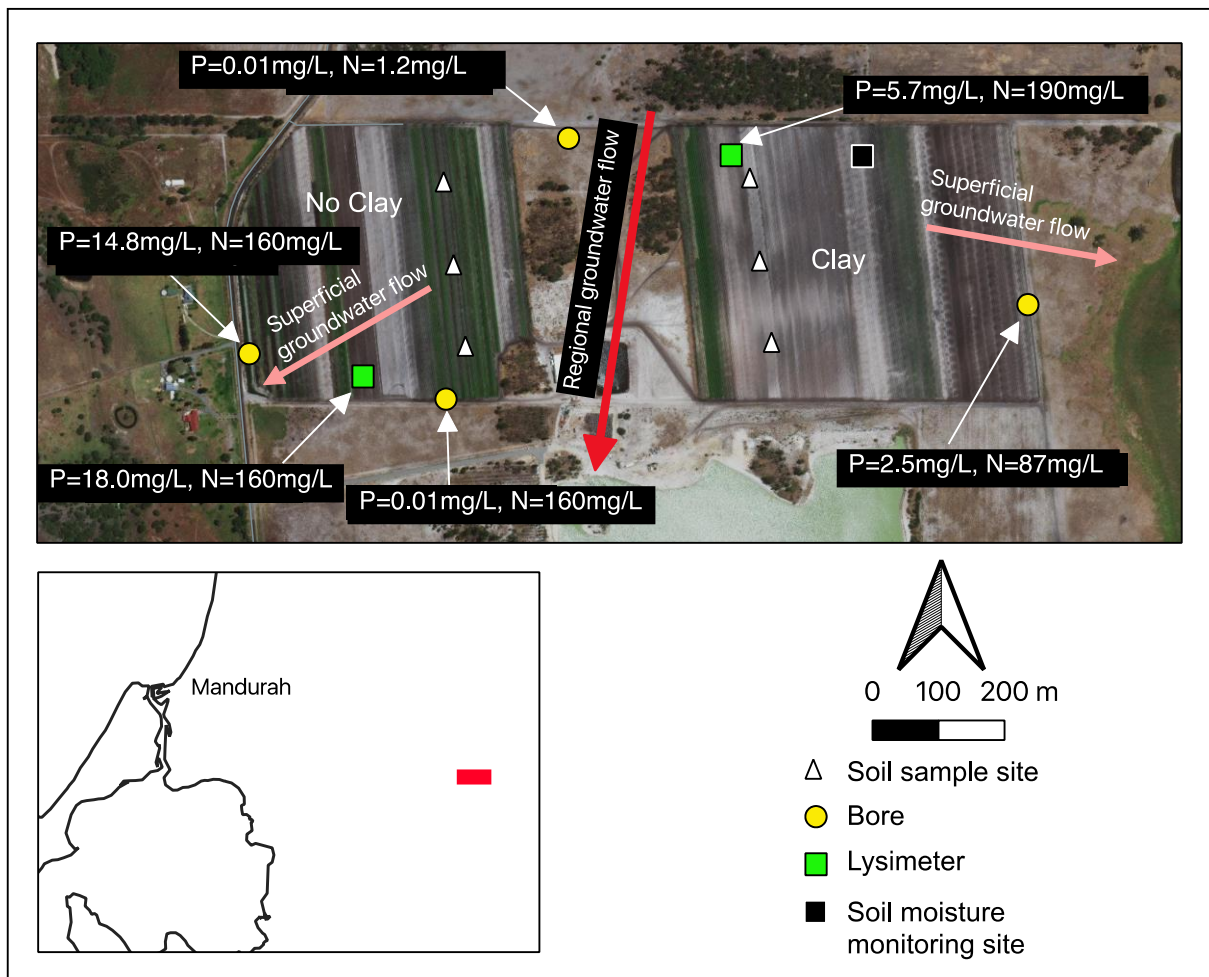
### 6.1.1 Methods

Previously, bentonite clay (20t/ha), lime sand (4t/ha) and prilled lime (7t/ha) were applied to the eastern half of the market garden (Figure 6.1). The owner has since met the staff at MZI to discuss a trial to see if their clay can provide similar benefits to the considerably more expensive bentonite clay. The trial of using MZI clay had not commenced at the time of writing this report. A residue of the stockpile of bentonite clay was sampled and the clay content was 80.9%, the PBI was 106 and the CEC was 38.

The market garden is rectangular and the long axis runs east to west. There are monitoring bores surrounding the property. The regional groundwater flow is from the



north-east to the south-west, parallel to a slightly raised remnant Bassendean sand dune (Figure 6.1). There is a small dune that runs from north to south through the middle of the property. The watertable under the dune system varies from 3–5m below ground level (BGL) to 1–2m BGL to the east and west boundaries of the property.



P = phosphorus; N = nitrogen

Figure 6.1 Soil sampling points, bores and groundwater flow on a horticultural property on Corio Road

### *Bore and lysimeter water sampling*

Existing bores constructed from 50mm PVC with depths of 5.5 to 6.2mBGL and screened intervals of 3–6m were sampled. Groundwater contours and flows were provided by the DWER from monitoring submitted by the farmer. Bores were purged prior to sampling and the lysimeters were sampled from a mixture of the entire collection after the purging.

Drum lysimeters measure the effect of superficial influences on the water draining through the profile. They measure what is effectively the highest concentration of nutrients, with little opportunity to dilute in groundwater or be retained in the deeper profile. Two drum lysimeters were buried about 30cm below the soil surface before the bentonite clay was applied by the market garden owner in 2016.

### *Soil sampling*

The soil was sampled on 16 November 2017 using a direct push Geoprobe sampler with a 65mm diameter core to a depth of 1m. The samples were split at 0–5cm, 5–10cm, 10–20cm, 20–50cm and 50–100cm depth intervals.

### *Soil moisture monitoring*

Soil moisture was monitored from 6 June to 10 July 2018. The monitoring equipment was installed on the northern edge of the eastern irrigation block (Figure 6.1). This site was chosen because of its bentonite amendment and its newly emerging spinach crop, which maximised the window for recording data before harvest. Sprinkler grid dimensions were 14.3m by 12m and the total size of the eastern irrigation block was 20ha.

Installed equipment included:

- three soil moisture probes (CS655 reflectometers) at 0–10cm, 10–20cm and 30cm depth
- a tensiometer at 15cm depth
- a tipping bucket rain gauge (in-crop to measure total water input)
- a WildEye data logger powered by a solar panel.

The logger recorded data from the sensors every 15 minutes and was uploaded remotely every six hours. Uploaded data was viewed and analysed using the Outpost Central online application. Rainfall data from the nearest Bureau of Meteorology (BoM) weather station in Mandurah was added to the dataset. Subtracting the BoM rainfall data from the in-crop rain gauge data created an estimate of the amount of irrigation applied at the site.

## **6.1.2 Results and discussion**

### *Groundwater*

The monitoring bores and lysimeters at the market garden were measured only once. The P concentration in the lysimeter leachate below the bentonite clay was only a third (5.7mg/L) of the P concentration in the lysimeter leachate from the untreated soil (18mg/L). The TN concentration at both bores was very high: 160mg/L in the untreated soil profile and 190mg/L in the treated soil profile. This suggests that the bentonite clay affected P retention in the soil profile, but not N retention. Further monitoring by the farmer as part of licence conditions may confirm this result.

The bores appeared to support the data from the lysimeters that indicated bentonite clay was retaining P from leaching. The area treated with bentonite clay drains to the eastern monitoring bore, where the P concentration was 2.5mg/L. The P concentration in the bore on the western boundary of the area not treated with bentonite clay was 14.8mg/L, indicating that the untreated soil provided no buffering against the P leaving the property.

The P concentration in the groundwater along the north and south of the property (0.01mg/L in both areas) was less than that in the groundwater to the east and the west (2.5mg/L and 14.8mg/L, respectively). These findings indicate that the surface of the

superficial flow at the edge of the property is to the east and west, while most of the deeper flow is from north to south.

An interception bore field on the southern border of the property appears to intercept enough water to pull the groundwater below the naturally occurring clay deep in the soil profile. For most of the year, the clay is below the groundwater level and the water is returned to the soak (often referred to as a dam), which minimises the peripheral groundwater losses from the site to the east and west. The N concentration rose from the north (1.2mg/L) to the south (160mg/L), indicating contamination from crop fertilisation. However, the P concentration stayed at 0.01mg/L, indicating that the groundwater was drawn through and that P was captured by the pre-existing clay deep in the soil profile. This interaction would not occur without the heavy pumping, pulling the water through the clay.

While this market garden data is preliminary, there is scope for further testing of a range of rates of soil amendment to determine the rate required to meet environmental targets for P leaching. However, N does not appear to be retained by soil amendment and remains a significant barrier for in-ground horticulture.

While the bentonite and lime treatment appear to have substantially reduced the concentration of P leaching from the site, the treatment did not reduce the P concentration in the groundwater enough to meet downstream water quality targets. The groundwater samples in the east and west bores also exceeded the DWER trigger value of 3mg/L for total P (TP).

Nitrogen concentrations in the groundwater throughout the site were extremely high, except in a bore upstream of the property (North Bore) that samples groundwater entering the property from a neighbouring farm in the north.

### *Soil*

Samples taken from the bentonite clay and lime amended soil on the eastern side of the property had greater retention of P and K, higher PBI, higher pH and higher CEC (Figure 6.2). The PBI of the treated soil increased to a depth of 50cm, which was also reflected in similar proportional increases in Colwell P. The increase in PBI is high enough to reflect a PRI of about 8 in the top 10cm, which compares to the P-retention capacity of Spearwood sandy soils that have retained P from leaching in horticulture after decades of P application (McPharlin et al. 1990). This increase in P retention was encouraging because the PBI of the bentonite clay was 106 and the PBI of the MZI clay was 1331, which suggests that less of the MZI clay would be required to achieve the same effect.

The increase in P retention in the soil strongly supports the measurement of a P reduction caused by bentonite clay application. However, the application was only sufficient to reduce the P concentration in the leachate from 18mg/L to 5.7mg/L in the lysimeters, which is insufficient to meet the reductions required for water quality in the Peel–Harvey estuary. Applying higher rates of bentonite clay, or perhaps the local clay from the MZI site, may reduce the P concentration in the leachate to meet these targets. Moreover, sourcing this clay from the MZI mine site may make this approach affordable if the opportunity eventuates.

The application of clay to the rehabilitated mine site will exceed the amount applied here. If the soil can be replaced in a landscape format that is well drained, the clay application will likely create a soil profile that will retain decades of P applications from horticulture similar to the Spearwood sandy soil of McPharlin et al. (1990).

Colwell P in the topsoil likely increased to a level at which P application can be reduced to rates equivalent to crop removal. At these soil P concentrations, tissue testing or sap testing could make a good supplement to soil testing to ensure plant requirements are met.

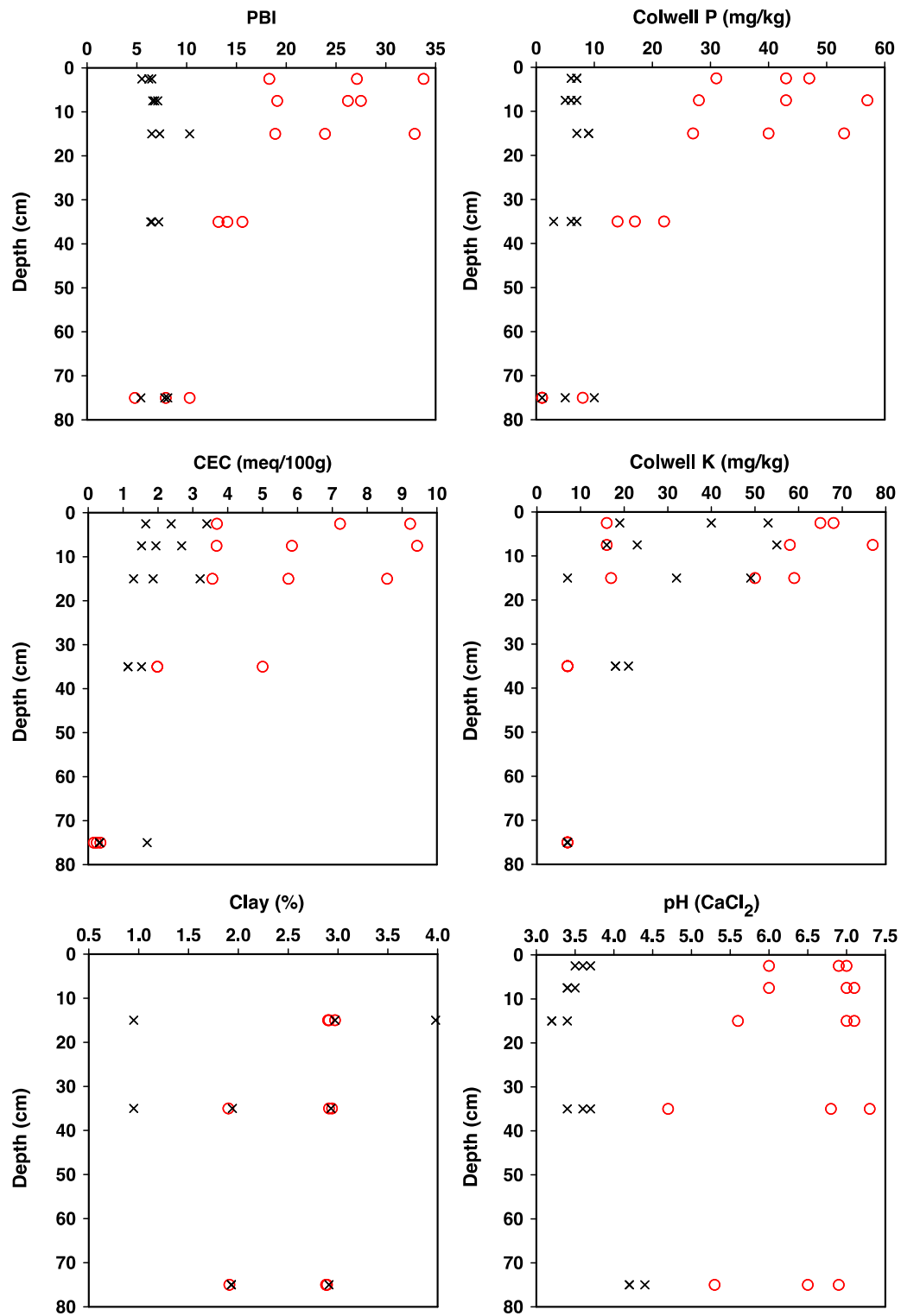
The bentonite clay treatment also increased the CEC, which was associated with increased Colwell K. Although the increase in Colwell K was not enough to maintain productivity, there may have been some benefit to plant growth through buffering the soil profile against loss of K to leaching and excess K immediately after application which may contribute to salt toxicity. The increases in all parameters are likely to have contributed to the increased productivity observed by the grower and the reduced P concentration in the leachate and downstream shallow bores.

#### *Soil moisture monitoring*

Soil moisture data was collected over five weeks. The soil water content data from the CS655 probes are shown in units of volumetric water content percentage (VWC) at the probes at 0–10cm and 30cm depth, respectively (Figure 6.3). Cumulative daily rainfall data from BoM's Mandurah weather station is shown as blue bars (front) that represent cumulative rainfall from 9am each day, with readings taken every 30 minutes. Data from the in-crop rain gauge is represented by the pink bars (rear) that show the total amount of water (rainfall and irrigation) that fell on the crop in 15-minute intervals. Reliable data from the in-crop rain gauge was only available from 13 to 26 June because the gauge became blocked.

When rainfall or irrigation events exceeded 7mm, all probes showed increased VWC, indicating drainage beyond 30cm. This drainage occurred after the initiation of rainfall on 10, 18 and 27 June and 3 July.

Between 12 and 25 June a period of less rainfall allowed the identification of the duration and intensity of irrigation events (Figure 6.4). For example, between 15 and 17 June, the rain gauge showed about 4mm of water fell on the crop each day over 30–40 minutes. Since there was no recorded rainfall during this time, this shows only the scheduled irrigation. During this period, the 0–10cm probe showed sharp increases in VWC of around 2%, which corresponds with the scheduled irrigation and a slow decline over 24 hours. However, there was almost no response from the probe at 30cm, indicating that the applied water was not moving down through the soil profile.



Note: Red circles are samples treated with 20t/ha bentonite and black crosses are samples of untreated soil.

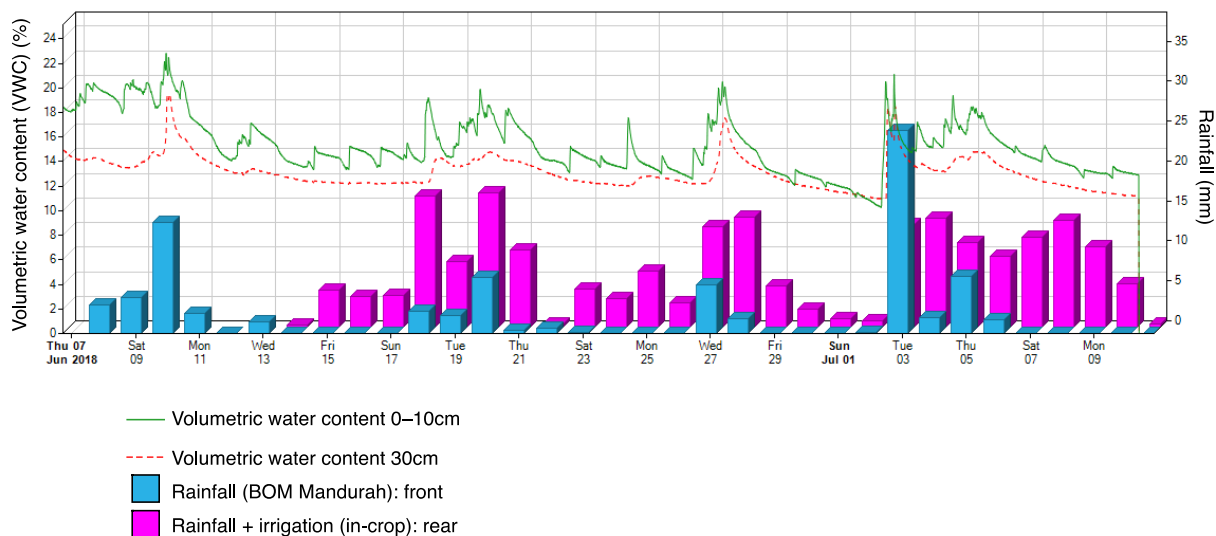
Figure 6.2 Analyses of soil samples to 1m on a market garden

Over this short period, the effect of several irrigation events during a period without rainfall — shown at points identified as 'a' in Figure 6.4 — shows no drainage beyond 30cm. The effect of several days of rain — shown at points identified as 'b' in Figure 6.4 — show sustained drainage beyond 30cm.

On 24 June, there was no recorded rainfall and the rain gauge recorded 7mm of water falling on the crop over about 2 hours. This event corresponds with an increased VWC reading from all moisture probes, indicating that some water drained down past 30cm. Therefore, irrigation was applied at twice the rate of previous applications and exceeded crop requirements. However, this event is an anomaly within the data and it is possible that the site experienced rainfall that was not detected by the Mandurah weather station.

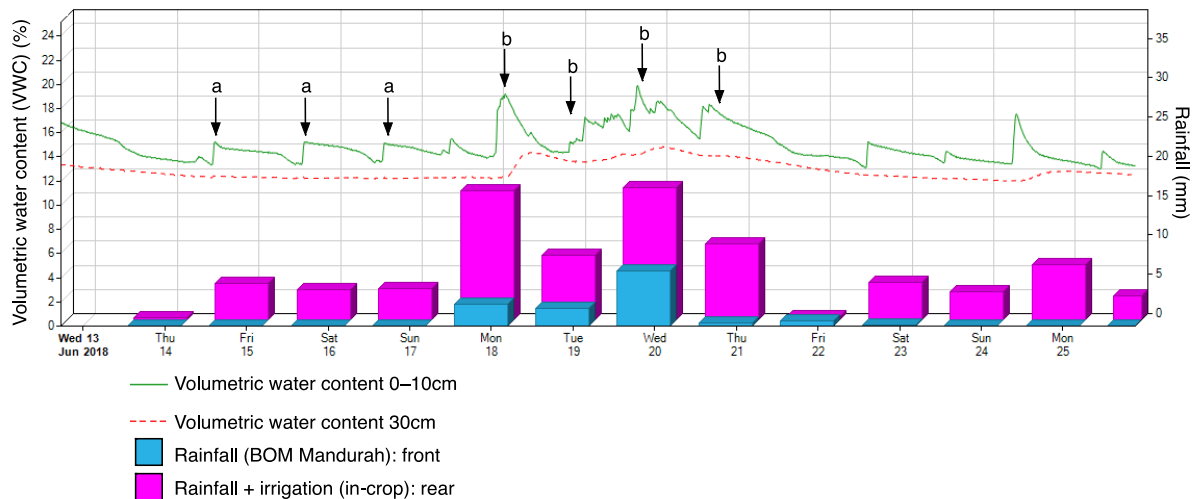
Water applied as irrigation generally did not move beyond 30cm deep in the soil profile. In the absence of rainfall, soil moisture was kept within a range of 10% to 20% VWC and soil water tension was kept within a range of  $-3.4\text{kPa}$  to  $-1.8\text{kPa}$ . These findings imply efficient use of water and good management of irrigation scheduling.

The main influence on the loss of nutrients beyond the root zone was rainfall, which overrides best practice irrigation. The loss of water beyond the root zone is common and occurs at a very low threshold of rainfall, which occurs weekly during winter.



Note: Disregard in-crop rain gauge data after 26 June because the gauge became blocked.

Figure 6.3 Rainfall and soil moisture between 7 June and 10 July 2018



Note: 'a' indicates the irrigation events and 'b' indicates the rainfall events.

Figure 6.4 Rainfall and soil moisture between 12 June and 25 June

### *Limitations of soil moisture monitoring*

The findings of these measurements are limited because data was obtained from one location within a 20ha irrigation block. A more representative picture of the water use efficiency requires data gathered from multiple locations. Moreover, rain fell on 19 days during the 34-day monitoring period, which made it difficult to determine whether irrigation occurred. It would be informative to conduct monitoring during the hot and dry summer months when the potential for plant stress is highest and irrigation scheduling is more critical. The rainfall data used was recorded in Mandurah, about 12km west of the study site, so some discrepancy was expected between the rainfall recorded and the amount that fell on the crop. Ideally, an internal rain gauge would be installed at the site to record more accurate rainfall.

A closer examination of water use efficiency may involve:

- leak testing irrigation supply lines
- conducting a distribution uniformity test of the sprinklers
- quantifying the effects of amending soil with bentonite through comparison with an untreated area.



## 7 Intensification of land use from grazing to horticulture

### Summary of findings:

- If the landscape was altered to increase water flow through the soil rather than across the soil, intensification could take place without much increase in P loss.
- Nitrogen losses would prohibit intensification unless they were managed in the drainage system of the crop site.
- Off-site management of N immediately downstream of the cropped area may be possible, but it needs to be assessed.

The increase in P retention from mixing the clay throughout the soil profile during rehabilitation has produced a soil that has enough P-retention capacity to retain many years of P fertiliser application at horticultural rates if well drained. The mine site and most future areas to be mined have previously been, and are likely to continue to be, periodically inundated.

The current landscape and rehabilitation process is returning the site to conditions that are restricted by inundation and waterlogging, which will greatly diminish the P-retentive improvements of clay throughout the soil profile. Increasing the height of the rehabilitated area by retaining and further excavating some of the mine voids could produce a landscape that will drain sufficiently to retain P (Figure 3.13).

As the Corio Road horticultural property demonstrated, P can be retained by soil amendment, but N is not because it rapidly leaches. Using the mined voids for water retention and water sources may increase the residence time of water and the opportunity for N to be recycled or released into the atmosphere.

Using the mine voids to process the water requires further assessment of the volume and movement of water across the landscape. The design is likely to require by-passing upstream water in a separate drainage system and keeping the drainage of the horticultural area within the ponds created by the mine voids.

Further assessment could include annual horticulture, less-intensive perennial horticulture or a combination of glasshouses on the elevated soil, as well as some perennial horticulture that could accept discharged crop solutions from glasshouses.

## 8 Soil amendment elsewhere in the Peel–Harvey Catchment

### Summary of findings:

- Soil amendment rapidly reduces P concentration at a small paddock scale.
- Treating larger catchments with soil amendment takes longer to reduce P concentrations.

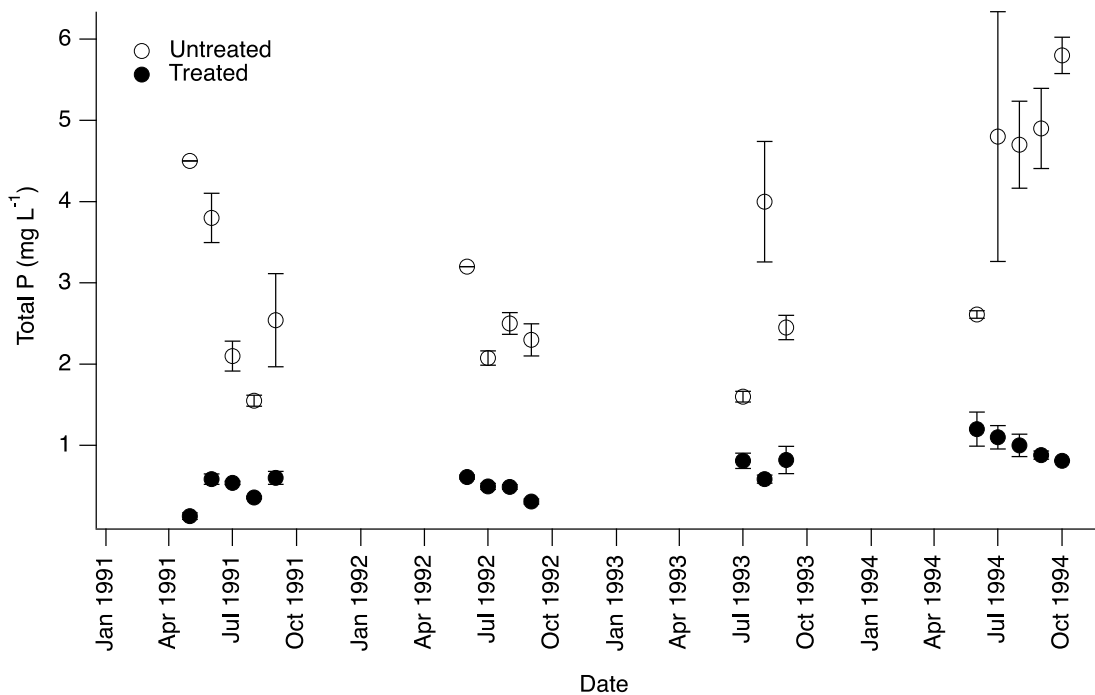
A 30ha catchment, 120km south of Perth and within the Peel–Harvey Catchment was treated with 80t/ha bauxite residue (Alkaloam<sup>®</sup>) derived from alumina refining. The P in the drainage water of the shallow farm drain was rapidly reduced in concentration (Figure 8.1; Summers, Guise & Smirk (1993)). This paddock scale trial had Alkaloam<sup>®</sup> applied throughout the catchment, including covering the base of the small farm drains.

This small catchment was within a 4300ha catchment which was also treated with Alkaloam<sup>®</sup> (20t/ha) and there was a time lag of over 10 years before the P concentration in the drainage water reduced to a new equilibrium. However, the effect of the reduced P concentration lasted over 25 years. The base of the larger drainage system was not treated with Alkaloam<sup>®</sup>. Although the P concentration of smaller catchments feeding the main drain dropped immediately, for larger catchments, P came into solution from the sediment in the drain bed in the main drainage system after the equilibrium was reversed. The P from the sediment acted to supply P into the main drain for many years (Figure 8.2). Comparatively, the coastal portion of the Peel–Harvey Catchment is more than 200 000ha with the major river systems being 30 000–40 000ha. Such large catchments are expected to take considerably longer to reduce the P concentrations in run-off because of the larger volumes of sediment in these larger drainage systems.

### *Soil amendment strategy*

Directing soil amendment to areas of sandy soils with the lowest capacity for P retention and in areas nearest to the Peel–Harvey Catchment is likely to have the quickest and greatest effects on P retention. Mapping of soil sampling from over 15 000 paddocks in the Peel–Harvey Catchment showed that these sandy areas with a low P-retention capacity (PRI or PBI) are located close to the estuarine system (Figure 8.3).

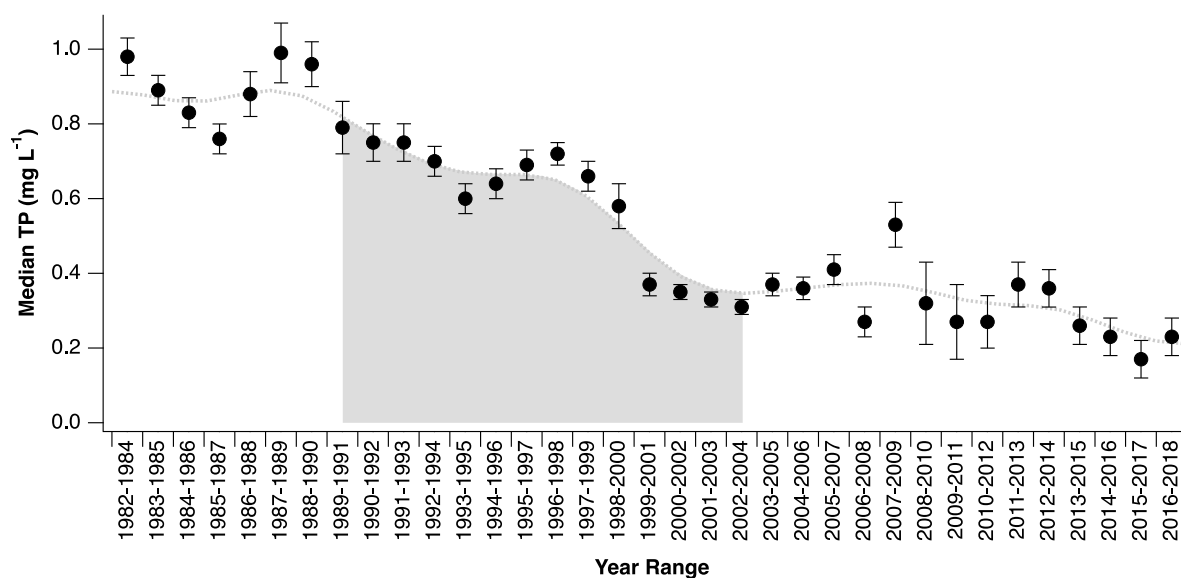
When soil amendment is combined with changes to fertiliser management and modelled, the reduction in P load is 51% or 90.3t (Kelsey et al. 2011), which meets the target for P reduction in flows to the Peel–Harvey Estuary. Combining soil amendment with improved fertiliser management merges a rapid effect with a long-term effect.



Notes:

1. Solid circles represent a catchment treated with Alkaloam® and the open circles represent an untreated control.
2. Data in the first year is presented in detail in (Summers, Guise & Smirk 1993).

Figure 8.1 The median P concentration of drainage water of a pair of small, 30ha subcatchments in the Meredith Catchment, west of Harvey, 1991–94 (90% confidence interval)



Notes:

1. Alkaloam® was applied in 1991 and the shaded area shows the slow run down in P concentration.
2. Raw water quality data was provided by the Department of Water and Environmental Regulation (2019).

Figure 8.2 The median P concentration of drainage water from the Meredith Catchment, west of Harvey (90% confidence interval)

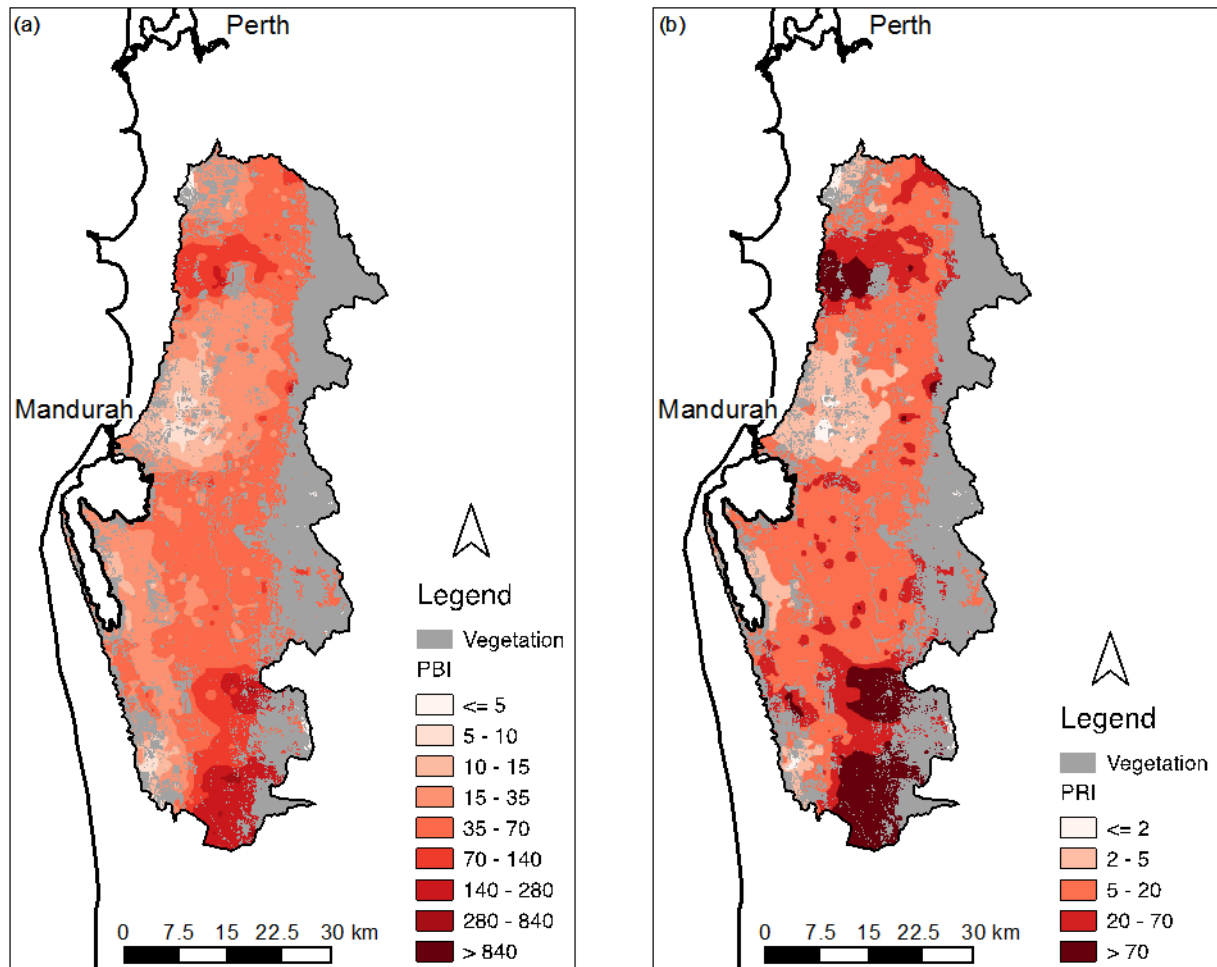


Figure 8.3 Levels of a) PBI and b) PRI for the Peel–Harvey Catchment based on interpolation of over 15 000 samples (1982–2018)

## 9 Effects of soil testing

### Summary of findings:

- The implementation of the Fertiliser Action Plan in the Peel–Harvey Catchment, including soil testing, has been modelled and predicts the P load in the Peel–Harvey Estuary will be reduced by 29% or 50.6t P per year (Kelsey et al. 2011).
- Most paddocks currently have more than enough P in the soil to reach production targets.
- Soil testing has shown that most paddocks do not need P, and declining sales of P fertiliser coincides with the locations where soil testing was focused.
- P fertiliser sales dropped after a large spike in fertiliser price in 2008 and remained lower after that.
- While sales of P fertiliser have declined, there has been no change in soil P measures over the period of soil testing. However, the P buffering by the soil and long lag times make it unlikely that change can be measured in the short term.
- Many paddocks have been found to be constrained by potassium, sulfur and pH, which must be overcome to increase productivity and consequently, motivation to replace unnecessary P applications is strong.

### *Soil testing*

A soil testing program that mapped all of the paddocks in a farm took place over much of the south-west of WA, including the Peel–Harvey Catchment since 2009 (Figure 9.1). Each paddock's soil was sampled to a depth of 10cm to assess the soil nutrient status using the response curves of (Gourley et al. 2007; Gourley et al. 2019). The sampling included 814 farms, 17 500 samples and 525 000 cores.

The results of the sampling showed a large proportion of paddocks could have reduced or suspended P fertiliser applications without reducing yield. Moreover, P fertiliser applications could be replaced with applications of other nutrients or with lime to increase productivity and reduce the risk of nutrient leaching to waterways. Most of the paddocks tested in 2009–18 in the Peel–Harvey Catchment had more P than was required to reach production targets (69–92%; Table 9.1). A large percentage of paddocks were deficient in potassium (32–84%), or sulfur (18–73%) and most had pH levels that were likely to be inhibiting production (29–97%). Please note that sampling was random and the variations in soil types and production systems make trends in this data difficult to attribute.

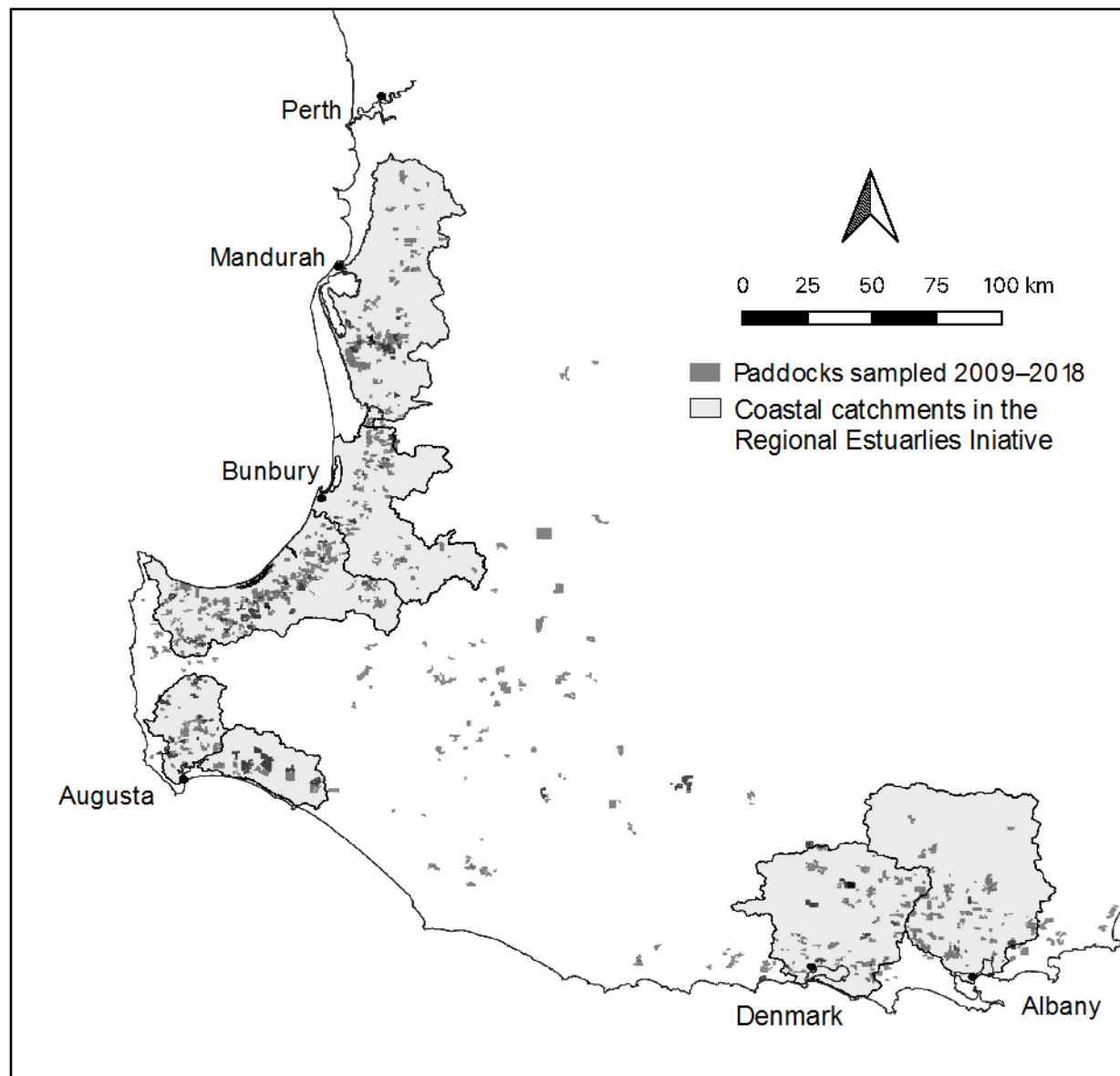


Figure 9.1 Sampling and mapping of farms from 2009 to 2018 in the high rainfall coastal areas of WA

Table 9.1 Summary of the results of soil testing of nutrients in the Peel–Harvey Catchment

Year	1982–91	2009–10	2010–11	2011–12	2012–13	2013–14	2014–15	2016–17	2017–18
Number of samples	15 334	376	676	378	59	285	207	287	308
Samples with excess P (%)	69	85	86	78	92	93	73	46	84
Median P fertility index for deficient soils	0.63	0.8	0.7	0.8	0.8	0.8	0.8	0.6	0.7
Median P fertility index for sufficient soils	1.9	1.9	2.5	1.6	2	1.8	1.8	1.4	2.9
Samples with pH constraint (%)	97	87	86	92	29	60	69	81	73
Samples with K deficiency (%)	73	69	32	59	43	37	57	84	54
Samples with S deficiency (%)	73*	57*	39*	59*	33*	29*	46*	33	18

\* Sulfur deficiency was estimated from PBI.

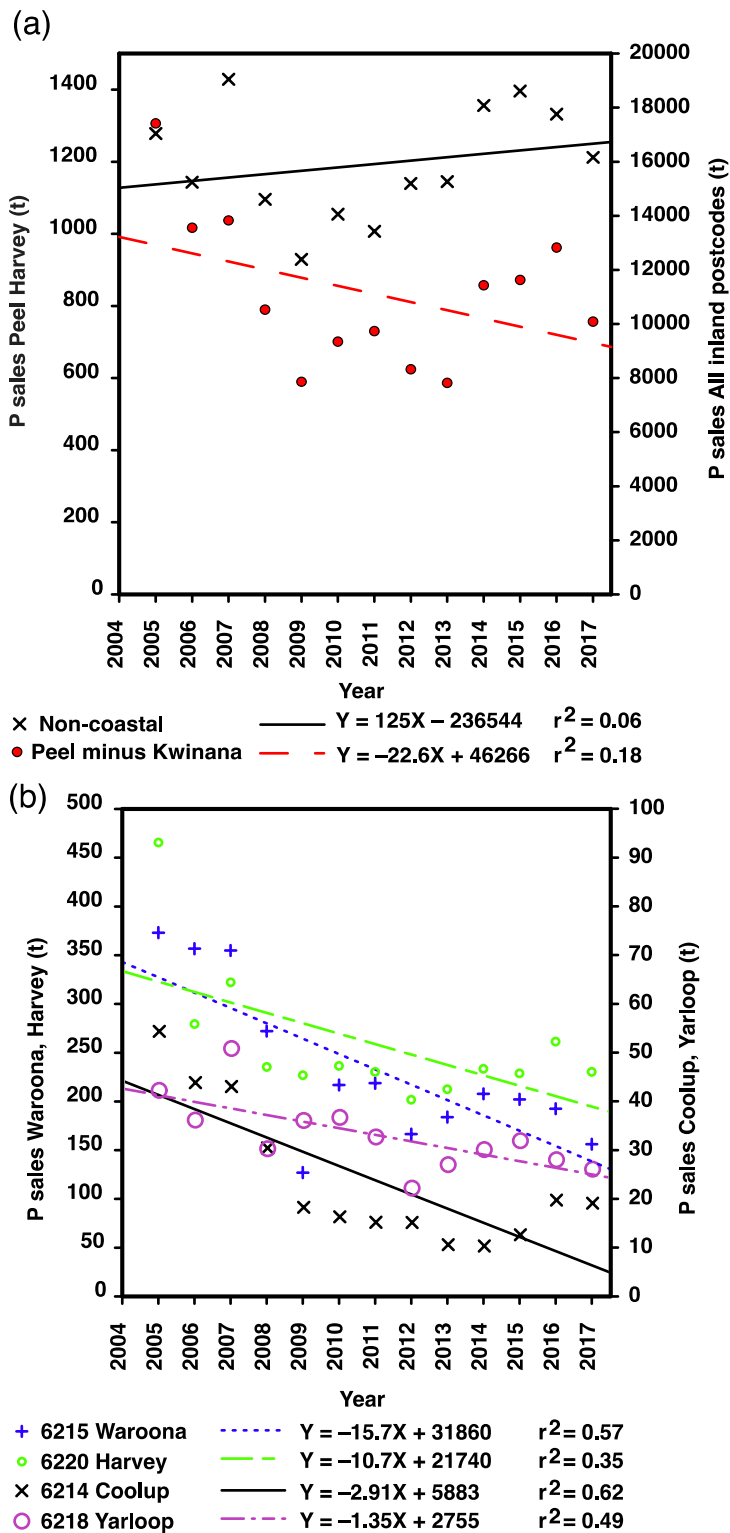
### *Phosphorus fertiliser sales*

The sales of P fertiliser have steadily decreased in the postcode areas of the Peel–Harvey Catchment compared with inland postcode areas (Figure 9.2). The raw data was supplied by Fertilizer Australia and was compiled from survey data of fertiliser suppliers and manufacturers in WA in 2018. Continued soil testing in the region may have affected purchasing behaviour, though the effect was not statistically significant for the entire Peel–Harvey Catchment ( $p = 0.154 > p = 0.05$ ). However, for the postcodes where widespread soil testing occurred, such as Waroona, Harvey, Coolup and Yarloop, there was a significant drop in P sales ( $p = 0.00284$ ,  $p = 0.03040$ ,  $p = 0.00145$  and  $p = 0.00758$ , respectively; Figure 9.2). Note that P sales per hectare were based on the total area and were not corrected for uncleared areas. Some areas, such as the Kwinana postcode, are inaccurate probably because of scenarios like non-agricultural sales to businesses that bag fertiliser.

Arguably, comparisons can be made between the areas that were receptive to testing, such as those who had progressively moved from dairy to beef after deregulation in 2000, and those who were applying more P than other areas because of a historical peak in productivity. The catchments that were receptive to testing align with the locations that had reduced P sales (Figure 9.2b, Figure 9.3).

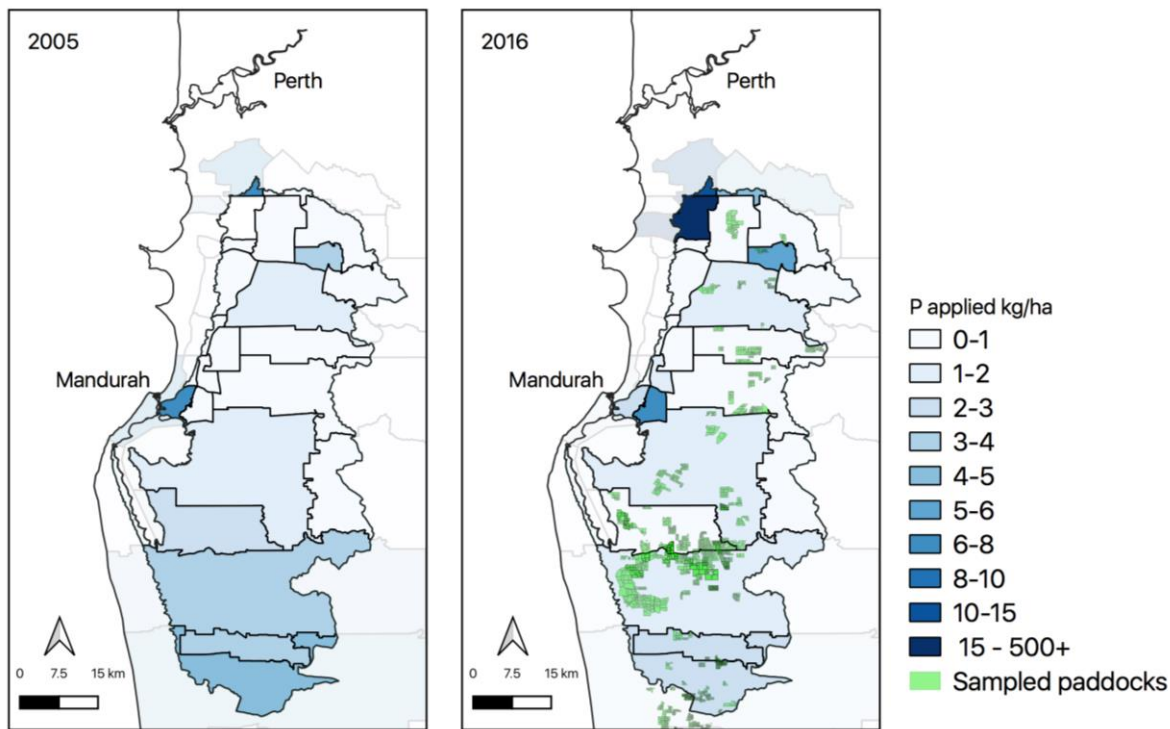
Note that the drop in P applications in 2009 coincided with a dramatic increase in the cost of superphosphate in late 2008. Although the prices reverted back to a similar rate in the following years, the P sales did not recover.





Note: Fertiliser sales data supplied by Fertilizer Australia in 2018.

Figure 9.2 Phosphorus fertiliser sales in the Peel–Harvey Catchment, approximated from postcode data and compared with a) fertiliser sales of all inland postcodes, and b) selected postcodes in the southern Peel–Harvey Catchment



Notes:

1. The geographic boundaries of postcodes are poorly defined. This postcode map originates from Landgate localities and has held constant between 2005 and 2016.
2. Fertiliser sales data supplied by Fertilizer Australia in 2018.

Figure 9.3 Phosphorus sales per hectare by postcode in the Peel-Harvey Catchment; on the right, the 2016 data is overlain by the farms that took soil samples by 2017

*Time lag for change in P concentration*

While reduced P application from soil testing will eventually affect the P running off the catchment, there is likely to be a considerable lag time due to the buffering of the soil reserves in the catchment and the P in the sediment of stream systems. This contrasts with the rapid effects of an intervention like soil amendment, which acts on the soil's reserves of P as well as the applied P. Despite this rapid impact of soil amendment on P concentration at a small scale, it also has a considerable time lag as the scale increases. Both practices of reducing P inputs through soil testing and immobilising P through soil amendment are required for a sustained improvement in water quality.

## Shortened forms

Short form	Long form
BGL	below ground level
BoM	Bureau of Meteorology
CEC	cation exchange capacity
cm	centimetre
DPIRD	Department of Primary Industries and Regional Development
DWER	Department of Water and Environmental Regulation
EC	electrical conductivity
g	gram
ha	hectare
L	litre
K	potassium
kg	kilogram
m, m <sup>3</sup> , mm	metre, cubic metre, millimetre
meq/100g	milliequivalents per 100 grams
mg	milligram
m/y	metres per year
MZI	MZI Resources Pty Ltd
N	nitrogen
NaF	sodium fluoride
OC	organic carbon
P	phosphorus
PBI	phosphorus buffering index
PFZ	Peel Food Zone
PIWI	Peel Integrated Water Initiative
PRI	phosphorus retention index
SW	surface water
t	tonne
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
WA	Western Australia
y	year

## References

- Allen, D & Jeffery, R 1990, *Methods for analysis of phosphorus in Western Australian soils*, report no. 37, Agricultural Chemistry Laboratory, Chemistry Centre of Western Australia, Perth.
- Alves, M & Lavorenti, A 2004, 'Remaining phosphorus and sodium fluoride pH in soils with different clay contents and clay mineralogies', *Pesquisa Agropecuária Brasileira*, vol. 39, no. 3, pp. 241–246.
- Asher, C & Loneragan, J 1967, 'Response of plants to phosphate concentration in solution culture I. Growth and phosphorus content', *Soil Science*, vol. 103, no. 4, pp. 225–233.
- Barnhisel, R, Gray, R & Skousen, J 1990, 'Managing restored prime farmland for corn production', in *Proceedings of the 1990 Mining and Reclamation Conference and Exhibition*, J. Skousen et al. (eds), University Morgantown, Charleston, West Virginia, pp. 143–149.
- Burkitt, L, Moody, P, Gourley, C & Hannah, M 2002, 'A simple phosphorus buffering index for Australian soils', *Australian Journal of Soil Research*, vol. 40, pp. 497–513.
- Churchman, GJ, Noble, A, Bailey, G, Chittleborough, D & Harper, R 2014, 'Clay addition and redistribution to enhance carbon sequestration in soils', in A Hartemink & K McSweeney (eds), *Soil Carbon*, Springer, Cham, Switzerland, pp. 327–335.
- Colwell, J 1965, 'An automatic procedure for the determination of phosphorus in sodium hydrogen carbonate extracts of soils', *Chemical Industry*, vol. 22, pp. 893–895.
- Daniels, W, Schroeder, P, Nagle, S, Zelazny, L & Alley, M 2003, 'Reclamation of prime farmland following mineral sands mining in Virginia', *Mining Engineering*, pp. 42–48.
- Diggle, A & Bell, L 1984, 'Movement of applied phosphorus following the mining and revegetation of mineral sands on Australia's east coast', *Australian Journal of Soil Research*, vol. 22, no. 2, pp. 135–148.
- Environmental Protection Authority 2007, *Water Quality Improvement Plan for the Rivers and Estuary of the Peel-Harvey System– phosphorus management, community consultation document*, Environmental Protection Authority, Perth, Western Australia.
- Fieldes, M & Perrott, K 1966, 'The nature of allophane in soils Part 3. Rapid and laboratory test of allophane', *New Zealand Journal of Science* vol. 9, p. 7.
- Gilkes, R & Hughes, J 1994, 'Sodium fluoride pH of south-western Australian soils as an indicator of P-sorption', *Australian Journal of Soil Research*, vol. 32, pp. 755–766.
- Gourley, C, Melland, A, Waller, R, Awty, I, Smith, A, Peverill, K & Hannah, M 2007, 'Making better fertiliser decisions for grazed pastures in Australia', Department of Primary Industries, Melbourne, Victoria.
- Gourley, C, Weaver, D, Simpson, R, Aarons, S, Hannah, M & Peverill, K 2019, 'The development and application of functions describing pasture yield responses to phosphorus, potassium and sulphur in Australia using meta-data analysis and derived soil-test calibration relationships', *Crop and Pasture Science*, vol. 70, pp. 1065–1079.

- Harper, R, Sochacki, S, Bell, R, Chittleborough, D, Summers, R & Tibbett, M 2012, 'Increasing soil carbon storage in sandy soils with clay amendments', in *Climate Change Strategy for the Primary Industries Conference*, Melbourne, Victoria.
- Hennig, K, Kelsey, P, Hall, J, Gunaratne, G & Robb, M in prep, *Hydrological and nutrient modelling of the Peel-Harvey estuary catchment (2006–15)*, Aquatic Science Branch, Department of Water and Environmental Regulation, Perth, Western Australia.
- Kelsey, P, Hall, J, Kretschmer, P, Quinton, B & Shakya, D 2011, *Hydrological and nutrient modelling of the Peel-Harvey catchment*, Department of Water, Perth, Western Australia.
- McPharlin, I, Delroy, N, Jeffery, B, Dellar, G & Eales, M 1990, 'Phosphorus retention of sandy horticultural soils on the Swan Coastal Plain', *Journal of the Department of Agriculture, Western Australia*, vol. 31, no. 1, pp. 28–32.
- Meredith, K 2007, 'The influence of soil reconstruction methods on mineral sands mine soil properties', MSc Thesis thesis, Crop and Soil Environmental Sciences, Virginia Polytechnic Institute and State University Blacksburg Virginia.
- National Research Council 2005, *Mineral tolerance of animals*, National Academies Press, Washington, DC.
- Reuter, D & Robinson, J 1997, *Plant analysis, an interpretation manual*, CSIRO publishing, Collingwood, Victoria.
- Russell, EJ & Russell, EW 1973, *Soil conditions and plant growth*, vol. 120, Longmans, Green London.
- Schroeder, P 1997, 'Restoration of prime farmland disturbed by mineral sand mining in the upper coastal plain of Virginia', MSc Thesis, Virginia Polytechnic Institute and State University, Virginia.
- Singh, B & Gilkes, R 1991, 'Phosphorus sorption in relation to soil properties for the major soil types of south-western Australia', *Australian Journal of Soil Research*, vol. 29, pp. 603–618.
- Stolt, M, Baker, J, Simpson, T, Martens, D, McKenna, J & Fulcher, J 2001, 'Physical reconstruction of mine tailings after surface mining mineral sands from prime agricultural land', *Soil Science*, vol. 166, no. 1, pp. 29–37.
- Summers, K, O'Connor, B & Fox, D 1993, 'Radiological consequences of amending soils with bauxite residue/gypsum mixtures', *Australian Journal of Soil Research*, vol. 31, pp. 533–538.
- Summers, K, Vlahos, S & Bell, T 1989, *Amendment of sandy soils with red mud residue – water quality and pasture growth response*, Alcoa of Australia Ltd, Booragoon, Western Australia.
- Summers, R 2001, 'The use of red mud residue from alumina refining to reduce phosphorus leaching and increase yield potential on sandy soils', PhD thesis, University of Western Australia, Perth.

- Summers, R, Guise, N & Smirk, D 1993, 'Bauxite residue (Red Mud) increases phosphorus retention in sandy soil catchments in Western Australia', *Fertilizer Research*, vol. 34, pp. 85–94.
- Summers, R, Smirk, D & Karafilis, D 1996, 'Phosphorus retention and leachates from sandy soil amended with bauxite residue (red mud)', *Australian Journal of Soil Research*, vol. 34, no. 4, pp. 555–567.
- Summers, R & Weaver, D 2011, 'Soil test and phosphorus rate for high rainfall clover pastures', *Bulletin 4829*, Department of Agriculture and Food, Western Australia, Perth.
- Summers, R, Weaver, D, Keipert, N & Steele, J 2014, 'Does Riparian Filtration Reduce Nutrient Movement in Sandy Agricultural Catchments?', *Environment and Natural Resources Research*, vol. 4, no. 4, pp. 155–168.
- Walkley, A & Black, IA 1934, 'An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method', *Soil Science*, vol. 37, no. 1, pp. 29–38.
- Ward, S & Summers, R 1993, 'Modifying sandy soils with the fine residue from bauxite refining to retain phosphorus and increase plant yield', *Fertiliser Research*, vol. 36, pp. 151–156.
- Weir, R & Cresswell, G 1993, 'Plant nutrient disorders 3: vegetable crops', *Plant nutrient disorders 3: vegetable crops*, Inkata Press, North Ryde, New South Wales.