NUTRITION AFTER AMELIORATING WATER REPELLENT SOILS – A REVIEW

Chris O'Callaghan, The Liebe Group
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Purpose

The purpose of this report is to review current and past work on nutrition management of ameliorated non-wetting soils in the Northern Agricultural Region (NAR) and wider Western Australian farming landscape. The review will provide an overview of our current understanding of the impact of tillage on nutrient availability and will determine areas that require further Research and Development (R&D) through field trial work.

Introduction

Water Repellence is a significant constraint to production in Western Australian broadacre farming systems. It is estimated that 6.9 million hectares are considered at moderate risk of water repellence, whilst 3.3 million hectares are considered at high risk, based on the area of coarse sands with low clay content (van Gool 2008). In the Geraldton Port Zone, approximately 52% of the arable soils are at moderate to high risk of water repellence, with the Shires of Irwin (87%), Coorow (67%), Northampton (66%), Three Springs (62%), Carnamah (53%), and Perenjori (50%) all having over 50% of their soils at medium-high risk (Table 1; van Gool et al. 2008).

Table 1: Soil Water Repellence Risk by Shire in the Geraldton Port Zone (van Gool et al. 2008)

Shire	Soil Water Repellence Risk Area Repellence			Total Agric.	% High
	Nil to Low	Moderate	High	(ha)	Risk
Carnamah	84,184	50,831	44,962	179,977	25
Chapman Valley	170,903	112,212	11,948	295,063	4
Coorow	87,966	118,879	63,197	270,042	23
Geraldton (city)	744	366	212	1,322	16
Greenough	84,758	40,111	29,437	154,306	19
Irwin	15,960	56,608	57,640	130,208	44
Mingenew	108,541	35,990	37,749	182,280	21
Morawa	176,238	77,280	266	253,784	0.1
Mullewa	275,760	177,962	13,062	466,784	3
Northampton	125,964	183,741	58,140	367,845	16
Perenjori	180,463	174,290	2,435	357,188	0.7
Three Springs	84,622	68,390	68,220	221,232	31

Water repellent soils are defined by having slow permeability to water, characterised by uneven wetting of soils, water run-off and ponding and/or flow through the soil via preferential pathways leaving surrounding soil dry (Roper et al. 2015). The consequential impact on the crop is uneven germination, poor crop establishment, reduced nutrient use efficiency and reduced yields. The opportunity cost of the constraint is an estimated $250 m for WA agricultural production, $68.8 m for the northern agricultural region (Herbert 2009).

In Western Australia, the incidence of water repellence is increasing due to drier autumns and increased volatility in opening rainfall events, increased areas of early and dry seeding practices and widespread adoption of narrow knife points on seeding bars that concentrate repellent soil into the seeding furrow (Grains Research & Development Corporation 2014).

In addition, farming systems have changed significantly over the last 15 years, where one year, wheat-pasture rotations grown with conventional tillage practices and regular cultivation were once common, farmers now grow a more diverse range of crops, sow with minimum tillage and crop more in the higher rainfall zones (Chen et al. 2009). These changes and in particular the widespread adoption of conservation tillage practices has subsequently exacerbated the repellency problem, due to the concentration of organic matter and associated waxes in the surface soil layer (Roper et al. 2015).

Over the years, farmers have adopted many practices, with various levels of success, that are aimed at reducing the impact of water repellent soils. These include: furrow sowing, which aims to plant seed into a deeper furrow created by seeder points that create repellent soil ridges exposing non-repellent soils underneath; using surfactants and soil wetting agents; and the addition of clay-rich subsoil to the repellent topsoil through either excavating and spreading or delving. More recently the use of deep cultivation through complete or partial inversion of the soil by a mouldboard plough, rotary spader or one way disc plough, has been successful in mitigating the water repellence issue (Davies, Scanlan & Best 2011).

With wheat once the dominant crop in a system utilising regular cultivation, many of the soil test calibrations and other associated Research, Development and Extension (R,D&E) efforts around crop nutrition were based on this system (Chen et al. 2009). The evolution of farming systems and technology now includes more diverse rotations sown with larger machinery using soil conservation practices such as minimum or no tillage. Whilst this evolution is widely accepted as being beneficial (Llewellyn & D'Emden 2010), it has contributed to the water repellence issue as well as other problems such as herbicide resistance in weeds (Renton & Flower 2015) and subsoil acidity (Cookson, Murphy & Roper 2008). This has led growers to evolve the system again to include strategic and deeper tillage practices such as deep ripping, mouldboard ploughing and rotary spading to ameliorate water repellence, remove subsoil compaction, bury weed seeds and/or incorporate lime.

It is these changes and developments in our farming systems that necessitate the need for continued R&D to ensure practices are adopted effectively and the agronomy around these practices is appropriately adapted.

The following provides a review of literature around nutrition on ameliorated soils, with focus on the farming systems in Western Australia and more specifically, the NAR where possible.

The impact of tillage on soil nutrition

Three processes have been identified that alter crop nutrition after tillage practices, these being: the alteration of nutrient availability and distribution in the soil through a mixing effect; the alteration of the physical aspects of the soil which influences root growth and; changes in soil biological activity (Robson & Taylor, cited in Vu et al. 2009).

Mouldboard ploughing and rotary spading have been implemented by growers seeking to overcome water repellence throughout the NAR. The Department of Agriculture and Food, Western Australia (DAFWA) research has shown that both practices ameliorate water repellence, with mouldboard ploughing, which completely buries repellent topsoil being more effective than spading which achieves only a partial burial (Davies, Scanlan & Best 2011).

The following extract from Davies, Scanlan & Best (2011) effectively summarises the issues around nutrient availability:

> *"The implication of the re-distribution of the organic matter and nutrient rich topsoil from the use of these implements varies for each of the nutrients. Both spading and mouldboard ploughing are likely to increase N mineralisation although this can vary due to a range of factors including the amount and type of stubble buried. Reduction of P levels in the surface soil may have a negative impact on crop growth because P is needed early for tiller production. Fertiliser strategies need to account for this. It should be remembered however, that while topsoil P concentrations may indicate the presence of adequate P in the control (non ameliorated) situation not all of this may be available in water repellent soils that remain dry for much of the growing season. The redistribution of K to depth poses less of a problem for crop growth because the crop can 'grow into' K in the 10-30 cm layer. This redistribution of nutrients highlights the need to conduct soil testing post-treatment including subsoil testing."*

Research on nutrition management post amelioration, is in its infancy. Development of this research is required to gain an understanding behind the short to medium term effects of amelioration techniques. It has been reported that in the first year after intensive tillage, there will be an initial burst of mineralisation and availability of nutrients to the plants, with the degree to which this occurs dependant on soil type, moisture and quality and availability of organic material returned to the soil (Silgram and Shepherd, 1999). It has been suggested that this effect is relatively short lived, however given the number of factors influencing this, more research is required to better understand the response to these amelioration practices to improve nutrient management decisions.

Potassium (K)

Potassium is an essential macro nutrient required by plants in large quantities, which until around the 1990's was applied as fertiliser predominantly to pasture crops. More recently, K deficiency has become apparent in broad-acre crops such as wheat, barley and canola driven by the removal of K in the product (grain, hay) and leaching (Brennan & Bell 2013). Potassium is subject to leaching in sandy soils in high rainfall environments and responses to K fertilisers on these soils are now commonly reported (Quinlan & Wherret 2017c). In recent years, as conservation farming practices have been widely adopted, the lack of soil mixing has led to depletion of subsoil reserves of K as well as the vertical stratification of K, particularly in controlled traffic/precision planting scenarios where repeated planting on preceding rows occurs (Brennan & Bell 2013; Chen et al. 2009).

This has implications for crop growth in drought situations, where dry conditions in the surface layers may lead to reduced nutrient uptake and consequential deficiency. This increases risk of yield losses in seasons that have longer periods of drought, combined with high crop demand for nutrients, where crops are forced to explore deeper in the profile to meet nutrient needs (Chen et al. 2009). Root exploration down the soil profile will vary depending on crop type as well as constraints such as soil acidity, compaction and water repellence, and therefore crop response will be dependent on subsoil K contents and the crops ability to access it (Quinlan & Wherret 2017c; Chen et al. 2009).

Analysis of the Better Fertiliser Decisions for Cropping National Database highlighted a generally poor wheat response to sub soil (0-30cm) K testing across a range of soil types indicating research gaps around understanding of the constraints to accessing subsoil K availability (Anderson et al. 2015).

In some systems, soil amelioration involves the addition of clay-rich subsoil through the surface layers of the soil. This practice may involve the addition of clay from an external source or delving clay from lower in the soil profile and spreading through the top soil layers. This practice has been shown to reduce water repellence and increase crop yield as well as increase soil cation exchange capacity and organic carbon (Hall et al. 2010).

Hall et al. (2010) summarised the effect of claying on potassium nutrition:

> *"The profitability of claying is highly dependent on the added clay not only reducing water repellence but also contributing to potassium nutrition and nutrient retention. Further experimentation is required to separate the effects of potassium nutrition and clay addition."*

Understanding the nutritional status of the clay and the soil to be amended is important to understanding where there will be a nutritional response to clay. Bell, Hall & Sochaki (2017) assessed 7 sites where sands were amended with clay, and observed a positive yield response to K present in the clay, in situations where there was low K levels in the topsoil. There is however a high amount of variation in levels of K in WA subsoils, dependant on the clay content and mineralogy of the area (Wong, Edwards & Barrow 2000). In the Western Wheatbelt it has been reported that many duplex soils have uniformly low levels of K, whilst in other areas such as the eastern and south eastern wheatbelt, clay subsoils are more typically enriched with K (McArthur 1991, cited in Wong, Edwards & Barrow 2000). Furthermore, whilst it has been shown that subsurface K can be a significant contributor to plant shoot K concentrations (Kulhmann 1990 cited in Scanlan, Bell & Brennan 2015) there is uncertainty in the literature over the predictability of a yield response in relation to differences in subsurface K levels. Scanlan, Bell & Brennan (2015), suggests that this unpredictability is a result of interactions between surface and subsoil K levels, soil constraints and rainfall timing and amount. This is compounded on duplex soils where there is variability of depth to clay, which has implications for fertiliser recommendation models.

This is complicated further in systems employing deep cultivation, which completely change the nutritional profile of the soil as well as the dynamics of soil wetting and soil constraints. Research studying the dynamics of K fertiliser responses in these systems is ongoing.

Nitrogen (N) & Organic Matter (OM)

Nitrogen is an essential nutrient for crop growth and is needed in larger quantities than any other nutrient. The majority of N present in the soil is in an organic form which is mineralised by microbes into inorganic forms such as nitrate and ammonia (Quinlan & Wherret 2017a).

Predicting soil N supply to crops is complex due to the number of factors influencing the mineralisation of organic N, the variation in potential yield as a result of changing seasonal conditions and the amount of N that can be leached through the soil as nitrate (Anderson et al. 2015). Soil type and the water holding capacity of the soil is an important factor impacting on the plants demand for N and the capacity of the soil to supply N. This is because it can give an indication of leaching potential of the soil and the crop water-limited yield potential of soil (Anderson et al. 2015).

Mineralisation processes are influenced by a number of management practices, including tillage and residue management, which manipulate the composition and size of the microbial communities responsible for the cycling of N. A large portion of N that is used by crops comes from the mineralisation of previous crop and pasture residues (Gupta 2016).

Tillage practices will result in an overall decline in total soil organic matter and a significant re-distribution of organic matter through the profile, which in turn has implications for crop growth and fertiliser recommendations. The complexity of the recommendation is increased in systems where clay-rich subsoil is spread or delved which further changes the properties of the soil. Claying has been shown to increase nutrient retention and organic carbon levels (Hall et al. 2010) and supports increased inputs of organic material back into the soil through improved plant growth (Carter, Gilkes & Walker 1998).

In terms of the impact of tillage on organic matter and N cycling, trial work conducted at Beverley showed that as soil disturbance levels increased through mouldboard ploughing, soil N supply increased due to a more rapid conversion of Ammonia to Nitrate and was distributed further down the soil profile. The drivers of this was less clear, although it was suggested that this may be a result of an increased rate of soil organic matter breakdown caused by disruption of soil aggregates and changes in soil water dynamics through the soil inversion (Hoyle & Murphy 2011).

In trial work at Badgingarra, both spading and mouldboard plough treatments caused major changes to the distribution of organic carbon in the top 40cm, with mouldboarding creating nutrient profiles that bulge at 10-30cm while spading created gradational changes to 40cm. Root measurements were conducted at this trial, and it was observed that whilst the total number of roots was not different between treatments, the distribution of these roots changed, corresponding to the changes in nutrient profile. Specifically, root concentration in the minimum tillage plots was greater in the top 10cm, whilst in the mouldboarded plot, more roots were concentrated in the 10-30cm layer. There were also fewer roots recorded below the 30cm layer in the tillage plots, whilst in the minimum till plots, despite the majority of roots concentrated in the top 10cm, there was some root growth past 30cm, with roots possibly following old root pathways (Scanlan, Davies & Best 2012).

In the following year of this trial differences in crop N uptake after mouldboard ploughing and spading were reported, reflecting changes in the vertical distribution of organic matter and soil moisture dynamics. Specifically, higher soil moistures were recorded at depth in the mouldboarded and spaded treatments as well as higher N uptake in these plots, indicating more effective utilisation of applied N (Scanlan, Davies & Best 2013).

Research conducted by CSBP (2015) indicates that the start of season nitrogen could be reduced or eliminated to make most use of that burst of available nutrients. A deep-ripping trial conducted by CSBP in Binnu, showed no difference between 50 L/ha Flexi-N banded at seeding + 100 L/ha at Z30 vs only the 100 L/ha at Z30. The importance of correct timing of inputs and the amount is demonstrated in this trial, with the 100 L/ha at Z30 yielding more than 100 L/ha at seeding.Overall however, there is limited information available around the longer term impacts of soil organic carbon profile changes created through deep cultivation and the implications of this for fertiliser recommendations. Roper et al. (2015) summarised this saying:

“The impact of deep cultivation on soil carbon levels in the soil surface needs to measured over time. Furthermore, the fate of buried organic matter and its role in nutrient and water retention in the crop root-zone requires further investigation because these may be drivers of longer term productivity benefits”

Scanlan, Davies & Best (2013) also iterated that

“fertiliser recommendation models are not calibrated to the organic carbon profiles created by soil inversion”

Phosphorus (P)

Phosphorus is an essential plant nutrient, which is fundamental to supporting agricultural production systems and farm profitability (Wong et al. 2012). However most Australian soils contain inherently low levels of soil phosphorus and most were largely unproductive until farmers began using phosphorus fertiliser (Mclaughlin et al. 2011).

It is this fertiliser use that has led to an accumulation of P in soil, with historical fertiliser application exceeding P removal through harvested produce (McLaughlin et al. 2011; Weaver & Wong 2011).

In a CSIRO phosphorus management improvement framework, Wong et al. (2012), reported that

> *"Current fertiliser practice is often causing build-up of soil available P beyond the levels required for near maximum crop production (the critical value). In Western Australia, 87% of 109, 000 soils sampled by farmers and analysed by CSBP in 2008-09 and 2009-10 exceed critical values"*

Despite conservation farming having significant benefits for Australian Agriculture, it has affected the distribution of nutrients and therefore has implications for fertiliser management. For example, Vu et al (2009) reported that the accumulation of P in the topsoil as result of conservation tillage may restrict plant access to P during dry seasonal conditions and that rapid drying of the soil surface may also result in immobilisation of soil P, decreasing P use efficiency and requiring higher rates of fertiliser. Analysis of the Better Fertiliser Decisions for Cropping National Database (Watmuff, Reuter & Speirs 2013) also indicates that soil P has become less available under conservation farming practices, particularly in wheat crops (Anderson et al. 2015). There is evidence however that wheat roots are able to take up immobile nutrients such as P from dry top soils as long as they have access to moist subsoils (Ma, Rengel & Bowden 2007), however this is an area requiring further research.

Understanding the soils ability to fix phosphorus is important to assessing whether there will be a response to applied P. A high fixing soil will require more P-fertiliser and understanding the soils phosphorus buffering index (PBI), reactive iron and/or phosphorus retention index (PRI) (Quinlan & Wherret 2017b) is vital to maximising nutrient use efficiency.

Further understanding is however required around the fate of applied P fertiliser. The soil processes around P cycling in the soil is complex and poorly understood, therefore predicting when P will be released from or tied up into organic forms is difficult (McLaughlin et al 2011). What is known is that P use efficiency decreases with drying soil, so the physical movement of soil and removal of repellence issues are two important drivers around P use efficiency.

The distribution of P through the soil profile is important when assessing likely responses to P fertiliser after amelioration. In a trial conducted at Badgingarra, where mouldboard ploughing and spading were compared to a min-till control, it was observed the distribution of P in the soil profile at this site was uniform prior to amelioration, which meant there was very little change in distribution due to mouldboard ploughing and spading (Scanlan, Davies & Best 2012). As a result, there was only a response to applied fertiliser P in the control plot, due to the crop being unable to access P in the dry water repellent soil. In the ameliorated plots, the crop was able access this stored P, thus negating the requirement of applied P (Scanlan, Davies & Best 2013).

It may be that in other situations a complete inversion of the soil would redistribute P stratified in the topsoil to the subsoil, leaving the top 10cm deficient. So, whilst non-wetting soils that are effectively ameliorated may have greater P availability deeper in the profile due to the increased soil moisture, this may not always translate into increased crop yield when additional P is not applied with the seed, given the crop's increased requirement for P in early vegetative growth. In addition, the renovation of the soil in some instances is reducing the top soils capacity to store P, due to the inversion practice bringing poorer soil to the surface with low buffering capacity that increases P leaching risk (Scanlan 2017).

There has been research conducted on the benefits of deeper placement of P (Jarvis and Bolland 1990), which as discussed in Anderson et al. (2015), can allow better P acquisition by roots. This research, conducted in lupin crops, resulted in higher yields, particularly evident in lower yielding seasons, where perhaps the drying of the soil surface prevented root accessibility of soil P banded with seed.

The other consideration is that while P may become more available, there are often other constraints, such as soil acidity, that limits root growth and yields, thus reducing any response to P. Trial work conducted at Wubin

(Scanlan, Sarre & Brennan 2014), demonstrated that when incorporating lime to overcome soil acidity, it would be feasible to reduce P fertiliser rates as the yield loss from omitting P fertiliser, was greatest in the untreated control and decreased in the cultivation + lime treatments.

Trial work conducted on forest gravels in Darkan (Bakker et al 2014) showed amelioration of soil acidity through ploughing in lime gave a significant lasting response over 4 years on a water repellent, acidic and P-responsive site. Here, improving the soil pH from 4.3 to 4.8 gave a large yield response, even when no additional P was applied. In addition, whilst not completely removing the water repellence, some improvement in water penetration was observed through cultivation which may have enhanced the accessibility of P. The main driver however here though was the pH change as yield responses to applied P were enhanced through the cultivation of lime into the profile.

Different forms of P fertiliser have various levels of effectiveness depending on the soil type and farming system. For example, liquid P has been shown to be more effective than granular P on alkaline and calcareous soils (McBeath et al. 2005), and slow release fertilisers such as reactive rock phosphate can be beneficial in high leaching environments such as pale coarse sands (Wong et al. 2012). However, there is no clear consensus in the literature on the P use efficiency of foliar applications and given the high P demand of annual crops early in the growing season, it is likely that small leaf area will restrict its success. Furthermore, it is likely that rock phosphate will not release enough P at this early stage when it is most required.

Sulfur (S)

Sulfur is present in soils in both organic and inorganic forms. Inorganic S is taken up by plants as sulphate, whilst organic S forms the bulk of soil S and is an integral part of soil organic matter. As a result, total soil S is greater in finer-textured soils than coarse soils, and many of the biological processes involved in the mineralisation of organic N in soils are also important for organic S mineralisation (Prasad & Power 1997).

In Western Australian Agricultural systems, historical use of fertilisers containing Sulfur has traditionally provided adequate S for plant growth, however a shift toward low S fertilisers in recent times has seen an increase in S deficiency (Anderson et al. 2015). Sulfur deficiency that affects grain yield in wheat crops is rare, however it is common in very sandy soils for S deficiencies to occur early in the growing season, before fertiliser is applied or plant roots have grown into subsoil reserves of S (Brennan & Bolland 2006).

It is common practice to apply sulfur fertilisers prior to planting canola crops as sulfur deficiencies in canola have been observed (Brennan and Boland, 2006) and canola has a higher requirement for sulfur earlier in its growing season compared to wheat or lupins (Anderson et al. 2015).

Brennan and Bolland (2006) summarised neatly the situation of Sulfur use below:

> *"Increasing use of fertilisers containing negligible S, improved canola yields due to using better cultivars and systems to grow the crop, and the higher requirement for S by canola than wheat or lupin are all likely to increase S deficiency of canola in WA in the future. Therefore, testing of deeper soil needs to be seriously considered for canola grain production on sandy WA soils as a means of determining likely S deficiency and when fertiliser S needs to be applied to prevent the deficiency decreasing grain yields."*

In a system that utilises mouldboard ploughing or spading, consideration needs to be given to subsoil S levels. Sulfur leaching through the subsoils is reduced with increasing clay contents and decreasing P and pH levels, which effects S adsorption (Anderson et al. 2015). Consequently, it is possible that more S is being brought to the surface with these aggressive tillage practices, which needs to be considered when planting canola after soil amelioration. This however is an area of limited research or demonstration.

Trace Elements

Trace elements are important for optimal crop growth albeit required in smaller quantities and deficiencies are not as common through in our agricultural areas. Whilst rare, it is important to consider the implications of aggressive soil tillage on the potential for trace element deficiencies, particularly in situations where the soil properties such as pH are rapidly changed as a result.

Removal of water repellence is generally beneficial as it can make immobile nutrients more available to the plant through increased wettability and mixing of stratified nutrients through the soil profile. For example Copper, Zinc and Molybdenum are immobile in soil (Department of Agriculture & Food, WA 2016) and can become unavailable to crops in dry soil, potentially benefiting from amelioration of water repellent soil and mixing through the profile.

Zinc, Copper and Manganese deficiency can however be induced by lime application and in soils with increasing alkalinity, whilst Molybdenum deficiency is induced in acidic conditions and is particularly acute on deep acidic wodjil soils (Department of Agriculture & Food, WA 2016).

Furthermore, whilst rare in Western Australian broadacre systems, Magnesium deficiency can be induced by the presence of competing cations such as in situations where there is high K supply (Ma et al. 2013).

Other water repellent soil management practices

Furrow sowing is a practice that can be used to manage non wetting soils, as it allows placement of seed deeper in the soil, into a less water repellent layer, whilst shifting the repellent sand to the ridges of the furrow, effectively channelling water into the furrow (Roper et al. 2015). This practice has been proven to improve plant emergence compared with conventional sowing, however the effects can be short lived due to furrow in-fill (Roper et al. 2015). There are also concerns around preferential flow of water in this system, and the increased risk of nutrient leaching, especially as rainfall amount and intensity increases (Blackwell 2000). Furthermore, as large volumes of soil remain dry, nutrients contained in these areas are unavailable to plants which reduces nutrient use efficiency earlier in the season. Conversely, these areas may wet up later in the season, thus making nutrition available when plant demand is higher (Roper et al. 2015).

It has been suggested that furrow size may also have an effect on leaching with wider furrows potentially contributing to significantly more leaching of nutrients that level sowing or narrow furrow, particularly after heavy rainfall events (Blackwell 2000). In these systems, tactical applications and placement of fertiliser and adjustments to furrow size may be beneficial to reduce leaching. Further field demonstration of these systems would be beneficial.

The use of surfactants and wetting agents have been used to improve crop establishment and water infiltration, with some success, however a potential negative to surfactant use is the increased risk of nutrient leaching and deep drainage and the results of research into the longevity of any benefit to surfactant use has been variable (Roper et al. 2015).

Roper (2004, 2005) has investigated the possibility of enhancing existing populations of wax-degrading bacteria in soils as a remediation strategy for overcoming non-wetting soils. This work explores the use of lime to raise the pH of soils to create a less-hostile environment for the bacteria to live in. This work has seen positive results in environments where water is not limiting, however in dryland agricultural systems, the period of time the soil spends in a dry state limits the microbial activity responsible for breaking down water repellence. Nonetheless, this type of system has implications for nutrient management as the use of high rates of lime and the promotion of microbial activity will affect nutrient availability and mineralisation of organic nutrients.

Summary & Future Research Considerations

In the context of our modern farming systems, deep, aggressive cultivation to ameliorate water repellent soils is a relatively new practice. Minimum tillage, conservation farming has been widely adopted in Western Australia and has been beneficial for soil moisture retention, reducing erosion and increasing soil carbon storage. However, it has resulted in less physical mixing of the soil and as a consequence, stratification of nutrients and organic matter in the top 10cm of the profile.

Research into crop nutrition strategies after soil amelioration is ongoing, however it is relatively young given the short period of time farmers have been using strategic deep cultivation to overcome repellent soils. Despite this, we do have an understanding of the processes involved, given previous research into conservation versus conventional tillage that has been conducted over the years.

These new systems though are much more aggressive in terms of soil disturbance, often reaching depths of 35cm and in the case of mouldboard ploughing, involves a complete soil inversion when done correctly. There is therefore little understanding around the long term consequences of this from a nutrition point of view and whilst hypotheses can be made about the implications based on existing knowledge, farmers would benefit from seeing these hypotheses tested and demonstrated in a field situation. For example, the possible role of buried organic matter in intercepting applied nutrients and retaining them in the root zone requires further investigation.

Furthermore, fertiliser recommendation models and crop simulation models don't necessarily account for such dramatic changes in the soil profile. In particular, changes in soil organic matter distribution and, the potential change in clay content as a result of soil inversion. It is therefore important for farmers and advisors to have a better understanding of the nutrition deeper down the soil profile and utilise tissue testing to be able to accurately assess whether there will be a response to applied fertiliser. Tissue testing is a particularly useful tool given there can be a high amount of variation in deep soil test results due to the uneven distribution of organic matter through the profile. This can make it difficult to get accurate and meaningful results from this type of testing.

It would be beneficial to better understand the effects of deep cultivation on soil water dynamics, organic matter breakdown and nitrogen cycling through further research. Farmers and researchers report that responses to fertiliser are limited in the first year after amelioration due to the increased availability of nutrients and mineralisation as a result of improved wettability of the soil. This poses questions around the longevity of this effect. This will impact on the length of time before the conventional 0-10cm soil test becomes relevant again, as well as what the optimum time and rate is, if any, of fertiliser to apply in the first season after amelioration.

Soil amelioration often reduces multiple soil and agronomic constraints resulting in large and ongoing grain yield increases over time. Increased productivity results in increased export and removal of nutrients and this may result in nutrient depletion over time if nutrient application rates are not increased to meet the greater demand. The interaction between soil nutrient levels and crop depletion through product export on fertiliser application rates and strategies requires further research.

Based on the findings of this review, there appears to be limited understanding of the interactions between surface and subsoil potassium levels. In addition, there is only a partial understanding of the processes around phosphorus release and immobilisation and how this can be optimised.

Given the complexity of the soil system, there also seems to be scope to continue improving our knowledge around how the amelioration practice affects other soil constraints such as subsoil acidity and compaction and how farmers can effectively balance their spend in future years between lime application, deep ripping requirements and fertiliser application.

Finally, developing tools to assist farmers to make better decisions around nutrition after amelioration would provide significant benefits. This would require continuing to improve fertiliser recommendation models, developing effective soil sampling strategies, understanding yield potential of ameliorated soil and developing economic models to help farmers optimise gross margins.

Key R,D&E Recommendations

1. Understanding amelioration impacts and fertiliser decision support
    a. Impact of OM reduction as a result of tillage on long-term nutrient supply.
    b. Functioning of buried OM at depth including role of subsoil nutrient supply, interception of nutrients.
    c. Soil sampling strategies for ameliorated soils and development of recommendation systems for fertiliser decision making.
    d. Tissue testing as a diagnostic and coupling with nutrient export in grain to determine future fertiliser strategies.
2. Potassium
    a. Impact of K fertiliser history and starting soil K levels on ongoing K requirements and responsiveness.
    b. K availability with depth and accessibility change as result of amelioration.
    c. Interaction between improved K availability with depth and increased crop demand for K.
    d. K export versus K application with improved yield potential.
    e. Availability changes over time
3. Nitrogen and OM
    a. Starting OM and N fertility
    b. Residue quality and quantity impacts at time of amelioration on crop responsiveness and longevity
    c. Access of deep N
    d. N mineralisation and longer term impacts on N supply
    e. Risk of 'boom then bust' in N supply across soil types
    f. Impact on N leaching
4. Sulphur
    a. Amelioration impacts on availability
    b. Soil type effects and availability with depth
5. Phosphorus
    a. Interactions between soil pH and P availability after amelioration across different soil types
6. Other nutrients
    a. Impact of starting levels – marginal supply versus adequate
    b. Redistribution of micro nutrients and impact of pH profile changes on availability – deficiency risks

Liebe RCSN Trial Focus

Based on the gaps identified in this Literature review and discussion held with the project committee, the Liebe Group will focus on N & K rates and timing in wheat after amelioration in 2017. Sites selected were ameliorated by spading or mouldboard ploughing 2-5 years ago with the aim to avoid the initial 'flush' of nutrients that occurs in the first year after tillage. The sites are located at Marchagee, Eneabba and Irwin and have the potential to be continued on in future years in order to assess the longer term implications of strategic deep tillage. The same trial design and treatment list will be used for each trial site to enable consistency across the sites and replication of data. Table 2 below outlines the treatments for each trial.

	Description	IBS (kg/ ha)	Banded (L/ha)	Banded (kg/ha)	Z23 (L/ha)	Z30 (L/ha)	N	P	K
1	Std N No K	-	54 Flexi-N	85 Agstar Extra	92 Flexi-N	-	70	12	0
2	Std N Std K	-	50 Flexi-N	100 K-Till Extra	92 Flexi-N	-	70	12	11
3	Liquid K	-	117 Flexi-NK	85 Agstar Extra	92 Flexi-N	-	70	12	11
4	Std N More K	-	50 Flexi-N	100 K-Till Extra/28 MoP	92 Flexi-N	-	70	12	25
5	No N	-	-	62 Big Phos/51 MoP	-	-	0	12	25
6	High N	-	50 Flexi-N	100 K-Till Extra/28 MoP	92 Flexi-N	68 Flexi-N	100	12	25
7	Very High N	-	50 Flexi-N	100 K-Till Extra/28 MoP	92 Flexi-N	140 Flexi-N	130	12	25
8	Very High N No K	-	54 Flexi-N	85 Agstar Extra	92 Flexi-N	140 Flexi-N	130	12	0
9	High K	200 MoP	54 Flexi-N	85 Agstar Extra	92 Flexi-N	-	70	12	99

Table 2. Treatment list for Liebe Group RCSN trial "N & K rates and timing after soil amelioration through strategic deep tillage"

Reviewed by: Stephen Davies, DAFWA

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