Chapter 14

Nutrient-management challenges and opportunities in conservation agriculture

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Introduction

Massive changes have taken place in the nutrient management of Australian crops and pastures in the past three decades. Before then the supply of nutrients had been mostly from soil reserves (apart from phosphorus fertiliser, which has been routinely applied in the south), but during the three decades those reserves have declined and plant demand is increasingly met by fertilisers. Additional amounts of nutrients are needed to meet the requirements of higher yielding crops, the increased crop area stimulated by conservation agriculture (CA) and the reduced area of pastures and their supply of residual nitrogen from biological fixation. The three macronutrients considered in this chapter (nitrogen - N, phosphorus - P and potassium - K) show different patterns of decline in cropping soils:

- There has been a national decrease in the soil N reserves of cropping soils averaging 2-3% per annum (Angus and Grace 2017);
- For P, low inherent fertility meant that acute deficiency occurred after a few years without P fertiliser in southern farming areas, while northern Vertosols had higher indigenous P fertility and deficiencies took longer to appear;
- South-eastern soils generally contain high K levels, but deficiency is now widespread in the lighter western soils (Brennan and Bell 2013) and increasingly in the north (Bell *et al*. 2012).

Crops recover a small proportion of the macronutrients in the year they are applied in fertilisers – about 45% in the case of N (Angus and Grace 2107), and there are similar low efficiencies for P and K (McLaughlin *et al*. 2011). More of the fertiliser is recovered in the second and later seasons but the total recovery is generally less than half. The three decades that are the subject of this chapter are a transition period as Australian agriculture starts to pay for nutrients that were previously mined from soil. If trends continue, fertiliser will supply most of the macronutrients and will supplement more of the other 12 essential nutrients.

CA concentrates P and K in the topsoil because of their low mobility (‘stratification‘), and this process is often accompanied by depletion of those nutrients in the subsoil and the emergence of subsurface acidity on some soil types. In both instances, the lack of thorough soil mixing with tillage means fertilisers and lime are no longer thoroughly incorporated into a deeper cultivated soil layer but remain concentrated in the upper layers that are prone to drying. The use of ‘challenge’ in the title emphasises the need to balance CA practices with fertiliser and lime placement. An example is introducing strategic tillage as an occasional rather than annual practice aimed at redistributing nutrients and lime (see Chapter 7). Nutrient supply and demand vary greatly across Australian agricultural environments and we aim to recognise the diversity of the dryland crop and pasture land; here we use ‘west’ to mean Western Australia, ‘south-east’ to mean South Australia, Victoria and NSW south of the Macquarie Valley, ‘south’ to include ‘west’ and ‘south-east’ and ‘north’ to mean from the Macquarie Valley to central Queensland.

Crops

In the last 30 years there has been a tripling of crop production, most of which has been due to increased yield rather than crop area (Table 1). The increased production has required large increases in inputs of N fertiliser and lime, with the latter information relating only to NSW, which is the only state with long-term data on agricultural lime. Unlike N, there has been little net change in P input, reflecting less input of single superphosphate to pasture offset by increased application of compound fertilisers to crops.

The doubling of K fertiliser is mostly due to increased applications to crops in the west and north. By 2017, the input of fertiliser N and P exceeded the estimated output in crops, but K removal exceeded input.

The size of dryland farms and the crop area per farm are increasing (Chapter 3), and both changes are facilitated by CA. Farmers want to minimise the number of times that implements pass over their crops and so welcome opportunities to combine inputs into a single pass or at least move application dates to off-peak periods. They want to increase the speed of operations without compromising their efficiency. Management of nutrients and acidity must fit with such logistics.

Pastures

Pastures grown in rotation with crops and permanent pastures represent a large part of the extensive non-cropping land on Australian farms (Table 1). Rotational pastures benefit from the nutrients and lime applied to crops. Cultivation during the cropping phase, even when it only consists of direct drilling, helps to mix nutrients and lime into the topsoil. From the start of 'sub & super' in the 1950s, improved permanent pastures based on subterranean clover were regularly topdressed with superphosphate. Since this practice concentrated P on the soil surface it was not readily available in dry conditions (Cornish and Myers 1977). However the practice persisted until the wool price crash and superphosphate bounty ended in the 1970s. Many graziers then reduced or abandoned topdressing with superphosphate. In the high-rainfall zone topdressing pastures is an efficient method of applying P (McLaren *et al.* 2017) and the graziers in this environment who persisted with annual superphosphate topdressing obtained profitable responses.

There are no data on the amount of lime applied to acid soils that support permanent pastures, but observations suggest that it is less than to crops with similar levels of acidity. It is generally unprofitable to apply lime where the main pasture species, subterranean clover, is acid-tolerant so the surface and subsurface soils on livestock farms in the high-rainfall zone are acidifying more rapidly than those in crop and mixed crop-livestock farms where lime is being applied. Since 2013-2015, increased prices for meat and wool have boosted the profitability of permanent and rotational pasture systems in the south and will perhaps lead to more sustainable systems through better management of pasture species, lime and P.

Table 1. Production and area of Australian crops and pastures, nutrient inputs in fertiliser, nutrient outputs in grain and animal products, and input of agricultural lime in NSW in 1987 and 2017.

	Amount in 1987	Amount in 2017	Ratio 2017:1987
Crop production (M t)*	28	69	2.5
Crop area (M ha)*	16	20	1.3
Non-crop area (M ha)*	65	55	0.85
*Input***			
Fertiliser N (M t)***	0.34	1.49	4.4
Fertiliser P (M t)***	0.39	0.43	1.1
Fertiliser K (M t)***	0.11	0.22	2.0
Lime (M t)****	0.05	1.10	22
Output §			
N (M t)	0.55	1.44	2.6
P (M t)	0.10	0.30	3.0
K (M t)	0.13	0.38	2.9

*Dryland grains, oilseeds and pulses plus cotton (lint and seed), raw sugar and irrigated cereal grain. Datasource www.apps.daff.gov.au/AGSURF/agsurf.asp
** Fertiliser input to pastures and intensive crops as well as to dryland crops
*** www.fertilizer.org.au
****Lime data are for NSW only: data source: NSW mining royalties
§Calculated from crop production and estimated average nutrient concentrations in product and residue.

Pastures in the Brigalow Belt bioregion face even more serious nutritional problems because of low and decreasing levels of available soil P and inadequate applications of P fertiliser (Peck *et al*. 2015). This report concluded that P fertiliser was a profitable investment for beef production in the ~40 M ha of this region, but there has been little research on the optimal methods to apply P. McIvor *et al.* (2011) report similar problems of P deficiency across the extensive rangelands of northern Australia where the most promising way to supply P is as a feed supplement to grazing cattle. The low P inputs to the Brigalow pastures and the difficulty in P management of crops in the north (discussed below) are reflected in the relatively small proportion of nutrient supplied as P in Queensland (Table 2).

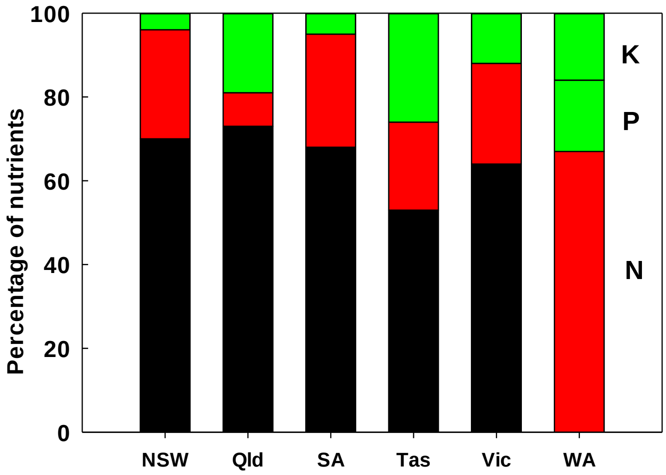

Table 2. Percentages of macronutrients in fertilisers applied during 2016 in Australian states (data courtesy of Fertilizers Australia)

Dual-purpose crops

Cereals and canola crops can be grazed by sheep and cattle in the vegetative stage before they regrow and produce grain. The practice has increased steadily in the south since 2005-10. Nutrients removed during grazing are not available for grain production and N fertiliser is normally applied after grazing to replace the amount removed. The N use efficiency (NUE) of this system is consistently lower than for ungrazed crops with fertiliser applied under the same conditions (Sprague *et al.* 2019). It appears that N-demand is temporarily reduced in small grazed plants and microbial immobilisers assimilate much of the fertiliser N before the plants grow large enough to compete with immobilisers. Livestock also graze stubbles on mixed farms and Hunt *et al.* (2016) showed that grazing increased accumulation of soil mineral N in pre-crop sowing measurements. Their explanation was reduced immobilisation resulting from less stubble as well as N cycling through manure and urine.

Interactions between nutrition and conservation agriculture

The practices of direct drilling and stubble retention have increased wheat yields in the north because of soil water conservation (Thomas *et al.* 1997). In the south these practices have had mixed effects, with increased yield in dry seasons reflecting the northern results, and reduced yield in wet seasons, partly due to microbial inhibition of root growth (Giller *et al.* 2015 and see Chapter 9). The other key component of conservation agriculture, rotation of cereals with broadleaf crops and pastures, also increases yield. Regardless of the cause, increases in crop yield potential lead to extra crop nutrient demand.

Conservation agriculture also affects nutrient supply, particularly the supply of mineral N, with stubble retention leading to increased immobilisation and deficiency of crop N early in the growing season. The degree to which immobilisation influences early N supply is determined by stubble load, climatic conditions and inherent soil N fertility. Stubble loads of 1-3 t/ha are unlikely to alter the optimum N fertiliser rate, but at higher stubble loads, the optimal N rate tends to be higher under stubble retention due to immobilisation (Mason 1992).

Soil disturbance is known to increase mineralisation by improving microbial access to parts of the soil that are relatively rich in organic matter. While overseas research has generally shown that tillage increases mineralisation (and hence accelerates long-term depletion of soil N), nutrients retained in stubble are a significant benefit of CA. Taking N in wheat stubble as an example, the average quantity of N contained in retained stubble is 15 kg N/ha, estimated from average yield (2.1 t/ha), harvest index (40%) and the nutrient concentration of stubble (0.5% N). This represents one third of the 45 kgN/ha applied as fertiliser to dryland crops (Angus and Grace 2017) but a smaller proportion of crop-N recovery. About 10% of stubbles were burnt in 2016, as reported by graingrowers to a GRDC (2017) survey. There is loss of N and, depending on the fire temperature and wind, other nutrients from these stubbles. In the 90% of stubbles that are retained, N represents a significant component of the N cycle. No directly comparable data about nutrients retained in stubble are available from 30 years earlier when average Australian wheat yield was ~30% lower and so, presumably, were stubble nutrient amounts. In previous decades, more stubble nutrients were recycled by livestock grazing in the mixed crop-livestock systems that then predominated, and sowing equipment could not operate without blockages by stubble after high-yielding cereal crops. In the future, nutrients are likely to be retained in all but the heaviest stubbles and if these are managed with a ‘cool burn’ there is unlikely to be large nutrient loss.

Matching nutrient demand and supply

Nutrients are managed efficiently when their supply from soil and fertiliser closely matches the demand by the crop. With increasing productivity, nutrient supply must increase to meet crop demand and to avoid nutrient deficiency or surplus. Formal supply-demand models and rules of thumb give a prognosis of nutrient response and machine learning has promise as a predictive tool to include several data sources (Lawes *et al*. 2019). We should not forget ‘test strips’ which were widely used by Australian farmers or advisers in a previous generation (Schroder and Curnow 1977). In this system single-element fertilisers were added to, or deleted from, a strip of crop or pasture. Decisions about fertiliser requirements were then made from a visual inspection of the growth response. The system is now reinvented as ‘N-rich strips’ and used in conjunction with a proximal sensor for variable rate N-fertiliser application (Colaço and Bramley 2018).

Nutrient demand

Crop productivity and nutrient demand depend on a combination of crop management, environment and genetics. Crop management practices that have increased yield are early sowing with long-season wheat (Hunt *et al*. 2019) and the use of break crops. Legumes provide not only a disease break but also residual N and a separate growth stimulus to following crops by the process of hydrogen fertilisation (Peoples *et al.* 2008). In a meta-analysis Angus *et al*. (2015) showed that the combined effect of these processes increased wheat yield by 1.2 t/ha more than wheat after wheat. Overcoming soil-compaction by deep ripping consistently lifts potential yield and increases wheat-yield response to N in the west (see Chapter 8), first shown by Delroy and Bowden (1986), and on sandy soils elsewhere in the south. Deep ripping gives inconsistent results in the south-east (Kirkegaard *et al*. 2008).

In the south, where growing-season rainfall provides the main water supply for winter crops, nutrient demand cannot be forecast accurately until relatively late in the growing season. With adequate N until tillering (from soil and sowing fertiliser), in-season N inputs can be estimated by a tactical approach based on a revised yield expectation, emerging seasonal conditions, empirical tests of crop N-status and grain price and protein premium. Yield responses to in-season N are more reliable in high-rainfall than low-rainfall regions, but can be highly profitable in exceptional seasons in semi-arid regions. In-season application is inappropriate for less-mobile nutrients that should be applied at or before sowing. Cropping areas in north-eastern Australia are less reliant on in-season rainfall than on moisture stored in the soil profile during summer and/or winter fallows. In these systems, soil moisture available at sowing provides a guide to the minimum yield potential and seasonal forecasts of in-crop rainfall can be used to estimate any additional productivity. In these systems, all nutrients are supplied at or before sowing, with one of the critical success factors for effective nutrient management being coincidence of water, nutrients and active roots in the same part of the soil profile.

The combination of improved crop management and breeding has increased Australian grain yields by annual rates varying from 1.1% for wheat to 2.1% for sorghum (Potgeiter *et al*. 2016). Genetic improvements in crop yield potential affects nutrient demand through nutrient uptake and/or internal nutrient utilisation efficiency. Selection for high wheat yield over many decades has simultaneously increased NUE (Cossani and Sadras 2019). Examples of more specific genetic effects are that semi-dwarf wheat cultivars require more N than tall cultivars (Syme *et al.* 1976) and long-duration cultivars also require more N than short-duration cultivars, provided that the water supply is adequate (Flohr *et al*. 2018). In sorghum, 'stay-green' genotypes have increased yields under terminal drought stress (Borrell *et al.* 2014). The use of molecular genetics for the development of cultivars with increased nutrient uptake has shown promise in laboratory studies (Krapp 2015) but has not yet shown increased NUE in the field. Breeding for nutrient efficiency may have benefits if it reduces nutrient losses but otherwise will simply deplete soil nutrient reserves more rapidly and lead to greater fertiliser requirement in later years.

Soil nutrient supply

Nutrients in the soil may originate from the pre-agricultural era, from residues of fertilisers and manures applied previously and from the biologically fixed N from legume crops and pastures. There is also a small amount from atmospheric deposition. Soil N is mostly found in organic forms, requiring microbial processes to convert to inorganic forms for plant uptake. In contrast, K (and in some instances P) in soil is mostly found in inorganic pools with differing solubility and bioavailability to plants. Examples of the cycles of N, P and K for wheat crops producing average yields in Australia are shown in Figure 1.

The largest source of crop N is from mineralisation, defined as the conversion of organic to mineral N (Figure 1a). The reverse process and second largest flux consist of immobilisation of mineral N that has not been taken up by the plant plus rhizodeposition, which consists of roots and root exudates (Wichern *et al.* 2008). The net N supply is mainly controlled by topsoil temperature, water content and the amount and quality of organic matter. Soil disturbance has been shown to increase mineralisation in overseas research, resulting in accelerated long-term depletion of soil N, but Australian experiments have shown little or no increase in mineralisation due to tillage or stubble retention (Angus *et al*. 2006). The difference is likely to be the different tillage methods: mouldboard ploughing to depths >0.2 m in many overseas farming systems, but in Australia scarifying with narrow tynes to a depth of <0.1 m (see Chapter 1).

Soil reserves provide a greater supply of P to the crop than fertiliser and crop residues (Figure 1). Isotope dilution studies have shown that between 73 and 85% of P taken up by the crop is from soil reserves (McLaughlin *et al*. 1988, McBeath *et al*. 2012) and that between 7.5 and 22% of crop P taken up is from fertiliser (McBeath *et al.* 2012). P supply from crop residues depends upon residue type; in the medium rainfall region in the west, estimated P supplies from green manure, canola, legume crop and wheat residues were 11, 0.9, 0.4 and 0.3 kg P/ha/year (Damon *et al*. 2014).

Soil K is present in several distinct pools which have been simplified in Figure 1 and are explained in detail in Bell *et al.* (2017b). The main source of solution K is from desorption of the ion from mineral surfaces and some clay interlayers. However, slower K release (or in some cases fixation) can occur from clay-mineral interlayers, while dissolution of K minerals can also occur under the action of plant roots. Most of the K in cereals is returned to the soil surface in residues from which it is leached by rain into the topsoil (Rossolem *et al*. 2017), so uneven straw distribution during harvest can increase the spatial variability in plant-available K.

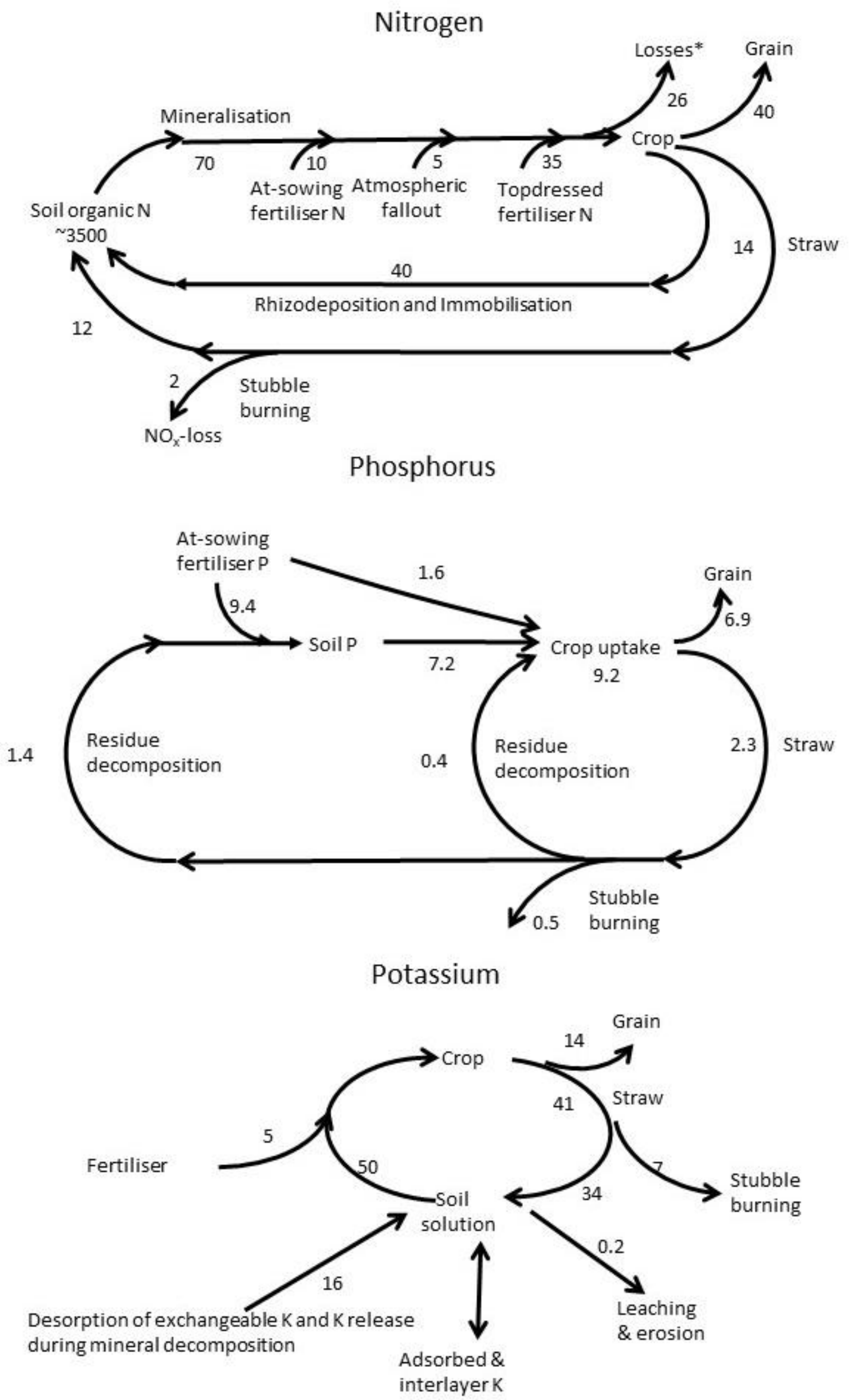

Figure 1. Annual cycles of N, P and K (kg/ha) for an average Australian wheat crop yielding 2.1 t/ha with a grain protein concentration of 10.5% and with grain removal of 3.3 ± 0.7 kg P/t and 4.6 kg K/t (Norton 2012)

Nutrient supply from fertiliser

The framework for discussing the supply of nutrients from fertiliser is the 4 Rs system (Snyder 2017) – right placement, timing, source and rate.

Fertiliser placement

Before the mid-1980s, single superphosphate was the main fertiliser applied to Australian crops and it was almost entirely banded with the seed. Compound fertilisers, such as monoammonium phosphate (MAP), that became available in the 1980s were, and still are, applied in the same way. Since the high ammonia concentration from such fertilisers damages germinating seeds, other application methods were needed to apply high N rates. One was to broadcast urea onto the soil surface and incorporate it by sowing (IBS). Another was to apply N to growing crops, either as broadcast granular urea or as liquid urea ammonium nitrate (UAN) sprayed on the soil and foliage.

In situations where P reactions in soil are dominated by sorption, banding P fertiliser near the seed can improve P fertiliser recovery (McLaughlin *et al*. 2011). This provides an additional advantage in cereal crops, with the close proximity to the developing root system providing an easily accessible source of P at floral initiation, when potential grain number is determined. The value of deep soil P to crop P nutrition is increasingly recognised (Bell *et al*. 2012, Lester *et al 20*17, McBeath *et al*. 2012). A meta-analysis by Nkebiwe *et al*. (2016) suggests that deep subsurface placement of fertiliser could offer a significant benefit in stratified soils, in particular soils where stratified fertiliser is positioned in the layer most vulnerable to frequent drying during the growing season. Deep P placement has increased yield by 5-25% compared to conventional P placement (Bell *et al*. 2015, 2016, Lester *et al*. 2017), with an optimum depth of ~20 cm and band spacing ≤50 cm.

Similarly, deep placement of K also seems to offer significant productivity benefits in northern Vertosols, especially in seasons where topsoils are dry for extended periods (Bell *et al.* 2015). Responses are often smaller than responses to deep P and are not observed unless P supply is adequate, suggesting that P is the primary limitation. In sandy soils there is much greater flexibility in K application strategies because the typically low CEC results in a very limited capacity to sorb K on the exchange surfaces. In this situation (*e.g.* sandy soils in the west), K broadcast onto the soil surface can ultimately leach into the subsoil.

Fertiliser timing

Nitrogen applied before sowing or at the early stages of crop development tends to increase yield and have little effect on grain protein concentration. Early N can even reduce grain protein due to dilution by additional yield. Excessive N applied early can lead to 'haying-off', the disorder of cereals in terminal drought leading to reduced yield and low quality grain (van Herwaarden *et al*. 1998). Canola crops do not hay-off as much as cereals (Norton 2016). Later N applications tend to increase grain protein concentration relatively more than yield but seldom cause haying off. Mineral N leached into the subsoil during a fallow also tends to increase grain protein because it is not accessed by the roots until late in crop development (Lotfollahi *et al.* 1997).

For environments where there is reliable rainfall during the growing season, applying N to the growing crop has advantages of delaying expenditure on fertiliser until there is more information on seasonal conditions, crop-N status, grain prices and protein premiums. N-fertiliser top-dressed onto alkaline surfaces of retained stubble or ash from burnt stubble is at risk of ammonia volatilisation. However, the model of Fillery and Khimashia (2016) predicted little or no N loss when N fertiliser is injected into the soil or top-dressed before rain. Fertiliser N applied onto a dry surface soil or into a dry topsoil, provided it is not dissolved in dew, is neither available to crops nor prone to loss.

The other pathways of N-loss, leaching and denitrification, are most active when the soil is very wet and contains a large amount of nitrate. In some situations, soil saturation can be reduced by land levelling and high concentrations of nitrate can be avoided with split fertiliser applications, both at considerable cost. With the development of autonomous robots, it may be possible to apply N in numerous splits at low cost.

The response of wheat to fertiliser P banded with the seed varies strongly with the date of sowing. Batten *et al*. (1999) showed that yield of crops sown in April required much less fertiliser P to maximise yield than those sown later, but higher P removal rates must ultimately lead to greater depletion of soil P reserves and potentially greater P-fertiliser requirement in later years. Many cropping soils in the south have accumulated sufficient available P to now require only maintenance P applications.

Placement and timing interactions

The fertiliser products listed in the *Placement* section can be applied before, during and after sowing. Application before sowing can cause a yield penalty because sowing is delayed. With dry sowing (see Chapter 18), nutrients on or near the soil surface are unavailable to crops but in winter-rainfall environments the topsoil is likely to wet up within a few weeks so that the nutrients become available. In the north, fertiliser applied just before sowing or at sowing is often ineffective because the topsoil remains dry after sowing. The solution may be deep-drilling of fertilisers containing N, P, K and micronutrients during the fallow period. In this system, nutrients are drilled at a depth of at least 0.2 m where the soil is likely to remain moist enough for nutrient uptake to meet crop demand (Bell *et al.* 2012). The residual effects of deep placement applications made early in the fallow period can persist for 4-6 years (Bell *et al*. 2016), and applications are made early during a winter or summer fallow so that subsequent rainfall can replace any tillage-induced moisture loss. The fertiliser N drilled in this system is normally leached into the subsoil as the soil water refills and the bulge of mineral N in the subsoil normally results in an N supply to the crop that is more synchronous with peak nutrient demand than when it is applied at or just before sowing. The option to apply N fertiliser well before sowing a winter crop is more suited to well-buffered clays and other alkaline soils than to light soils that are prone to nitrate leaching and acidification.

Applying N fertiliser in mid-row bands as part of a one-pass sowing operation separates seed from fertiliser and prevents seedling damage from ammonia. A one-pass sowing operation also minimises soil disturbance. The agronomic advantage of mid-row banding at sowing of winter crops is that urea or anhydrous ammonia, when placed at high concentrations (>500 µg N/g) suppresses nitrification and immobilisation and can remain in the ammonium form for several months. The high ammonium concentrations are achieved with one band of fertiliser between every second seed row, so that each seed row has access to one fertiliser band. Mid-row banding has given greater NUE than other application methods in several experiments (Angus *et al.* 2014, Sandral *et al.* 2017). An alternative to mid-row banding is side banding using tynes that deliver seed behind the 'boots' and fertilisers to the side of the crop row, far enough from the seed to minimise damage to germinating seedlings (Barr *et al.* 2016). More than half the N applied to dryland crops in Canada, for example, is applied at sowing in side or mid-row bands and PAMI (2015) reported no significant difference between the methods.

Mid-row banding of N fertiliser during crop growth is another promising method of application provided there is highly precise guidance using GPS. Wallace *et al*. (2016) showed that this system was more efficient than in-crop application of solid or liquid fertiliser to the soil surface. The probable reason for the higher NUE was that N was neither stranded on dry soil nor lost by ammonia volatilisation. There have not yet been comparisons between mid-row banding during crop growth and one-pass mid-row banding at sowing.

Form – inorganic fertilizer: implications for CA

Fertiliser price, nutrient concentration and convenience influence the form of nutrient applied. Urea dominates the N market because it is cheaper per unit N than alternatives such as liquid UAN, granular ammonium sulphate or ammonium nitrate. Ammonium nitrate often gives greater 'agronomic efficiency' (AE) than urea but the additional yield does not usually justify the additional cost. The N in UAN is also more expensive than in urea but it has advantages that justify the additional cost in some circumstances. The AE for UAN may be slightly greater than for urea (Loss and Appelbee 2006) and it can be applied uniformly and rapidly through a spray boom. Little UAN is applied in the north or south-east but it makes up half the fertiliser N applied in the west. Anhydrous ammonia is also convenient to use but the cost of transport and storage vessels is high unless spread over high yields, or two crops per year. Enhanced efficiency N fertilisers (EEF) contain urease and/or nitrification inhibitors and/or a coating such as polyethylene and epoxy resin that slows dissolution of nutrients. The effect of all EEFs is to retain soil N in the form of urea or ammonium so that less N is lost through ammonia volatilisation, nitrate leaching or denitrification. There is good evidence that nitrification inhibitors reduce emissions of the greenhouse gas N_2O but little evidence of consistently increased yield (Rose *et al*. 2018).

Most P fertiliser for crops consists of granular ammonium phosphates while, for pastures, graziers still apply single superphosphate, partly because of the additional sulfur. In most cases the solid-P sources (single superphosphate, MAP and DAP) perform quite similarly except in calcareous soils where the solubility of superphosphate and DAP is poor (Lombi *et al*. 2005). On highly calcareous soils (>15% $CaCO_3$ w/w) liquid P fertilisers, although expensive, can be more cost-effective than granular phosphates but there is no individual liquid P product that is consistently superior to the others on these soils (McBeath *et al*. 2007). Foliar application of liquid P is an attractive option because it allows for tactical applications of P in response to the season. However, while it has been shown to be absorbed by foliage, it has not given consistent yield responses (Noack *et al*. 2010). While soil-banded liquid P has not been shown to lead to a yield disadvantage compared with granular, foliar applied liquid P that has not been absorbed will land on the soil surface where roots have minimal access, potentially reducing P availability compared with soil application. Applying two or more nutrients in a band can increase the efficiency with which crops recover each. In a K-deficient soil in the west, co-locating P and K fertilisers in a band soil increased root proliferation in the band and increased K uptake by crops (Ma *et al*. 2011). Similar results have been reported in a northern Vertosol (Bell *et al*. 2017a), but high concentrations of co-located P and K fertilisers were needed to stimulate additional K uptake.

Form – manures and residues

Beef feedlots and dairy farms produce ~4 M t/yr of manure (Bunemann *et al*. 2006). Most feedlots are in the north, while poultry and pig manure are applied to croplands in the south close to the source. Most dairy manure is applied on the farms where it is produced. Nutrients in manures vary considerably in concentration, depending on feed rations, age of the manure and the duration of stockpiling (Beegle *et al.* 2008). Nutrient concentrations are typically low and are not in the correct ratios to match crop requirements or balance nutrient removal, so manures should form part of a sustainable nutrient management plan (Abbott *et al*. 2018). The low concentrations also result in high transport costs/kg of nutrient, resulting in distribution patterns centred within a <50 km radius of the source.

Most manure is broadcast onto the soil surface and generally not incorporated. This reduces efficiency of manure nutrient use, with N loss through ammonia volatilisation and positional unavailability of immobile elements. Beegle *et al*. (2008), in a survey of 89 experiments, found that the average NUE of manure was 39±21% of inorganic fertiliser in the year of application, when applied at the same rate and in the same conditions. Celestina *et al*. (2018) found that applying high rates of manures and other organic amendments into slots in dense subsoils increased yield of winter crops, mainly due to increased N supply.

Long-term stubble retention has little effect on soil carbon (C) because the humification is limited by low levels of N, P and sulfur (see Chapter 16). Manures generally contain sufficient N, P and S to increase soil C, but when applied sporadically at commercial application rates (1-5 t/ha), provide small C inputs. Incorporating manure to supply crop nutrients also limits the longevity of any potential C benefit. Added C is less persistent in sands than in finer textured soil.

Rate – paddock averages

Nitrogen fertiliser decisions can be made at or before sowing, and, in winter-rainfall regions, during crop growth. When N is applied at sowing, soil tests of mineral N to an appropriate depth (60 cm in the south and 90 cm in the north) are inputs to a supply-demand equation

$$F = (D - SE_{soil}) / E_{fert}$$

where F is fertiliser requirement, D is demand calculated from expected yield, grain protein and the proportion of N the grain, S is the supply of nutrients from soil and E is efficiency, expressed as the proportion of nutrient from soil or fertiliser that is taken up by the crop. Where it is feasible to apply N during crop growth the yield target can be adjusted as the season unfolds. In these regions a useful measure of crop-N status is shoot density at the start of tillering. This is closely related to the mass of above-ground N and yield response to applied N. The mass of N in the crop is a better predictor of yield response to fertiliser than above-ground N concentration, apparently because self-dilution of tissue N tends to compress the range of concentrations (Angus 1995). Foliar cover of vegetative crops is also closely related to the mass of N which justifies the use of remote and proximal sensors for variable rate application (Li *et al*. 2010). The limitation of relying on canopy cover alone is that it may be related to soil constraints as well as nutrient status. Where canopy cover is low because of N deficiency more fertiliser is needed but where low canopy cover is due to soil constraints there is less need for N (Angus *et al*. 2010).

For nutrients applied at sowing, the critical values for macronutrients have been developed in the 'Better Fertilisers Decision Framework' (N - Bell *et al*. 2013b, P - Bell *et al*. 2013c, K - Brennan and Bell 2013), and the utility of different soil testing methods has been evaluated for P (Speirs *et al*. 2013). The critical nutrient concentration may vary with management practices and, for example, much more P may be required for crops supplied with high levels of N fertiliser than is estimated from established critical values (Duncan *et al*. 2018).

The supply-demand approach is inappropriate for P (Bell *et al*. 2013a, c) and K (Brennan and Bell 2013) because the critical soil test values are not closely related to crop yield, and for P are more related to the buffer capacity of the soil and application method (Moody 2007). The CEC and resulting K buffer capacity influence the optimum K application rate (Bell *et al.* 2017a).

For P and K, applications are typically made at or before sowing. Given the lack of quantitative relationships between yield and P/K demand, the appropriate rate will be determined by the efficiency with which the crop exploits the applied fertiliser. This will primarily be determined by positional availability in the soil profile in interaction with the amount and distribution of seasonal rainfall.

Rate – variable

Spatial sensing of soil constraints and crop conditions provides information that can be used to vary inputs of fertiliser and lime. Variable P application can be prescribed to replace P removed in grain, as estimated from a yield monitor. Variable lime application to neutralise surface soil acidity (but not subsurface acidity) can be prescribed using a pH sensor (*e.g*. www.veris.com). Variation in target yield due to subsoil salinity or sodicity can be estimated by electromagnetic induction (*e.g*. www.geonics.com). But the greatest interest in variable rate technology is with N fertiliser.

Only about 20% of Australian grain growers adopt variable N inputs based on soil-specific management (Robertson *et al*. 2012), despite significant yield and profit benefits being demonstrated in distinctly variable environments, for example between sand dunes and clay loam swales (Monjardino *et al*. 2013). Sensors of crop-N status, which in turn inform variable fertiliser application strategies, have significantly evolved in the last 20 years, although several constraints to their widespread adoption remain. Colaço and Bramley (2018) suggest that the limitations lie within the experimental approaches used, the implementation of the N application algorithms in farmers' fields and the ability to deliver consistent and profitable outcomes. They conclude that further development via the integration of a range of sensors is likely to improve the adoptability of the technology.

Nutrient and pH stratification

Positional availability of nutrients

Soil sampling in Australia has usually been to a depth of 10 cm which is too shallow to identify nutrient-depleted subsoils or stratification of immobile nutrients and subsurface acidity. Sampling the 10-20 cm layer identifies presence of an ‘acid throttle’ (a soil layer sandwiched between a limed topsoil and a naturally neutral or acidic subsoil) and, in the north, sampling the 10-30 cm layer identifies nutrient depletion (Moody *et al*. 2010). In sand-surfaced soils in the west there was an economic benefit from sampling the subsoil when exchangeable K was near-adequate (40-60 mg/kg) in deep sands, or when it was less than 40 mg/kg in duplex soils (Scanlan *et al*. 2015).

Crops extract nutrients from moist topsoils and subsoils, and the latter can supply up to 70% of the N, P and K accumulated by crops in temperate climates (McBeath *et al.* 2012, Kautz *et al*. 2013). Where the topsoil is dry and crops are reliant on subsoil moisture for extended periods, root access to the nutrient-rich topsoil layers is limited and stratified nutrient reserves in these layers are effectively unavailable. In such conditions, crops rely more on subsoil nutrients if they are present. In the west, P accumulates in subsoils when P fertiliser has been repeatedly applied in excess of crop demand (Weaver and Wong 2011). In such circumstances, a test of P concentration in the topsoil underestimates the supply of P from the whole soil profile (Bell *et al*. 2013a). In clay soils in the north there is evidence of P depletion at soil depths >10 cm and <60 cm (Norrish 2003), and of increased yield in response to deep banding P and K fertiliser (Bell *et al*. 2015, 2016, Lester *et al*. 2017).

Nutrient stratification and subsoil depletion can be addressed by periodic ‘strategic tillage‘ to redistribute nutrients concentrated in the topsoil into deeper soil, or by direct placement of nutrients into the depleted subsoil layers (see Chapter 7). The ‘strategic tillage’ option of cultivation every 5-10 years is considered by some to be inconsistent with conservation tillage because it leads to temporary reduction in surface cover, accelerated soil C loss and disruption of microbial communities. However there are situations where periodic tillage is already occurring to control herbicide-resistant weeds, to incorporate lime, increase topsoil clay content or reduce the severity of hydrophobicity. These operations also redistribute stratified nutrients through larger soil volumes (Scanlan and Davies 2019). The balance between these benefits and costs associated with tillage needs further research (Dang *et al.* 2015). The value of the alternative approach, to inject nutrients directly into depleted subsoil layers, depends on seasonal conditions (Bell *et al*. 2012).

Reversing subsurface acidification

In situations where no lime has been applied, the topsoil becomes acidified and the acid layer spreads down and becomes thicker, retarding penetration of roots of acid-sensitive species to reduce yield. Applying lime to the topsoil layers without incorporation by tillage leads to development of an ‘acid throttle’. This pH profile is an increasingly common occurrence in cropping land in the high and medium rainfall regions of the south. Surface lime applied at normal rates moves slowly through loam-textured topsoils (Kandosols, Chromosols and Tenosols) in the south-east (Li *et al*. 2019) but is more mobile in sandy topsoils in the west (Whitten *et al*. 2000).

Practices to neutralise subsurface acidification are expensive. The simplest is to apply larger than normal amounts of lime to the surface soil, with or without tillage (Scanlan *et al.* 2017). Other methods are directly injecting lime into subsurface soil through tubes behind rip tynes, or extensive profile modification using a rotary spader to mix surface-applied lime through ~30 cm of soil (see Chapter 8). With enough lime, all of these practices eventually reduce the level of subsurface soil toxins, increase crop access to subsoil water, increase yield potential and hence nutrient demand. The more vigorous the soil disturbance the faster the subsurface acidity will be neutralised. There is evidence that neutralising subsurface and subsoil acidity can unlock indigenous P, as Shierlaw and Alston (1984) found by ameliorating subsoil compaction. Alternatively, there may be a greater requirement for fertilizer as yield potential increases.

Conclusions

The many interactions between plant nutrition and CA have been the subject of research over the past 3 decades. The results have led to changes in management of fertiliser rate, timing and placement appropriate for CA. The optimum rates of N fertilisers for crops are known to vary in response to N immobilisation by retained stubble, N contributions from legume rotation and increases in potential yields through improved water use efficiency. Rates of P and K fertilisers also reflect changes in yield potential and hence nutrient demand, but perhaps a bigger issue for both the less mobile nutrients is placement to ensure good root access.

Two nutritional challenges stand out because of the cost they impose on Australian agriculture and the relatively small amount of research that is underway. One is neutralising the looming acidification of subsurface soil in high and medium-rainfall agricultural regions in the south-east and west. The second is to start restoring the P status of pasture soils in the Brigalow bioregion.

Both challenges apply to large areas of land, about 40 M ha in each case, located in relatively favourable climatic regions. In both cases the land will become more degraded if left untreated, and research is needed to find effective and economic treatments. Neither challenge is directly related to CA, although subsurface acidification is partly due to the reduction in profile mixing of lime applied to topsoils due to reduced cultivation. Given the presence of both constraints in subsoil as well as topsoil layers (the latter in the case of low soil P in the Brigalow bioregion), strict adherence to CA principles represent a limitation to the management strategies that can be deployed. Use of strategic/occasional tillage appear to be part of any future solution. However, the profitability of both systems needs to be increased to cover the cost of additional inputs. New application strategies will be needed to maximise the efficiency of use of these inputs.

The low recovery of applied nutrients by crops and pastures is a large cost to Australian agriculture that will only grow larger as fertilisers provide an increasing proportion of the nutrient supply, although there is currently little evidence that CA has affected nutrient use efficiency. Future research will need to improve fertiliser recovery and use efficiency. Based on this review, the most promising lines of research are the placement of fertilisers and soil ameliorants into layers and bands of the soil that support root growth and supply nutrients in amounts and at times that synchronise with crop demand. This may ultimately require the development of new farm implements.

It will also be important to retain legume-based pastures and pulses as part of CA because these species require no N fertiliser, contribute residual N to following crops and increase potential yield of rotational crops in other ways. Despite their importance, the area of rotational pastures is declining, and pulses make up only 11% of cropped land (ABARES 2018). The greatest contribution of pulses was in the west from the early 1980s to the late 1990s, when the area of lupin crops grew from zero to 20% of the cropped land. At the same time, the trend of wheat yield increased rapidly suggesting that lupins made a major contribution to system productivity. The area of lupins in the west has subsequently decreased but their brief success shows the potential contribution that pulses can make. Support for pulse growing will enhance CA.

Australian dryland farmers make most of their income in relatively few favourable seasons and on their most fertile soils. In winter-rainfall regions tactical management of in-season N fertiliser in these exceptional seasons can help capture high yields. Improved seasonal weather forecasts and variable rate systems could assist farmers with risky decisions about applying N to ‘feed the crop’, while deep placement of P, K and lime ‘feed the soil’ and provide an environment in which N can be managed to achieve the water-limited yield.

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