Chapter 5
Challenges and Opportunities in Fertilizer Placement in No-Till Farming Systems

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Abstract No-till (NT) farming systems are now widespread and are part of Conservation Agriculture. The adoption of any new system brings consequences, and NT means changes in fertilizer practices to realise the potential of improved soil conditions. Less soil mixing results in the vertical stratification of immobile nutrients and banded, deep placement of fertilizers away from the seeding rows is a common approach to address stratification. Lateral stratification will require adjustments to soil sampling strategies and soil test interpretations. Nitrogen dynamics also alter where crop residues are retained, requiring a review of the source, rate, time, and placement of fertilizers Wider seeding rows and higher fertilizer rates present an increased risk of fertilizer damage in the seed row. Banding nutrients away from the seed row with improved machinery design and selecting fertilizers with low damage potential are options to manage the risk of damage. A significant challenge to NT is to manage soil acidity, given the relatively low mobility of lime. Consideration of interventions with strategic tillage have been proposed to address lime incorporation as well as alleviate nutrient stratification, although the guidelines for the application of these strategies are still developing.

Keywords Nutrient stratification · Fertilizer damage · Nutrient banding · Soil acidity · Liming

5.1 The Need to Address Fertility in No-Till Systems

It is generally accepted that "conventional" tillage (CT) and crop residue burning has substantially degraded the soil resource base. As a consequence, the concept of no-till (NT) systems or Conservation Agriculture (CA) has developed to encompass what is now considered crop management best practice (Giller et al. 2015). This is

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defined as a sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region, whose farming and soil management techniques protect the soil from erosion and degradation, improve its quality and biodiversity, and contribute to the preservation of the natural resources, water and air, while optimizing yields (Gonzales-Sanchez et al. 2015). Fundamental to NT/CA is minimum soil disturbance, continuous soil cover with crops or crop residues and crop rotation (FAO 2015).

Adopting NT and crop residue retention presents a new set of challenges to farmers and land managers. This chapter will provide a perspective on nutrient management challenges (e.g. Angus et al. (2019)). The principles of 4R nutrient stewardship aim to develop nutrient best management practices based on the use of the Right nutrient source, applied at the Right rate, at the Right time, and in the Right place (Roberts 2007). In the transition to a NT farming system, all these elements and their interactions need to be reconsidered.

5.2 Impacts of No-Till on Soil Fertility

Stratification is one of the main consequences of moving to a NT system as the lack of soil disturbance can mean that nutrients are no longer mixed through the "plough layer". Stratification can be both vertical, where the nutrients are concentrated in one or more of soil layers, or lateral, where the nutrients are concentrated in the bands where they were applied.

An important component of moving to a NT or CA system is to combine crop residue retention with NT. Crop residue retention impacts on nutrient dynamics, by modifying nitrogen mineralization and immobilization as well as protecting the soil surface from wind and water erosion so preserving topsoil where organic matter and mineral nutrients are present.

It would seem obvious, but the development of improved soil conditions that result from NT should be expressed in higher crop yields, but as Van der Putte et al. (2014) noted, this is not always achieved. Appropriate crop protection strategies, plant nutrient supply, well-adapted varieties, and management practices that balance these activities represent the other aspects of achieving yield potentials. Where this occurs, increased yields will also mean higher nutrient removals and so a higher input of nutrients from either mineral or organic sources will be required. Adjusting fertilizer rates is an important aspect of achieving the higher yield potential due conserved soil moisture and preserved topsoil fertility through erosion prevention.

5.2.1 Vertical Nutrient Stratification

In NT systems, the surface soil is not remixed with soil deeper in the profile and so while mobile nutrients like nitrogen (N) and sulfur (S) can leach into the subsoil, immobile nutrients like phosphorus (P) and potassium (K) can become enriched in the topsoil. (e.g. Cornish 1987; Alam et al. 2018).

The degree of vertical stratification observed in NT systems will vary with soil pH, P fixing or K retention capacity, soil texture (sand or clay), profile type (duplex or uniform), and rainfall (leaching potential). As a result, stratification is likely to be highest in highly buffered soils, with low hydraulic conductivity, and in low rainfall regions. In NT systems in winter rainfall areas of south-eastern Australia, for example, P is generally less stratified in NT soils than in semi-arid regions due to higher rainfall (Vu et al. 2009; Armstrong et al. 2015). In the sub-tropical summer dominant rainfall grain production regions of northern Australia, the P and K availability decreases markedly down the profile (Grundon et al. 1985) so that winter crops growing in that environment cannot access those nutrients in the dry topsoil.

The impact of nutrient stratification on crop yield will largely depend on the timing of water supply. In environments that experience rapid and frequent drying of the topsoil, crops will rely more on subsoil nutrients than crops grown when the nutrient enhanced topsoil is moist (Bell et al. 2015). In regions where stored water is less important, nutrients in the topsoil may still be available, a consequence of the surface soil remaining moist for most of the growing season (Alam et al. 2018).

Addressing vertical stratification in NT systems requires identification of the locations where nutrients are depleted and then placing nutrients in those locations to make them root accessible. Rather than a diffuse mixing of soil and fertilizer, placing the fertilizer in a band near the seed enables higher fertilizer rates, depending on species and the edaphic conditions. Ma et al. (2009) found that placing fertilizers deeper in the soil profile could increase nutrient acquisition and utilization by plants as fertilizer nutrients are in the moist soil for a longer part of the growing season. The coincidence of water and nutrients will largely affect the response to nutrients placement, and this in turn is a consequence of soil texture, fertilizing history, nutrient mobility, and crop species, as well as tillage practices (Ma et al. 2009).

In Mediterranean-type or temperate climates, a yield response of winter crops to deep fertilizer placement mostly occurs on infertile sandy soils in low rainfall regions (Ma et al. 2009). This contrasts with the responses of winter and summer crops in northern Australia on soils with optimum-to-high nutrients but subjected to rapid and frequent drying of topsoil because of high temperatures and high evaporation demand during the growing season (Singh et al. 2005). Banding of nutrients into the subsoil has been evaluated in those summer rainfall areas, where a blend of P and K is banded at about 0.25 m on rows 0.5 m apart (Bell et al. 2015). This results in significant soil disturbance in the year of application and the rate applied is aimed at supplying adequate nutrients for four to six crops, and then the field is returned to standard NT practises for around 5 years.

A consequence of vertical stratification is that a standard soil testing depth (0.1 m) may overestimate the supply of nutrients. Soil test calibration relies on a standard sampling depth to relate to crop responsiveness. However, the sampling depth may need to be reconsidered under NT systems for P (Bell et al. 2013), although Yin and Vyn (2003) indicated that soil test K levels are generally not affected under NT. Lester et al. (2016) suggested that soil samples be taken from the 0.1–0.3 m layer in addition to the 0–0.1 m layer, and tests used for both bicarbonate extractable P and K, as well as for the less available acid extractable P and the less available pools of K. Diagnostic criteria are being developed to better identify situations where crop responses may occur with deep placed nutrients.

5.2.2 Banding Fertilizer

Under traditional tillage practices, seed and fertilizer are placed together in the furrow and often mixed with soil. The fertilizers used are often low nutrient analysis types, such as single superphosphate, applied at relatively low rates that are balanced to meet the demands of relatively low yielding crops. Alternatively, fertilizers are broadcast over the soil surface and either incorporated by sowing or by rainfall. Deep subsurface placed ammonium fertilizers (e.g. MAP, DAP), urea, potassium, and solid or liquid manure are also used and are more effective at improving deep rooting, nutrient uptake, and yield compared to broadcast fertilizers (Nkebiwe et al. 2016).

To deal with higher stubble loads, the spacing of seeding rows has increased from 0.12–0.15 m to 0.25–0.30 m for small grains such as wheat and canola, and wider with crops such as corn and soybean (Scott et al. 2013). As seeding rows become wider, the concentration of the fertilizer in the seed row increases, and when combined with minimal soil disturbance with a NT furrow opener, can lead to fertilizer damage to the seed (e.g. Carter 1967; Mason 1971; Scott et al. 1987; Grant et al. 2010; Mooleki et al. 2010). Banding the fertilizer away from the seed row is now a common strategy and allows higher rates of fertilizer to be applied at seeding, as well as reducing the competitiveness of some weeds such as wild oat in barley (Donovan et al. 2008). Compared to surface applied nutrients, subsurface banded fertilizer applications can assist in reducing nutrient losses, even on flat fields (Yuan et al. 2018).

The response to deep banded nutrients varies among species (Rose et al. 2009a). The roots of wheat and canola, but not lupins, have been reported to proliferate around P bands, although root distribution away from the bands was the same. Banding of P at 0.17 m increased canola P uptake and seed yields in low P soils compared to shallow (0.02 m) placement of P (Rose et al. 2009b).

The distribution of soil moisture has an important effect on the response to deep placement, and when the topsoil is moist most P is taken from the topsoil, but in above average seasons P banded below the seed increased plant P uptake in lupins (Jarvis and Bolland 1990) and wheat (McBeath et al. 2012). Banding near the seed (0.02–0.05 m) enables root proliferation around those bands and enhances the access of the plants to fertilizer P, while moist soil conditions improve the plant access to diffuse P in the soil (Officer et al. 2009a), and a similar relationship occurs with K in corn and soybean (Bordoli and Mallarino 1998; Ebelhar and Varsa 2000; Borges and Mallarino 2003), although Borges and Mallarino (2003) note that stratification of K is less pronounced than P.

There is also evidence that having N and P together in the band can improve uptake of both nutrients for wheat (Officer et al. 2009a; McBeath et al. 2019), flax (Lafond et al. 2003) and maize (Ma et al. 2013). Similarly, Weligama et al. (2008) showed that the greatest shoot growth was achieved where N and P were applied together irrespective of depth. They explained this partly in terms of enhanced root proliferation around the P bands and increased rhizosphere pH, while Officer et al. (2009b) measured higher root length density generally, but not necessarily, in proximity to P bands. There was a substantially greater, but still generalized, increase in root length density in a Vertosol when both N and P fertilizer were applied, although there was no response to N fertilizer alone.

The position of bands relative to the seed rows is also important. Immobile nutrients such as P and K should be in close proximity to the developing seed (Yin and Vyn 2003), but not close enough to cause damage to the developing roots or shoots. There have been adaptations to seeding equipment to separate seed and fertilizer (Desboilles et al. 2019) using ‘double chute/shoot openers’. The placement of seed can either be in paired seed rows with fertilizer beneath and between the rows, or as single seed row with the fertilizer band below and to the side. The effectiveness of side-banding and separation of seed and fertilizer has been demonstrated in wheat and canola (e.g. Johnston et al. 2001). Part of the evolution of seeding equipment in NT farming systems has been the development of mechanisms to separate seed and fertilizer and the narrow furrows created by disc openers makes separation even more important.

An extension of side-banding is to place fertilizers between seeding rows, termed mid-row banding. Each fertilizer band serves two seeding rows, and this approach can be done either at seeding (Norton et al. 2003) or in-crop (Wallace et al. 2017). This applies particularly to nitrogen fertilizers, where nitrification is inhibited in the bands where soil solution ammonia concentrations exceed 3000 mg kg^{-1} and pH exceeds 8 (Wetselaar et al. 1972), or nitrate concentrations become high enough to inhibit root growth (Passioura and Wetselaar 1972). Banding provides a slow-release form of N to wheat crops, thereby reducing excessive seedling growth and the risks of haying-off (Angus et al. 2014). In a NT system, nitrogen sources such as urea, fluid urea-ammonium nitrate, or gaseous ammonia can be “knifed” in using a straight disc or a very narrow point (Kelley and Sweeney 2007; Angus et al. 2014), and precision applicator guidance enables accurate placement between seed rows for post-sowing applications (Wallace et al. 2017).

5.2.3 Lateral Nutrient Stratification

As sowing row width has become wider to cope with high stubble loads at seeding, and fertilizers are banded in rows, horizontal or lateral stratification of fertility bands can occur. The consequence of this stratification is that P and K concentrations are higher in the banded zones, and pH can lower (Duiker and Beegle 2006). As a consequence, a soil sampling strategy to take account of banded fertilizers is required, otherwise soil test data may over-estimate P and K availability and under-estimate lime requirement.

Fernández and Schaefer (2012) proposed that where precision guidance is used and the drill row position it known, a ratio of 1:3 in-row to between-row samples seemed adequate to estimate soil fertility across a wide range of P and K fertilizer rates and soil test levels. Kitchen et al. (1990) suggested that, in a situation where a residual P band was obvious, a ratio of 1:20, 1:16, and 1:8 in-row cores to between-row cores could be considered for 0.76, 0.61, and 0.30 m band spacing, respectively. However, in a situation where the location of the P bands was unknown, random sampling is the only alternative, although the greatest errors occur when samples are taken on the bands in NT systems (Bolland and Brennan 2006).

An additional issue with lateral nutrient stratification is the choice of whether to sow on or between the prior sowing rows. Because of enhanced concentration of immobile nutrients in the row, it is tempting to sow back on the same row. However, there is evidence that crown rot (*Fusarium pseudograminearum*) inoculum can be at higher levels in the drill row and can lead to higher levels of disease, particularly if there is very little disturbance in the row, such as when a disc furrow opener is used (Verrell et al. 2009).

5.2.4 Changes in N Dynamics

No-till systems with residue retention can affect N cycling. Crop residues reduce soil temperatures, slowing germination (Bruce et al. 2005), reducing the amount of soil evaporation (e.g. Lascano and Baumhardt 1996) as well as slowing mineralization. During crop residue decomposition, immobilization of N is common and so reduces the immediate availability of N. The amount of N immobilized will be affected by the carbon to nitrogen ratio of the residue. High C:N materials (e.g. cereal residue) will have a higher net immobilization than low C:N materials (e.g. legume residue) (Peoples et al. 2017). Field results suggest immobilization rates of 5–13 kg N ha^{-1} with 1 Mg ha^{-1} of wheat stubble (Mary et al. 1996). Where stubbles are burnt, about 90% of the N in the residue is lost (Angus et al. 2019).

The net effect of NT and residue retention is to increase the overall demand for N (e.g. Mason 1992; Newton 2001). Kirkegaard et al. (2018) estimated that surface retained stubble in modern NT systems can immobilize sufficient N to reduce crop yields by 0–0.5 Mg ha^{-1}.

Where crop residues are retained on the surface, higher rates of top-dressed N may be required (Malhi et al. 1996; Grant et al. 2001). This is likely a consequence of the increased concentration of urease enzymes on retained materials, although increased immobilization of the applied N could also contribute. Under reduced or NT systems, changing the N source and placement would be alternatives to increasing the rate to account for potential losses. For example, Grant et al. (2002) proposed that using spring banded ammonia produced higher canola yields than either urea or urea ammonium nitrate (UAN) under reduced tillage. Similarly, Malhi and Nyborg (1992) found that under reduced tillage, the grain yield and N accumulation of barley were less than broadcast urea under CT. Responses to deep placed or side banded N were similar between the two systems. Reconsidering the source, rate, time, and place of fertilizer use is therefore a critical part of the transition from conventional to NT systems.

5.3 Fertilizer Damage in No-Till Seeding Systems

The trends for wider seeding rows and the use of furrow openers that provide little soil mixing in NT systems means the concentration of fertilizer within the seed row is higher. Even at relatively low rates, seedling damage can occur and reduce yields. For example, compared to deep place DAP, 50 kg DAP ha^{-1} drilled with the seed using a knife point furrow opener at 0.28 m row spacing with wheat seed was enough to reduce wheat plant establishment by nearly 20% and yield from 3.94 Mg ha^{-1} to 3.44 Mg ha^{-1} (McBeath et al. 2016).

It is possible to separate the time of fertilizer application from the time of seeding by either pre-drilling fertilizer or applying fertilizer in-crop as either top-dressed granular forms, as a fluid fertilizer, or as either form mid-row banded. These options work well for mobile nutrients such as N and S, but both pre-crop and in-season P application are less successful. Volatilization of urea and UAN spread on the surface in-crop can also lead to N losses of 2–24% of N applied (Turner et al. 2012), with higher losses on bare soils, under warm conditions, and with little rain. In the presence of crop residues, there may also be increased ammonia volatilization compared to bare soil because of the presence of urease in plant residues (Goos 1985). Placing N at 0.075 m below the soil surface is reported to result in negligible ammonia losses from urea (Rochette et al. 2013).

The relationship between furrow opener disturbance and seeding row width can be summarized in terms of "seed bed utilization" (SBU), which is an index of the amount of soil disturbance with the furrow opener compared to the area sown. A low SBU typically makes a uniform seeding job easier, but increases the risk of fertilizer toxicity. Figure 5.1 gives some examples of the pattern of disturbance of a range of common tyned furrow openers, with a 0.125 m conventional share giving seed spread of around 0.065 m (5.1A), while a 0.03 m spearpoint giving about 0.025 m spread (5.1D). Then using these openers at 0.15 m spacing, the SBU for the conventional share would be 0.43, while for the spear point the SBU would be 0.17.

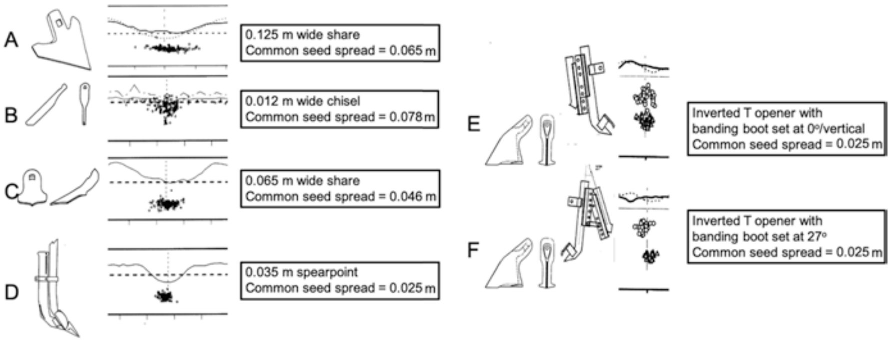

Fig. 5.1 Seed and fertilizer placement patterns with a range of tyned furrow openers. (Used with permission, University of South Australia)

While a low SBU means that the fertilizer is more concentrated in the seed row and so has a high potential for damage, other factors such as fertilizer type, soil texture, crop type, and soil moisture status also have effects, as discussed below.

The patterns of seed and fertilizer distribution shown in Fig. 5.1a to d have the propensity to cause seedling damage, and so the alternative strategies in Fig. 5.1e,f provide physical separation of the seed and fertilizer. In general, a distance of 0.025–0.035 m between the band of fertilizers and the seed is adequate to reduce seed damage (Grant et al. 2010).

5.3.1 Fertilizer Type

The two main aspects that contribute to fertilizer damage to seed are the osmotic or salt effect and the propensity of the fertilizer to produce ammonia (Carter 1967), although NH_4^+ toxicity has occurred at concentrations lower than can be explained by salt toxicity (Barker et al. 1970). There are also reports of fertilizer contaminants such as fluorine in single superphosphate leading to crop damage at high application rates (Loneragan et al. 1966). The acidity of fertilizers such as single superphosphate (Table 5.1) can also affect applied seed-surface inoculum of rhizobia in legumes.

Salt index (SI) is a measure of the salt concentration that a fertilizer induces in the soil solution. The SI is expressed as the ratio of the increase in osmotic pressure of the salt solution produced compared to the osmotic pressure of the same weight of $NaNO_3$, which is set as the reference value of 100 (Mortvedt 2001). High SI fertilizers can decrease seed germination and increase seedling injury. The SI does not predict the amount of damage, but does allow a comparison of different products. Table 5.1 gives the salt index of a range of fertilizers. In general fluid fertilizers, which are already in solution, give a lower osmotic pressure in the soil solution than granular products of a similar grade (Mortvedt 2001).

Table 5.1 The composition, approximate pH, salt index, water solubility and equivalent calcium carbonate (ECC) value per kg N of a range of fertilizers (IPNI 2011; Mortvedt 2001)

Fertilizer	%N	%P	%K	pH	Salt index per kg nutrient	H_2O solubility g L^{-1}	ECC kg $CaCO_3$ kg N^{-1}
Urea	46			~7	1.62	1080	3.6
Ammonium nitrate	34			~7	3.06	1900	3.6
Calcium nitrate	16			~6	4.19	1212	0
Ammonium sulfate	21			5–6	3.25	750	7.2
Potassium nitrate	13			7–10	1.22	316	0
Urea/ammonium nitrate	~30			~7	2.24	Fluid	3.6
Ammonium polyphosphate	10	15		~6	0.46	Fluid	3.6
Monoammonium phosphate	11	20		4.3	0.46	370	7.2
Diammonium phosphate	18	20		7–8	0.41	588	5.4
Triple superphosphate		22		1–3	0.22	–	–
Single superphosphate	9			<2	0.39	–	–
Potassium chloride			50	~7	1.93	344	–
Potassium sulfate			42	~7	0.85	120	–
Potassium thiosulfate			20	7–8	2.72	Fluid	–

Fertilizers containing ammonium (eg MAP, DAP, ammonium nitrate or sulphate), or which produce ammonium can damage seed germination and seedling development through the production of ammonia (NH_3) (Källqvist and Svenson 2003; Haden et al. 2011. Partial inhibition of germination occurred with low (<0.01 N) concentrations of ammonium salts (Barker et al. 1970). Ammonium can cause toxicity effects, but is adsorbed onto the cation exchange and is converted to ammonia, such that ammonium toxicity is an unusual event in the field. When corrected for N concentration, there are only small differences among N sources in terms of ammonia toxicity (Gelderman 2008), although Dowling (1998) and Moody et al. (1995) had contradictory evidence on the differences between DAP and MAP damage potentials.

Urea is most often the cheapest N source, and the use of enhanced efficiency products have been evaluated to improve its in-furrow safety. Treatments of in-furrow N fertilizers such as N-(n-butyl) thiophosphoric triamide (NBPT) (Grant et al. 2010), polymer coating (Mahli and Lemke 2013) and sulfur coated urea (Severson and Mahler 1988) have been shown to improve emergence in a range of crops compared to untreated urea, although damage is moderated by soil moisture conditions. Treatment of urea with these materials may enable increased in-furrow rates to be used depending on crop and SBU (Karamanos et al. 2004).

5.3.2 Crop Type, Soil Texture, and Soil Moisture

Tap-rooted species (canola, faba bean) are more susceptible to ammonium/ammonia bands that wheat, which avoid the toxic bands (Pan et al. 2016). In general, large seeded species are more tolerant to fertilizer toxicity than small seeded species, and seed with a thick testa are likely to be more tolerant than seeds with a thin testa. Canola is probably the most sensitive to fertilizer damage of the common crop species.

Soil moisture and soil texture also have effects on osmotic potential and ammonia retention, so that consideration of these factors with crop, fertilizer, SBU, and soil conditions is required to determine damage potential (Karamanos et al. 2008). Gelderman (2007) undertook as series of controlled environment assessments with a range of crops, soil textures, soil moisture contents and fertilizers to develop a comprehensive set of linear regression coefficients for in-furrow fertilizer rates and crop stand. These data were developed into a spreadsheet calculator and later into a web-based decision support tool (https://seed-damage-calculator.herokuapp.com) to assist with risk assessment under a wide range of conditions. This tool has been widely used by growers and agronomists, although it is relatively conservative in its recommendations because a linear, rather than a plateau, function is used to estimate crop damage. A summary of some of the recommendations derived from this decision support tool is shown in Table 5.2. These data are in general agreement with commercial sources of information such as Laycock (2019).

Table 5.2 Approximate safe rates of N as urea (kg N ha^{-1}) with the seed of canola and wheat for different soil textures and soil moisture status, with 10% acceptable stand loss using the web based seed damage calculator tool (https://seed-damage-calculator.herokuapp.com) as derived from (Gelderman 2007, 2008)

	0.02 m seed spread		0.05 m seed spread		0.10 m seed spread	
	Row spacing (m)		Row spacing (m)		Row spacing (m)	
	0.15	0.31	0.15	0.31	0.15	0.31
	SBU	SBU	SBU	SBU	SBU	SBU
Crop type & soil texture	14%	8%	29%	17%	57%	33%
Canola seed	Moist seedbed conditions (kg N ha^{-1})					
Coarse (sand)	3	1	8	4	16	8
Fine (clay)	6	3	15	8	64	34
Canola seed	Dry seedbed conditions (kg N ha^{-1})					
Coarse (sand)	2	1	5	2	10	5
Fine (clay)	3	2	8	4	15	8
Wheat seed	Moist seedbed conditions (kg N ha^{-1})					
Coarse (sand)	10	5	24	12	48	23
Fine (clay)	19	9	48	23	96	46
Wheat seed	Dry seedbed conditions (kg N ha^{-1})					
Coarse (sand)	6	3	14	7	29	14
Fine (clay)	10	5	24	12	48	23

5.3.3 Machinery Configuration

Desboilles et al. (2019) summarized the development of seeding machinery in Australia used in NT systems. Modern seeders have no tillage tynes, narrow furrow openers, wide seed-row spacing, press wheels, high underframe clearance, and the ability to separate seed and fertilizer. There has also been a move towards disc seeders, which are able to operate at higher speeds than tyned openers because of the high soil throw with the latter (Desbiolles and Saunders 2006). Disc openers also tend to more expensive than tynes openers with complex designs and poor penetration into hard soils (Barr et al. 2016). New types of furrow openers that can operate at high speed but with little soil throw are being developed (Desboilles et al. 2019).

Mid-row or inter-row banding can be used with adaptations to existing equipment, which enables separation of seed and nitrogen fertilizers in different rows. Mid-row banding can be successfully deployed in-crop given precise equipment guidance using either tyned or disc openers (Wallace et al. 2017). Another option for in-crop application of fluid fertilizers such as UAN is the use of a point injection applicator, which enable fertilizer placement in the root zone with little soil disturbance and also no need for rain to wash it into the root zone (Baker et al. 1989; Schlegek et al. 2003).

5.4 Liming in No-Till Systems

Acidification rates under NT systems can be higher than CT (Blevins et al. 1978; Conyers et al. 2003), possibly a consequence of less soil mixing, higher productivity, and higher rates of nitrogen use. The standard practice for addressing acidity is the use of lime (Moore et al. 1998; Conyers et al. 2003). Under CT, lime is placed at the surface of the profile and 2–3 Mg ha^{-1} worked into the topsoil between crops. Obviously under NT, mechanical incorporation is not undertaken, and the mixing of lime into the soil is contingent on the leaching of lime down the profile. This movement is a function of the soil texture and the amount of rainfall, but is often less than 0.075 m (Godsey et al. 2007).

Subsoil acidification occurs as a consequence of many processes, including acidification by deep rooted legumes (Loss et al. 1993) and nitrate leaching beyond the root zone (Tang et al. 2000). Acidification at depth is less amenable to amelioration with lime, particularly on clay or loam texture soils, due to its low leaching rate (Conyers and Scott 1989). Surface application of gypsum has been shown to reduce Al toxicity through the formation of a soluble Al sulfate complex (Pavan and Bingham 1982). Because gypsum is more soluble than lime, it will move much more readily into the subsoil and it has been found that the surface application of phosphogypsum reduced the level of exchangeable Al and improved crop performance in a NT corn system (Caires et al. 2011).

Applications of organic materials on the surface has also been shown to ameliorate subsoil acidity in leaching columns based on the hypothesis that organic molecules assist the downward movement of Ca, which in turn react with Al in the subsoil so reducing Al toxicity (Hue and Licudine 1999).

Direct placement of lime into the subsoil has been evaluated with mixed success, with little responses in some regions with loam soils (Swan et al. 2011; Li and Burns 2016) but a favorable response on deep sands with acidic subsoils (Gazey and Davies 2009). Lime can be injected through tubes behind ripping tynes (Li and Burns 2016) although the equipment is both expensive and complex. Kirchhof et al. (1995) developed equipment that could place lime into the subsoil via a slot 0.15 m wide and up to 0.8 m deep, where the soil was excavated, mixed with 20 Mg ha^{-1} of lime and then returned to the slot. While effective, the cost both of the lime and the specialized equipment has meant this option has not been pursued commercially (Davies et al. 2019).

Given the difficulty of moving lime into the soil either mechanically or by leaching, consideration has been given to the use of periodic or strategic tillage to mix lime and soil in otherwise NT systems (Dang et al. 2017; Conyers et al. 2019). It has been recognized that more aggressive tillage, such as the use of disc ploughs rather than tyned implements, gives better lime incorporation (Scott and Coombes 2006). More aggressive tillage options such as deep spading and mouldboard ploughing have also been reported to reduce the impact of acidity on deep sands (Davies et al. 2015). The review of these approaches by Dang et al. (2017) notes that while effective at achieving the amelioration of subsoil acidity, there is a need for better diagnostic criteria to incorporate strategic tillage into what would be considered a NT system without compromising the economic and environmental imperatives behind NT farming.

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