9 Fertilizer Placement

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Simultaneous banding of seed and fertilizer by the openers is more important in no-tillage than for tilled soil and follows somewhat different principles.

It is especially important in no-tillage to sow fertilizers at the same time as the seed, but only if the fertilizer can be placed in a separate band from the seed. Much recent experience has documented the growth and yield advantages from fertilizers banded near the seed at the time of seeding. For autumn seeding this is often only a 'starter' amount of fertilizer, while for spring seeding it is usually the total seasonal requirements.

Crop responses to banded fertilizer at the time of seeding are nearly always larger in no-tillage than in tillage. There are several reasons for this.

- Tillage mineralizes organic matter to release nitrogen and this becomes readily available to the newly establishing plants. The downside is that, because no fertilizer is actually added to the system, the nitrogen is from 'mined', mineralized, SOM, which depletes this precious resource cumulatively. Because mineralization and nitrogen release are minimal under no-tillage, young no-tilled plants can appear nitrogen-deficient, particularly during early growth. Banding nitrogen fertilizer alongside the seed during no-tillage seeding cures the problem.

- Surface residues are often decomposing about the same time as seeding in no-tillage. The microorganisms responsible for residue decomposition temporarily utilize ('lock up') nitrogen during this process. Even though the nitrogen they demand may become available again later in the growth cycle as the microorganisms themselves die, it is temporarily made unavailable to young no-tilled plants.

- Soluble nutrients, nitrogen in particular, broadcast on to a no-tilled soil surface (as is common practice in tilled fields) are often preferentially carried by water flow down earthworm channels and other bio-channels (e.g. old root channels), which largely bypass young plant roots. In tilled soils, these bio-channels are destroyed and replaced by a smaller, more evenly dispersed pore system, which provides a more uniform infiltration of water and broadcast fertilizers.

- Under repeated no-tillage, surface-applied nutrients that readily attach to soil particles, such as phosphorus, accumulate in a narrow layer near the ground surface and may not be readily available to young plants.

Many of these factors often combine under no-tillage regimes to make nutrients less readily available to both seedlings and growing crops. Thus banding of fertilizers simultaneously at seeding becomes all the more important.

Numerous experiments and field observations have confirmed that the broadcasting of fertilizers during no-tillage often results in poor crop responses. Figure 9.1 illustrates a typical field response. A contractor (custom driller) had been sowing pasture species in New Zealand with winged openers into an otherwise fertile field while simultaneously banding 300 kg/ha of an N : P : K fertilizer mix alongside (but not touching) the seed. Near the end of the field the contractor ran out of fertilizer. The farmer asked him to carry on sowing seed alone while he (the farmer) broadcast the same rate of fertilizer on the remaining area, which he did. Inadvertently the farmer had set up a comparison of banded versus broadcast fertilizer. Figure 9.1 clearly shows the difference in plant response 8 weeks after drilling.

Nor are such responses restricted to grasses. In fact, responses to placed fertilizer under no-tillage were first identified with wheat in the USA in the 1980s (Hyde *et al.*, 1979). Almost every crop and soil have the potential to show a similar response to that illustrated in Fig. 9.1. Both narrow-leaved (monocotyledonous) and broadleaved (dicotyledonous) plants have regularly shown similar responses.

Figure 9.2 shows a marked response to banded fertilizer in France with maize. The four rows in the centre and left of centre in the photograph had broadcast fertilizer applied at the same rate as the placed fertilizer in all other rows. The differences are remarkable.

There are two important considerations when applying fertilizer by banded placement:

1. Possible toxicity of the fertilizer to the seeds and seedlings, often referred to as 'seed burn'.
2. Yield responses of the growing plants to the placed fertilizer.

We shall discuss these two aspects separately.

Toxicity

There are three options for applying fertilizer under no-tillage: (i) broadcasting on

Fig. 9.1.   Pasture established by no-tillage in New Zealand with broadcast fertilizer in the foreground and banded fertilizer in the background at 8 weeks' growth.

Fig. 9.2. The difference between broadcast fertilizer (left-of-centre four rows) and banded fertilizer (all other rows) in no-tilled maize (France).

the surface; (ii) mixing with the seed; or (iii) banding separately from the seed at the same time as the seed is sown.

Since broadcasting of fertilizer is a separate operation either before or after seeding and not a function of the no-tillage drill or planter, we shall not consider it further here.

Mixing of fertilizer with seed is a risky undertaking at any time because of potential toxic chemical damage to the seed and seedlings. In tilled soils, a measure of dilution of the fertilizer with loose soil will often reduce the risk of 'seed burn'. But in an untilled soil, particularly one that is damp, soil dilution by mixing becomes minimal.

In general, fertilizer–seed toxicity will be affected by the following:

- The formulation of the fertilizer. Most forms of nitrogenous and potassic fertilizers are likely to 'burn' seeds, as well as some forms of phosphatic fertilizers.

Secondary nutrients such as boron and sulphur can be particularly toxic.
- The form of the fertilizer. Dry granular fertilizers are more often placed directly with the seed than liquid fertilizers. While it is easier to direct the liquid placement away from the seed than the granular, either form will cause toxicity.
- The age of the fertilizer. 'Fresh' superphosphate may contain free sulphuric acid, although this dissipates over time in storage.
- The moisture content of the soil. Dry soils concentrate the fertilizer salts in the limited soil solution, which may damage or kill the seeds by the effects of reverse osmosis.

Mixing seed and fertilizer and sowing them together or alternatively allowing them to mix in the opener or the soil is therefore a very unsatisfactory way to provide nutrients for young no-tilled plants. At best, small amounts of starter fertilizer might be applied in this manner. Usual upper limits are considered to be at about 15–20 kg/ha of nitrogen. But a higher level of risk must be accepted compared with separate banding of seed and fertilizer.

Banded fertilizer

For separate banding of seed and fertilizer, the seed and fertilizer must be placed in different positions in the soil and remain in these positions after the opener has passed and the slot has been closed.

There are three realistic geometric options. The fertilizer can be placed directly below, to one side of or diagonally below and to one side of the seed. Placing fertilizer above the seed is not a logical option because this is very similar to broadcasting.

The ability of no-tillage drills and planters to simultaneously band seed and fertilizer without the two coming into contact with one another is widely recognized as one of their most essential functions. Indeed, an informal survey of no-tillage

experts in the USA in the 1980s revealed that separate banding of seed and fertilizer was unanimously regarded to be the single most important design improvement that should be made to no-tillage openers. Unfortunately, providing this function has proved to be an elusive capability for many machinery manufactures.

Some no-tillage drills and planters employ two separate openers, one for seed and another for fertilizer. Others combine the two openers together into one (often complicated) 'hybrid' opener, while still others use one dedicated fertilizer opener between each pair of seed openers. But there are also modern openers designed specifically for no-tillage that band seed and fertilizer in the same slot without compromising seeding accuracy, row spacing or residue handling for a wide range of forward speeds, soils and residue conditions.

Vertical banding versus horizontal banding

The absence of friable soil makes vertical separation of seed and fertilizer more difficult in no-tillage than in tilled soils, even by successive openers or duplicated components.

Some drills and most planters in loose or tilled soils use a leading opener to place fertilizer at a given depth and then follow that with a scraper that fills the slot with loose soil. This in turn is followed by the seeding opener which opens a new slot that is either shallower and/or to one side of the fertilizer slot. Such repeated manipulation of loose soil is generally not possible or desirable under no-tillage, so the choice is to either broadcast or inject the fertilizer as a separate operation before seeding or simultaneously seed and place (band) the fertilizer to one side of the seed by a separate opener.

Experience with tilled soils suggests that vertical separation of seed and fertilizer should be at least 50 mm (known as 'deep banding'). Experience with no-tillage, however, shows that extrapolation of results from tilled soils requires adjustment for the nature of the soils and the machine performance.

The disc version of winged openers provides a physical barrier between the two sides of a horizontal slot in the soil, thus allowing seed to be deposited on one side and fertilizer on the other to provide adequate horizontal separation or banding. As the disc withdraws from the soil it tends to draw the soil up a little, resulting in a final horizontal separation distance of 10–20 mm. Figure 9.3 shows the horizontal separation of seed and fertilizer in an inverted-T-shaped slot created by a winged opener.

It is also possible to separate the seed and fertilizer vertically with this opener by arranging a long and short blade on the same side of the disc. Figure 9.4 shows a prototype winged opener with long and short blades to provide vertical separation of seed and fertilizer.

Yet another option exists with this opener using a long and short blade on opposite sides of the disc, thus creating diagonal separation (i.e. both vertical and horizontal). Figure 9.5 shows an excavated slot created by a winged opener in which there is a distinct step down from the seed shelf to the fertilizer shelf (i.e. diagonal banding). Figure 9.6 is a diagrammatic representation of diagonal banding using two separate disc openers. Similar placement patterns have recently been achieved with modified hoe-style openers using configurations to introduce the seed and fertilizer at different depths of penetration.

Baker and Afzal (1986) compared the effects of vertical and horizontal separation distances of ammonium sulphate (21 : 0 : 0 : 24) fertilizer from canola (rape, *Brassica napus*) seed in an untilled silt-loam soil using a winged opener. Canola seed is known to be particularly sensitive to the presence of ammonium sulphate fertilizer. Figure 9.7 shows seed damage determined by counts of seedling emergence, and Table 9.1 shows the seedling growth.

Figure 9.7 shows that horizontal separation by as little as 10 mm was equivalent to vertical separation by twice that distance

Fig. 9.3. A cross-section of an inverted-T-shaped slot showing the horizontal banding of seed (left) and fertilizer (right) (from Baker and Afzal, 1986).

Fig. 9.4. A prototype winged opener with long and short blades for vertical separation of seed and fertilizer (from Baker and Afzal, 1986).
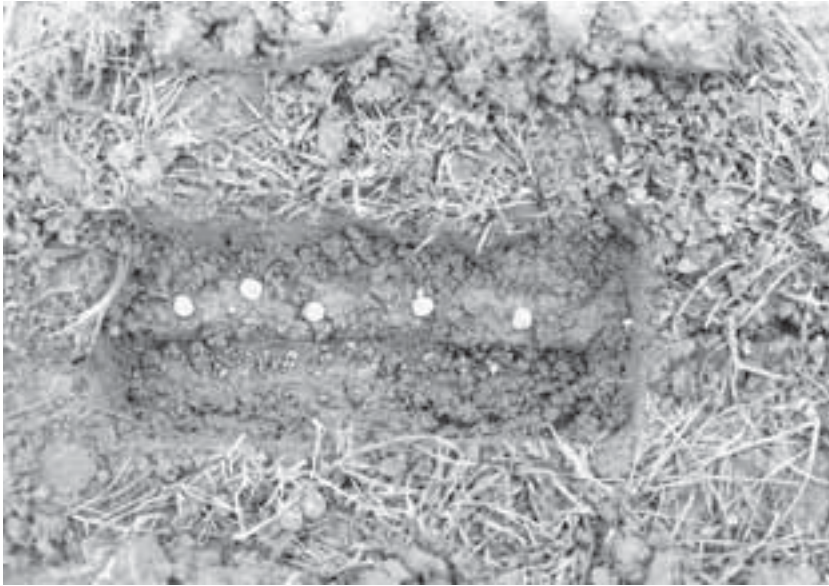
Fig. 9.5. Diagonal separation of seed and fertilizer in the soil (fertilizer below the seed towards bottom of photo) using a winged no-tillage opener with an elongated blade on one side.
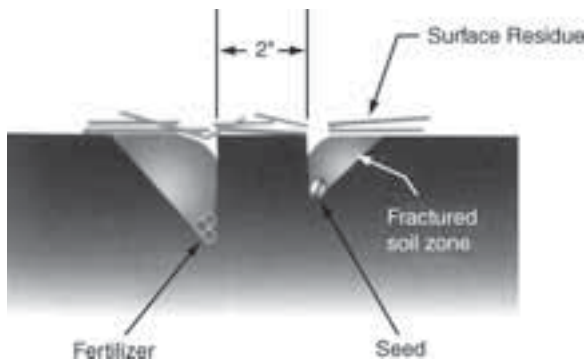

Fig. 9.6. A diagrammatic representation of diagonal fertilizer banding with two angled disc openers.

(20 mm) for reduced germination and emergence.

Table 9.1 shows that not only was there less seed damage from 20 mm horizontal separation, there was also a significant growth advantage for the 20 mm horizontal separation option compared with mixing of the seed and fertilizer together or separating the two by 10 mm either horizontally or vertically. Neither the horizontal nor the vertical separation by 20 mm was significantly different from where no fertilizer had been applied, which confirmed that no seed damage had occurred.

Afzal (1981) also compared the effectiveness of horizontal separation by a winged opener in tilled and untilled soils, to gauge the extent to which results from tilled soils could be safely extrapolated to untilled soils. Table 9.2 shows the results. At all three sampling dates (10, 15 and 20 days after sowing), the no-tilled soil contained more plants than the tilled soil, indicating that some seeds in the tilled plots had either been killed by the fertilizer, or had failed to germinate for other reasons.

An explanation for the effects in Table 9.2 seems to lie in the fact that, with
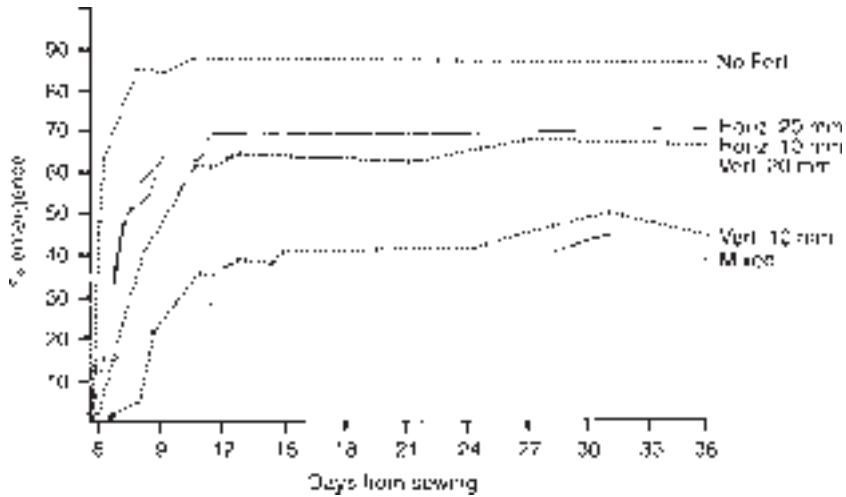
Fig. 9.7. Effects of the position of fertilizer placement, relative to the seed, on seedling emergence of no-tilled canola (from Baker and Afzal, 1986).

Table 9.1. Effects of method of fertilizer placement on seedling performance of no-tilled canola.

	Number of true leaves	Plant height (mm)	Plant weight (g)
No fertilizer	4.1 ab	63 ab	46 ab
Seed and fert. mixed	3.3 b	36 b	22 b
Horizontal separation by			
10 mm	3.3 b	34 b	19 b
20 mm	4.3 a	71 a	80 a
Vertical separation by			
10 mm	3.3 b	38 b	25 b
20 mm	4.2 ab	60 ab	54 ab

Unlike letters in a column denote significant differences ($P < 0.05$).

Table 9.2. Effects of tillage and no-tillage on horizontal separation of canola seed and fertilizer in the slot.

	Days after sowing		
Establishment method	10	15	20
No-tillage (plants/square metre)	25.1 a	50.7 a	55.2 a
Conventional tillage (plants/ square metre)	19.4 b	41.6 b	44.8 b
Increase of no-tillage over conventional tillage	29%	22%	23%

Unlike letters in a column denote significant differences ($P < 0.05$).

this particular opener design, the central disc cuts a thin vertical slot in the soil 50–75 mm deeper than the horizontal shelves on which the seed and fertilizer are placed. In an untilled soil, the integrity of this disc cut remains more distinct than in a tilled soil, where the friable nature of the soil allows soil to collapse into the disc-cut zone as the disc withdraws from the soil.

It is thought that this disc cut, in an untilled soil, effectively interrupts solute movement from the fertilizer, which might otherwise reach and damage the seed or seedling roots. It is also possible that the high humidity in the inverted-T slot in an untilled soil helps prevent reverse osmosis, which is one of the mechanisms by which seeds are damaged by high salt concentrations in dry tilled soils (see Chapters 5 and 6). Because the general humidity of a tilled soil is lower than that of an untilled soil, due to the artificially high porosity and the absence of surface residues, even the inverted-T-shaped slot is unable to maintain a high humidity zone around the seed when operating in a tilled soil.

Another important point in the tilled/ no-tilled soil comparison is that the effects of separating the seed from the fertilizer are most apparent as the soil became drier. Collis-George and Lloyd (1979) had earlier noted that, in tilled soils, dryness tended to result in more fertilizer damage to seeds than where the soil was moist. Baker and Afzal (1986) examined whether or not this trend extended to untilled soils, using a winged opener.

Their results, shown in Table 9.3, indicate that plants suffered with both vertical separation and mixing together when the soil became dry, but these were equivalent to the other treatments in the moist soil.

The only treatment that almost ignored the moisture status of the soil was the horizontal separation within an inverted-T-shaped slot. This may have been partly the result of the high humidity this slot maintains and partly the result of the disc cut. The result is that the optimum horizontal separation distance within an inverted-T-shaped slot was less than the distance commonly recommended for vertical separation by other openers and for tilled soils.

Field experience has shown that the particular disc version of the winged opener used in these experiments is equally well suited to separating seed from liquid or gaseous fertilizers as it is to separating it from dry powdered and granulated forms of fertilizer.

In two separate experiments (C.J. Baker, unpublished data), the author found that the upper limit of dry urea (46 : 0 : 0 : 0) application with this opener, sowing maize in 750 mm spaced rows, was about 200 kg/ha of urea (92 kg/ha/N), equivalent to 15 g urea per metre of sown row, before seed damage was detectable. Field applications of 780 kg/ha of 30% potassic superphosphate (0 : 6 : 15 : 8) with peas in 150 mm rows (117 kg/ha/K) have also been achieved with this no-tillage opener with no measurable toxicity damage to seed germination when compared with no fertilizer.

K.E. Saxton (unpublished data) also tested the ability of the same winged opener to effectively separate wheat seed from toxicity damage arising from the use of a range of rates and two forms of nitrogenous fertilizers sown in 250 mm rows in the USA. He found no detrimental effect on the seed from applying either dry urea (46 : 0 : 0 : 0) or liquid 'aqua' (ammonium hydroxide

Table 9.3. Effects of position of fertilizer placement and soil moisture status on germination of no-tilled canola (germination %).

Horizontal separation by 20 mm		Vertical separation by 20 mm		Mixed together	
Dry soil	Damp soil	Dry soil	Damp soil	Dry soil	Damp soil
89	81	64	90	58	85

solution in water: 40 : 0 : 0 : 0) at concentrations of up to 140 kg/ha of nitrogen.

Operators in New Zealand commonly apply up to 400 kg/ha of high-analysis fertilizer mixes (which sometimes include boron and/or elemental sulphur) in the field with this opener with no measurable effect from 'seed burn' but with substantial positive growth and yield responses (Baker *et al.*, 2001).

Although horizontal separation appears to be somewhat more beneficial than vertical separation in most instances, a range of vertical separation systems have been designed. Hyde *et al.* (1979, 1987) reported attempts to separate seed and fertilizer vertically with a single opener by modifying a hoe opener so that it deflected soil back over the fertilizer before the seed exited the opener. The deflecting action, however, was dependent on forward speed and soil moisture conditions, especially plasticity. In favourable conditions, its crop yield performance was comparable to horizontal separation by winged openers.

One solution that allows vertical separation of seed and fertilizer in no-tillage to be largely independent of soil moisture conditions is the use of slanted double disc openers. The leading (fertilizer) opener cuts a slanted slot and places the fertilizer at its target depth. The seed opener, which follows, is positioned either vertically or at the opposite slant and shallower, thereby placing the seed in the undisturbed soil above the fertilizer. This option appears to be effective but the downforces required to make two double disc openers penetrate the soil for each row limits it to reasonably soft soils. Figure 4.8 shows two slanted double disc openers so configured.

Another, more laborious but effective, method is to pre-drill the fertilizer as a separate operation to drilling of the seed at a shallower depth, and this can be achieved with virtually any design of opener.

Retention of gaseous fertilizers

Inverted-T-shaped slots are known to retain water vapour in the slot (see Chapters 5 and 6). It is possible that this slot also retains volatile gases from nitrogenous fertilizers (especially ammonia) within the slot in a similar manner to water vapour. It is well known that soil injection of both organic (animal waste) and inorganic forms of nitrogen as gas or liquid leads to problems with ammonia gas volatilizing and escaping into the atmosphere. With disposal of animal waste using knife-type openers (U-shaped slots), this is often overcome by deep (0.5 m) injection. Inverted-T-shaped slots also offer the option of shallow injection of this material (Choudhary *et al.*, 1988b).

During the no-tillage drilling of seeds, simultaneous deep injection of inorganic nitrogen is impractical because of the limitations on depth of placement and available tractor power. The result of simultaneous shallow placement has usually been a noticeable smell of ammonia at drilling as it escapes from the sown slots.

With the winged opener, less ammonia smell is evident, indicating entrapment of the valuable fertilizer within the slots. This was first noticed in the field in the USA by farmers using a winged opener. They were intrigued by the fact that the farm dogs ran along behind the drill. This apparently did not occur with other drills because the escape of ammonia from the soil immediately behind the drill made an unpleasant environment for the dogs.

Crop Yield

As previously discussed, broadcast fertilizers on no-tilled fields are often infiltrated by water moving into preferential flow paths and bypassing the early plant roots, or those constituents that bind to the soil remain on the soil surface. In contrast, tilled soils have more diverse flow paths through their microporosity and blend those binding constituents within the tilled zone. As a result, while broadcasting of fertilizers has been practised successfully for years with crops grown in tilled seedbeds, under no-tillage the same crop responses to broadcast

fertilizer cannot be relied upon. Hyde *et al.* (1979) highlighted the problem in the Pacific Northwest of the USA, and a long-term experiment conducted by the authors over a 6-year period in New Zealand also illustrated the problem (Baker and Afzal, 1981).

In the New Zealand experiment, the scientists compared the continuous growing of summer maize, sown with a winged opener, on the one hand, into untilled soil and, on the other hand, into a conventionally tilled seedbed. It also coincided with some important technological developments of winged openers, which had an impact on the experiment.

Figure 9.8 illustrates the first 5 years of the maize yield results. To eliminate seasonal variations in yield, conventional tillage was given the arbitrary value of 100% each year and no-tillage was compared with it on a percentage basis. The seed was sown into inverted-T-shaped slots on all occasions with Class IV cover.

In year 1 no fertilizer was applied, either at planting or after the crop became established. The crop relied solely on the already high fertility of the soil, which had been under intensive pasture for 20 years. The maize yield under no-tillage was not significantly different from that under tillage.

In year 2 again no fertilizer was used. By this time, however, the advantages of mineralization, which is enhanced by the tillage process, had become evident. Only slow mineralization rates occur under no-tillage because of the absence of soil disturbance. As a result, the no-tillage maize yield was only 35% of that under tillage.

In year 3 a comprehensive NPK starter fertilizer (10 : 18 : 8 : 0) was surface-applied at 300 kg/ha by broadcasting on to all plots. At that time, simultaneous banding of seed and fertilizer by winged openers was not possible without risk of seed damage. The seed was sown with the simple original winged opener and mixing of seed and fertilizer together was not considered a viable option.

The disc version of the winged opener, which allows simultaneous banding, had not by then been invented. None the less, the surface-applied fertilizer lifted the yield under no-tillage to 60% of that under tillage.

In year 4 it was decided to apply a greater amount of broadcast NPK fertilizer than in year 3 (400 kg/ha) to both treatments to try to raise the no-tillage yield still further. Doing so had the opposite effect, however, and the no-tillage yield of maize fell to an all-time low of only 30% of the yield under tillage.
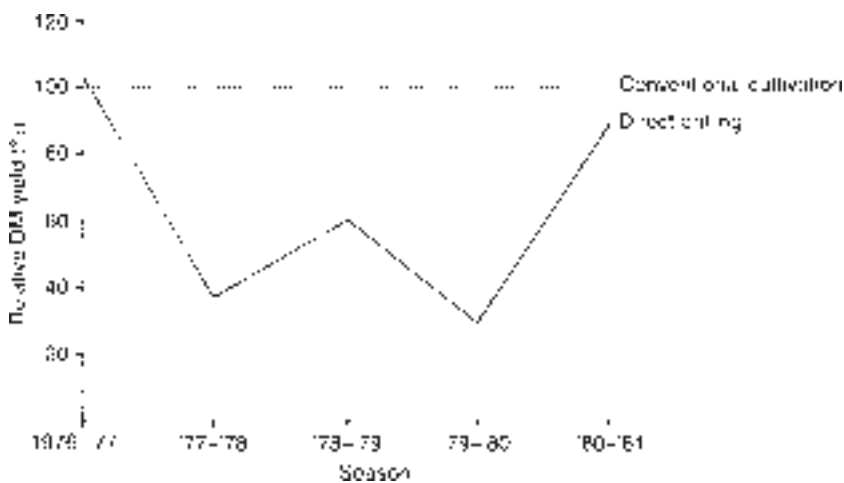

Fig. 9.8.   Relative dry matter (DM) yield of no-tillage compared with tillage as affected by fertilizer application on no-tillage maize yields over a 5-year period (from Baker and Afzal, 1981).

Table 9.4. Effects of fertilizer placement on yield of maize (DM yield kg/ha) in the sixth year of a 6-year experiment.

	Fertilizer placed	Fertilizer broadcast	No fertilizer applied
No-tillage	10,914	4,523	1,199
Tillage	10,163	5,877	2,999

Year 5 coincided with the development of the disc version of the winged opener concept, which, amongst other things, allowed seed and fertilizer to be banded simultaneously with 20 mm horizontal separation in inverted-T-shaped slots.

The effect on the yield of no-tilled maize was immediate and spectacular. It raised the yield to again be not significantly different from the tilled yield.

In year 6 the experiment was altered to directly compare banded and broadcast fertilizer application under tillage and no-tillage and to check if the year 5 results were repeatable. Indeed, they were.

Table 9.4 presents the results for year 6. Clearly, the no-tilled soil benefited more from banding of fertilizer than the tilled soil. The final yields of the two methods with banded fertilizer were not significantly different.

Perhaps just as important were the yields of maize obtained from plots that had not received any fertilizer in the entire 6-year period. Although the unfertilized yields from both the tilled and untilled soils were poor in comparison with the fertilized plots, the enhanced mineralization that had occurred in the tilled soil each year produced plants almost three times as big as those under no-tillage. This mineralization, however, represents a 'burning out' of the SOM, with associated loss of soil quality, and is the reason why tillage is no substitute for no-tillage where fertilizers are applied correctly, in terms of both sustainability and crop yield.

An on-farm comparison was made in 2004 by a New Zealand farmer. He chose 11 fields and sowed a forage brassica crop into a randomly chosen selection of the fields over a 17-day period with two different no-tillage drills (M. Hamilton-Manns, 2004, unpublished data).

One drill was equipped with vertical triple disc openers. The triple disc openers had wavy-edged leading discs, which reduce the compacting effects normally associated with such openers. But they were not capable of banding fertilizer, so diammonium phosphate (DAP) fertilizer was broadcast at 300 kg/ha. The other drill was equipped with the disc version of winged openers, which banded the same amount of fertilizer 20 mm to one side of the seed at the time of seeding. Soil moisture conditions were not limiting and seedling germination was adequate with both drills.

The fields drilled with triple disc openers and broadcast fertilizer yielded, on average, 7069 kg dry matter (DM)/ha. The fields drilled with winged openers and banded fertilizer yielded, on average, 10,672 kg DM/ha.

While it cannot be said with certainty that the entire 51% average difference was the result of banded fertilizer alone (there may also have been opener differences), there is little doubt that most of the difference was due to fertilizer banding, and the heavier crops were worth, on average, US$468/ha more than the smaller crops.

Banding options

We have already seen that the need to band fertilizer beneath the soil without 'burning' the seed is greater under no-tillage than with tilled soils. Mixing of seed and fertilizer risks 'seed burn'.

Recourse to 'skip-row' seeding, in which every third opener sows only fertilizer in order to fertilize the two seeded rows either side of it (Little, 1987), has not been a feasible alternative either, although certainly better than broadcasting. Choudhary *et al.* (1988a) showed only mixed success with the 'skip-row' option, even when sown in narrow (150 mm) rows. Table 9.5 shows their results.

The 'skip-row' treatment produced the lowest fertilized barley yield (2072 kg DM/ha) but was equal to all other treatments when

Table 9.5.   Effects of fertilizer application method on yield of two no-tilled crops.

	Barley grain DM yield (kg/ha)	Fodder radish[a] (whole plant) DM yield (kg/ha)
No fertilizer	1889 b	3240 ab
Horizontal separation by 20 mm	2580 a	3763 a
Fertilizer and seed mixed	2538 a	2809 b
Broadcast fertilizer	2432 a	3543 a
Skip-row separation	2072 b	3526 a

Unlike letters in a column denote significant differences ($P < 0.05$).
[a]*Brassica napus* L.

fodder radish was sown. In the latter case mixing of the seed with the fertilizer gave the poorest yield (2809 kg DM/ha). All other treatments were not significantly different.

Two other important points are evident in Table 9.5. The results are the mean of two soils, one of which was a fine sand, in which few, if any, preferential flow channels were present because of the exceedingly friable nature of the soil. Thus, even in its untilled state, surface-applied nitrogen fertilizer would have flowed more or less evenly through such a profile as if it had been tilled and showed less difference in favour of banding than where the soil was more structured.

The other point is that one of the fertilizer/seed combinations used in this experiment (DAP and barley) was not particularly damaging to barley seed. Consequently, mixing of barley seed and fertilizer together showed no disadvantage. On the other hand, mixing of the DAP fertilizer with the more susceptible brassica crop showed results similar to those of Afzal (1981) and Baker and Afzal (1986), who had used an even less compatible mix (canola and ammonium sulphate).

There is no evidence from any experiments conducted by the authors that greater amounts of fertilizer are needed under no-tillage. That which is applied just needs to be used more effectively by banding it alongside the seed. In fact, data from seven different experiments involving wheat (*Triticum aestivum*), drilled with double disc openers in a skip-row configuration (where every third row was sown with fertilizer only, at 100 mm depth), compared with horizontal separation by 20 mm with a drill equipped with winged openers, showed that fertilizer rates could actually be reduced with the latter openers (Saxton and Baker, 1990). Figure 9.9 shows the results.

On average, the winged openers showed a 13% increase in wheat yield compared with the skip-row drilling with double disc openers. Until then, that particular skip-row configuration had out-yielded all other methods with which it had been compared in the USA.

Not only did the plants sown with horizontal banding out-yield those sown with the skip-row method, but further measurements showed that the plants had been more vigorous from the outset. The improved vigour is likely to have been partly because of the positioning of the fertilizer and partly because of the high-humidity environment in which the seedlings developed beneath the ground in the horizontal (inverted-T-shaped) slots.

Table 9.6 shows analyses of the carbon and nitrogen contents of seedlings grown by these two fertilizer banding methods. Figure 3.1 had earlier shown the contrasting development of the seedlings in which the heavier and more fibrous nature of the root systems (more root hairs) from the horizontal banding and inverted-T-shaped slot was clear. Apparently, both the carbon and nitrogen levels were higher in the plants sown by the winged openers with horizontal banding of fertilizer compared with
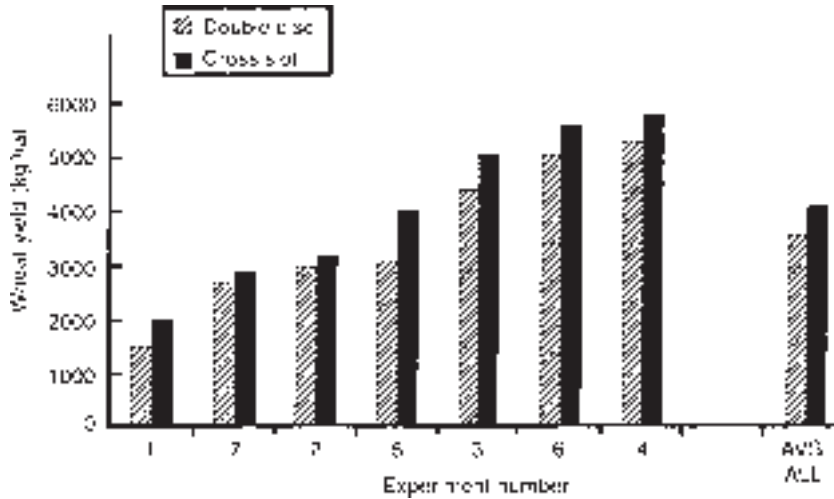
Fig. 9.9. Wheat yield comparisons from no-tillage using two different fertilizer banding options (from Saxton and Baker, 1990).

Table 9.6. Carbon and nitrogen contents of no-tilled wheat seedlings sown with two different openers.

Opener type	Field no.	Carbon (% DM)	Nitrogen (% DM)
Winged opener (inverted-T,	1	38.00	4.16
horizontal banding)	2	38.60	4.70
	Mean	38.30	4.43
Double disc opener (V-shaped	1	36.50	4.00
slot, skip-row application)	2	34.69	3.83
	Mean	35.60	3.92

those sown with the double disc opener and 'skip-row' fertilizer application.

Even where vertical banding of seed and fertilizer has been accomplished using a single opener, no clear advantage has yet been shown for this option.

Further, the technical difficulty of achieving satisfactory vertical banding in a wide range of conditions with a single opener makes implementation on a field scale unreliable. The problem is that, to achieve vertical separation, the fertilizer is usually drilled first at a greater depth than the target depth for the seed. In tilled soils it is relatively easy to induce soil to fall on to the fertilizer before the seed is sown. But in untilled soils this is much more difficult to achieve, particularly when the soil is damp

and 'plastic'. For this reason, horizontal separation has become a more 'fail-safe' alternative since effective separation is not affected by soil looseness, surface cover or operating speed.

A comparison of horizontal banding (winged opener) and vertical banding (prototype hoe opener with a deflector to scoop soil on to the fertilizer prior to deposit of the seed) was made over several years by the authors. The results are shown in Fig. 9.10.

The figure shows that the winged opener with horizontal banding produced a greater yield in the first year of spring wheat (SW 87) and perhaps in the final year of winter wheat (WW 89), but there were no differences in yield in the other three seasons.
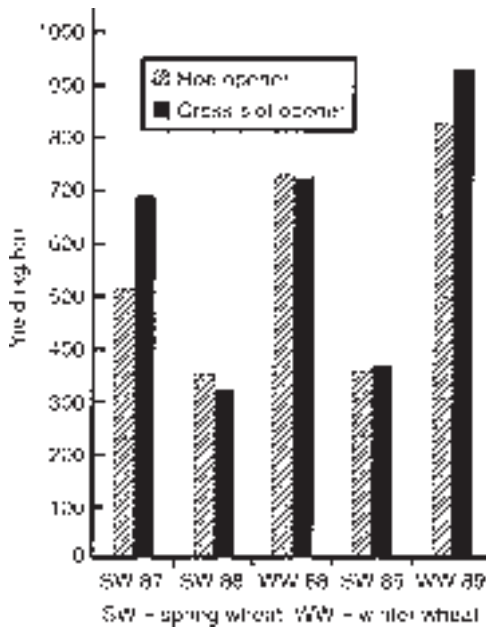
Fig. 9.10. No-tillage wheat yields from vertical banding of fertilizer with a hoe opener and horizontal banding with a winged opener.

A long-term double cropping experiment in Australia compared yields of soybean crops sown under no-tillage and tillage for 14 years using winged openers (Grabski *et al.*, 1995). For the first 2 years (1981/82 and 1982/83) the conventional tillage yields were superior, presumably because of the previous history of tillage. But for the following 12 years the no-tillage treatment was never bettered and averaged 30% higher yield of soybean than conventional tillage.

How close should banded fertilizer be to the seed?

Ferrie attempted to answer this question in Illinois, USA, in 2000. His results were reported by Fick (2000). Ferrie compared several diagonal distances of separation of starter fertilizer from maize seed sown with double disc openers, ranging from 90 mm deeper than and 50 mm to one side of the seed to 15 mm deeper than and 20 mm to one side of the seed. He concluded that, in

terms of crop responses, 'the closer the starter was to the seed the better', provided that the fertilizer was not actually mixed with the seed and the action of banding the fertilizer did not disturb the accurate placement of the seed. The treatment with the greatest separation distance actually produced no measurable yield response to the starter fertilizer at all.

Ferrie also pointed out that slot wall compaction could have an effect on the ability of juvenile roots to access the fertilizer, especially in clay soils. He felt that, in such soils, even a narrow knife opener could cause problems.

Dianxion Cai (1992, unpublished data) tested two options for placing dry and liquid nitrogenous fertilizers at increasing rates of applied N, using winged openers and drilling wheat seeds 25 mm deep. The two options were: (i) standard horizontal banding 20 mm to one side of the seed (i.e. the fertilizer was also drilled 25 mm deep); and (ii) diagonal banding in which the fertilizer was banded 20 mm to one side of and 13 mm deeper than the seed (i.e. the fertilizer was drilled 38 mm deep). Figure 9.11 shows the effect on plant stand and Fig. 9.12 shows the resultant crop yields.

From Figs 9.11 and 9.12, it is apparent that the effects on seedling emergence (stand) were similar to the effects on yield, demonstrating the importance of initial plant population for final yield. In both experiments the horizontal banding (25 mm) produced more plants and heavier crops than the diagonal banding (38 mm) with both urea and aqua. These differences became most pronounced at an application rate of about 120 kg N/ha. At higher application rates, while the differences remained largely unaltered, both the plant stands and crop yields began to decline, possibly because of fertilizer toxicity. The decline of both plant stand and crop yield at the high application rates (160 kg N/ha) used in these experiments was considered to be of no consequence because these application rates were well in excess of normal application rates of nitrogen in any form (160 kg N/ha is equivalent to 350 kg urea or 400 kg aqua/ha).
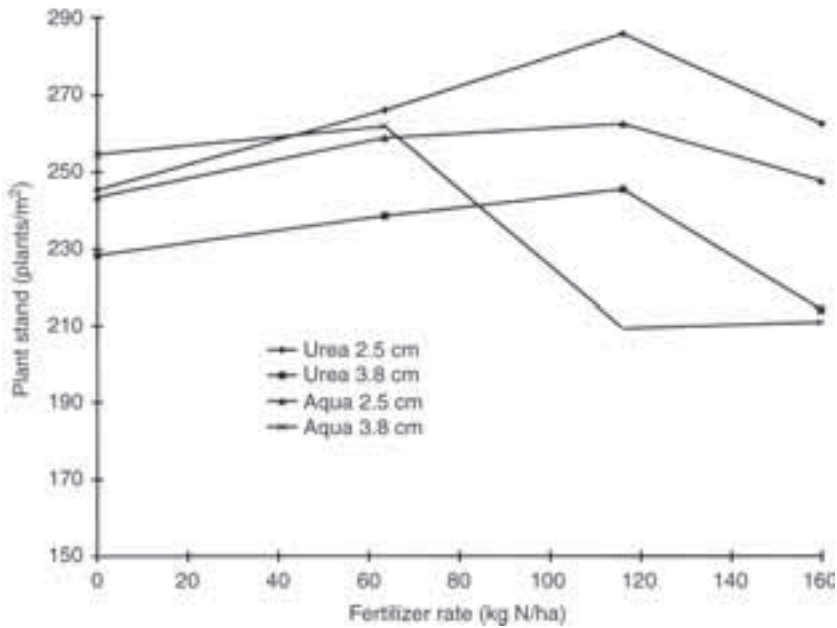
Fig. 9.11. Wheat stand responses to horizontal and diagonal banding of two forms of nitrogenous fertilizer separated from inverted-T-shaped slots.
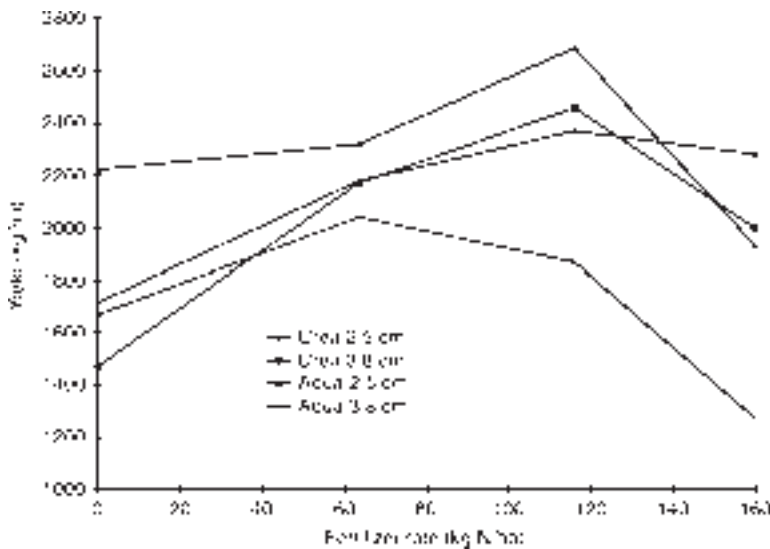

Fig. 9.12. Wheat yield responses to horizontal and diagonal banding of two forms of nitrogenous fertilizer separated from inverted-T-shaped slots.

Conclusion

One of the more noteworthy advances in no-tillage technology has been to develop a machine with the capability to separate fertilizer from the seed in horizontal bands and effectively entrap volatile forms of nitrogen in the slot. At the same time, these

openers maintain the effectiveness of the separation function without being materially altered by forward speed, soil type, soil moisture content or the presence or absence of surface residues. From a field perspective, farmers find it easier to identify with this single factor, among all others, when assessing the performance of no-tillage versus tillage, and even when assessing the merits of competing no-tillage systems and machines.

It is interesting to speculate how many experiments and field observations showing poor yields for no-tillage crops have been the result of opener inability to adequately band the fertilizers.

Summary of Fertilizer Placement

1. Less nitrogen is available by organic matter mineralization under no-tillage than under tillage, making nitrogen application particularly important at drilling under no-tillage.

2. Some temporary nitrogen 'lock-up' may also occur under no-tillage as soil bacteria decompose organic residues.

3. Broadcast fertilizers are less effective in no-tillage than in tillage because soluble nutrients often bypass roots by infiltration occurring in preferential channels created by earthworms and decayed roots.

4. 'Deep-banding' of fertilizers at drilling is less effective or necessary in untilled soils than in tilled soils.

5. Fertilizer close to the seed is better than at a distance, so long as the two are not mixed.

6. Horizontal separation between seeds and fertilizer at distances as small as 20 mm have been more effective in no-tillage than vertical separation by any distance.

7. Relatively few no-tillage openers provide effective seed and fertilizer banding with a proper distance or direction.

8. Of those no-tillage openers that do provide effective separation, horizontal separation is preferable to vertical separation.

9. Where no-tillage openers are incapable of separating seed from fertilizer, other options include:

- Drilling every third row with only fertilizer ('skip-row' planting).
- Mixing seed and fertilizer together in the slot.
- Doubling the number of openers on a drill so as to provide separate fertilizer-only openers in addition to seed-only openers.
- Surface broadcasting of the fertilizer.
- Drilling seeds and fertilizer as two separate field operations at different depths.

10. Most double disc openers are incapable of banding fertilizer separately from the seed with a single opener.

11. Some angled disc openers have provided a fertilizer-banding capability.

12. One version of winged openers with a single disc effectively separates seed and fertilizer horizontally or diagonally.

13. Crop yields with winged openers have been good when using horizontal separation of seed and fertilizer, due to improved seed/seedling micro-environment and fertilizer response.

14. Only recently designed hoe openers separate seed and fertilizer in any direction.

15. Two disc openers (double or angled) slanted in opposite directions may be capable of providing vertical separation of seed and fertilizer.

10 Residue Handling

C. John Baker, Fatima Ribeiro and Keith E. Saxton

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Successful no-tillage openers not only handle surface residues without blockage but also micro-manage these residues so that they benefit the germination and seedling emergence processes.

The second most valuable resource in no-tillage is the residue left on the ground surface after harvest of the previous crop. The only resource more valuable than residue is the soil itself – in its untilled state.

Unfortunately, the history of tillage is littered with descriptions of methods for disposing of residues so that they do not interfere with the operation of machinery. In tillage, surface residues have been regarded as a major nuisance and therefore have often been referred to as 'trash'. Those who take no-tillage seriously have dispensed with the term 'trash' in favour of the term residue. Trash is something unwanted. Residue is something left over, but in this case wanted and useful.

Before considering how well various openers and machines handle or manipulate surface residues, it is necessary to identify the various forms that residue can take (Baker *et al.*, 1979a). Then it will be appropriate to look at how the residues should be macro-managed on a field scale (Saxton, 1988; Saxton *et al.*, 1988a, b; Veseth *et al.*, 1993) and finally at the options for micro-managing residues in, around and over the slot zone (Baker and Choudhary, 1988; Baker, 1995).

The Forms that Residues can Take

Short root-anchored standing vegetation

Pasture (either growing or recently killed by herbicide)

Short root-anchored pasture is commonly encountered by no-tillage drills designed for pasture renovation or renewal in intensive animal grazing agricultural systems and for crop establishment in integrated crop/animal systems. In such systems, animal management can usually be sufficiently controlled to allow deliberate intensive grazing of selected fields prior to drilling, thus reducing the length of grass and therefore the residue-handling demands on such machines. This allows relatively inexpensive drills to be used for such conditions.

Short standing pasture usually presents few residue-handling problems as the vigorous root anchorage and firm soil beneath the plants allows even a 'rigid' tine or shank, without a pre-disc, to burst reasonably cleanly through it. If the pasture has been recently killed, the time-interval between

spraying and drilling can have a profound effect on the handling properties of this residue. As decomposition starts soon after death of the plant, the material becomes progressively weaker and more likely to break away from its anchorage. At an advanced stage of decay, it may break away from the soil anchorage altogether and start to behave more like loose-lying residue than short anchored residue and therefore be more prone to causing blockage. Sometimes it pulls free in large pieces.

Pasture plants that have stoloniferous or rhizomatous growth habits (i.e. with horizontal and/or underground connecting stems), even though they might be grazed short by animals, present a different problem, since their creeping habit makes them likely to become entangled in non-disc-type openers. At least a pre-disc is essential for satisfactory handling of such residues with tine or chisel openers.

Short clean crop stubble after direct-heading with a combine harvester and baling of the straw

Clean crop stubble that has negligible loose straw lying on or amongst it offers only moderate residue-handling problems because the standing plants can usually be pushed aside by relatively unsophisticated no-tillage openers. In common with pasture plants, the key element is the anchorage offered by the root systems. The time interval between harvesting and drilling and the intervening weather will also influence the level of decay that has set in by the time drilling takes place. In the case of crop stubble, however, because harvesting normally takes place at a dry time of the year, the onset of decomposition may be slower than with pasture plants.

Standing stubble has important additional functions in no-tillage systems that experience snow and freezing winters or in which the crop is swathed prior to harvesting.

Where swathing takes place, long stubble, especially in narrow drill rows, will hold the cut swathe off the ground, which aids drying and makes harvesting easier as it aids the pickup mechanisms on combine harvesters compared with when the swathe lies close to the ground.

Where snow is expected, stubble holds the snow from blowing away. Snow, in turn, provides effective thermal insulation of the soil beneath and may be responsible for maintaining soil temperatures some 10° to 15°C higher than in soils that have no snow cover and are allowed instead to freeze (Flerchinger and Saxton, 1989a, b). In this respect, long stubble is better than short stubble (see below).

In either case, at the end of a cold winter, when such soils are drilled, stubble that has endured the cold months is usually brittle, though often it has not actually decayed much. It may break off at ground level, but due to its shortness will seldom present major residue-handling problems for no-tillage drills. On the other hand, no-tillage systems increasingly require that the full amount of residue disgorged from combine harvesters (including the threshed straw as well as the standing stubble) remains on the ground over the winter in such climates. This combination presents quite another problem as far as residue handling is concerned, which will be discussed later.

Standing stubble also has an important function in dry climates, by reducing wind velocity at the soil surface, which significantly reduces drying and soil movement. In windy conditions, standing stubble may protect young seedlings sown between the stubble rows from being blasted by wind-blown sand and other soil particles. In Australia, for example, planting between the rows of tall stubble offers wind protection to the new plants, while, in England, long stubble has another value, that of camouflaging wildlife, such as pheasants. Since many farmers in that country rate the commercial shooting of pheasants as an important source of farm income, no-tillage offers an opportunity through stubble retention for an extended game-shooting period that was not possible with tillage.

In tropical climates, tall standing stubble can result in etiolation of the new crop. But short standing residues lead to more vegetative material entering the combine

harvester, resulting in a higher power requirement, more fuel consumption or decreased field capacity.

For all of these reasons, there has been recent interest in the use of stripper headers in association with no-tillage because such harvesting devices maximize the length of the standing stubble.

Tall root-anchored standing vegetation

Tall grass, sprayed-off cover crops and tall clean stubble (300 mm and longer), together with bushy weeds, present somewhat greater problems than short vegetation, even with root anchorage, but less than lying straw. There is a critical height above which each of these plants will collapse in the pathway of no-tillage openers (or simply over a period of time), at which point the residue behaves more like lying straw than standing stubble. Taller material may also trap a more humid microenvironment within, with the result that decay of the bases of the straw may be initiated more quickly than with short stubble and breakage is more likely.

Figure 10.1 shows the effect of drilling with the disc version of a winged opener through a partially standing matted legume crop 0.75 m high that had been sprayed. It is not common to drill into such very tall residue; not only because of the spatial constraints, but because it is difficult for seedlings to obtain sufficient light during early development to emerge satisfactorily.

Lying straw or stover

Detached stalk material, of any length, presents the most difficult residue-handling problems for no-tillage drills but is also a very valuable biological resource unique to no-tillage. Where such residues lie on firm ground (e.g. after a no-tilled crop has been harvested, or even when hay has been fed directly on to an established pasture and not fully consumed by animals), there will be less tendency to block no-tillage openers than where the residues lie on softer ground. Similarly, if the residues remain dry and brittle, they will be easier to handle and cut than where they have
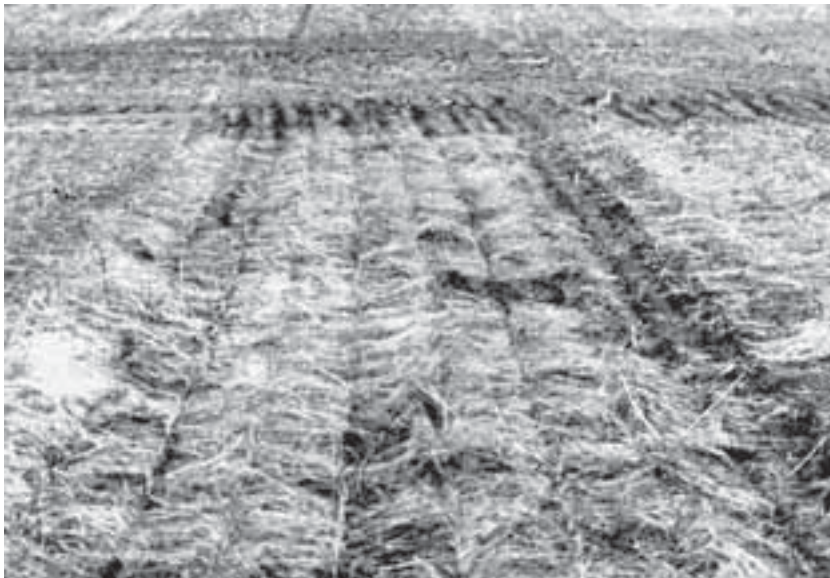

Fig. 10.1.   The effects of drilling with the disc version of winged openers into heavy partially standing residue.

become damp. Often dampness is a function of both the amount of straw (yield of the crop) and the weather. Heavy residues may generate their own dampness and increase in temperature from bacterial action.

The immediate history of the field may also be important. If the previous annual crop was established into tilled soil, for example, the soil background against which disc components of no-tillage openers will need to push to shear the straw, will be softer than if the previous seedbed had been untilled. This 'anvil effect', of course, will be influenced by soil type, which has an important influence on the effectiveness of some residue-handling mechanisms and presents farmers with some difficult choices when converting from tillage to no-tillage.

For example, a no-tillage machine that is good at drilling into residues previously established in a tilled seedbed (during the changeover period) may not be the best machine for drilling into residues previously grown in an untilled seedbed. Further, some farmers believe (usually erroneously) that they will still need to occasionally till their soil even under a predominantly no-tillage regime. There may be little logical basis for this belief, but it will none the less influence the farmer's choice of machine, perhaps to the detriment of the true no-tillage phase. The problem seldom exists when drilling into pasture because it is unusual for pasture to have been established for less than 12 months, during which time even a previously tilled soil will have consolidated again.

Fortunately, some no-tillage openers are equally well suited to soft and firm (or even hard) soils. The function of most tine- or shank-type, power till and winged openers is relatively unaffected by soil softness or firmness (except for downforce or power requirements), but those that tend to hairpin residue into the slot (double disc, angled flat disc and angled dished discs) have their hairpinning tendencies accentuated by softer soils. On firmer soils, they are more likely to shear the straw (which is desirable) than to push it bent over into the slot (which is undesirable). In firm soils, however, some openers are also more likely to compact the soil in the slot zone.

Lying residues have no anchorage to the ground and are therefore very easily gathered up to become entangled in 'rigid' machine components. Firmer ground provides greater friction (traction) for discs that may operate in conjunction with rigid components, ensuring that they keep revolving when they encounter lying residues. Some discs are especially shaped to further assist traction. Wavy-edged discs and notched or scalloped discs are cases in point. Even so, if the height of the lying straw is above the axle height of an approaching disc, it is likely to stall the disc, causing sledging and blockage. This is accentuated by dampness under the straw, especially if such dampness results in partial decay close to the ground. The decaying straw can become quite slippery on the ground and will often slide ahead of a disc, rather than allow the disc to grip and ride over or cut through it. Straw lying amongst standing stubble is less likely to slip than where it is lying on bare ground.

This sliding tendency is dependent to some extent on plant species. It is also soil-dependent and obviously weather-dependent. For example, pea straw becomes particularly slippery when partially decayed, especially on firm untilled soil, while most cereal straws do not. Sparse straw, such as soybean, canola, cotton or lupin, is less likely to remain damp long enough to promote decay close to the ground than crops that produce heavier vegetative growth. Further, the rigidity of the cut stubble of these somewhat woody crops helps prevent sliding of the lying residue.

Numerous methods have been devised to handle lying straw. Some of these are summarized below. The successful methods almost invariably involve openers where discs are used, either simply as the opener itself or where the discs assist the operation of other rigid components, such as winged blades, chisels or tines. In both cases, discs have become a common, though not exclusive, component of no-tillage openers designed for the handling of residues.

Management of Residues on a Field Scale

Macro-management refers to the way in which the residues are managed on a field scale. Their management is discussed separately for: (i) large field-scale no-tillage; and (ii) small-scale no-tillage. But in either case, surface biomass, whether from killed cover crops or harvested residues, plays a key role in no-tillage systems. For any no-tillage system (large or small), the handling of residues should:

1. Assist (or at least not hinder) the passage of no-tillage openers.
2. If possible, contribute to the biological functions of the openers.
3. Ensure that the residues decompose and add to soil carbon but at the same time remain on the soil surface long enough to protect the soil from erosion, keep the soil cool in tropical climates, retain soil moisture and suppress weeds;
4. Ensure that the residues do not compete with the sown crop.

These are demanding and sometimes competitive requirements, and compromises are often necessary. For example, tine (shank)- or knife-type openers do not handle residues well, so some farmers resort to burning or otherwise removing the residues to avoid blockages when drilling a field. But this compromises some of the other listed functions. For this and other reasons, the burning of residues is banned in several countries, although up to 45% of the biomass will be in the roots that remain even after burning.

In this respect, it is interesting to note that it makes little difference whether harvested residues are baled, burned or buried in terms of the amount of carbon they provide for the soil (see Chapter 2). Unless they are left to decompose on the soil surface, much of the carbon content of the above-ground plant residues will be lost from the system (oxidized and lost as carbon dioxide to the atmosphere). Therefore, to get the best out of a no-tillage system, the challenge for machinery designers is to provide no-tillage

openers that can cope with any amount and type of surface residue without blockage. But, more than that, as is explained in Chapter 5, an opportunity exists for openers to harness the surface residues as an important resource to aid germination and emergence of the new crop.

Large field-scale no-tillage

Weed control and management of cover-crop residues

In larger field-scale no-tillage, weeds and cover crops are normally killed by herbicides. Indeed, the very feasibility of the modern concept of no-tillage owes its existence to the development of 'non-residual' herbicides in the 1960s and 1970s. This contrasts with small-scale agriculture (see below), which is more dependent on mechanical means of plant competition control.

No attempt is made here to analyse the pros and cons of specialist spraying machinery or different herbicides. Suffice to say that the control of existing competition is the first step in any no-tillage programme and that, unless this is achieved effectively, all other steps will be compromised. Effective chemical weed control is a function of understanding the biology of the plants to be killed and the efficacy of the herbicide(s) to be used and the mechanical performance of sprayers. Some herbicides (e.g. glyphosate) work best on actively growing unstressed plants, while others (e.g. paraquat) are more effective when plants are stressed. And, of course, there are species differences (and sometimes varietal differences) in the resistance of plants to different herbicides.

Management of harvested residues

CHOPPED OR LONG? The first and most important opportunity to correctly manage residues on a field scale occurs at harvesting. Once crops have been threshed and the residues ejected from a combine harvester in discrete windrows, they are very difficult to spread out again.

Modern combine harvesters gather together the material from cut widths of 5–10 m and process it in such a way that, unless spreading devices are added to the combine harvester discharge, the residues are ejected out of the back in the form of a windrow of light fluffy straw 2–3 m wide. Underlying this windrow will be the chaff from the separation processes, which consists of very short pieces of straw, awns, leaf material, empty glumes, chaff, dust and weed seeds. The chaff row forms a dense surface covering, somewhat narrower than the straw windrow covering it.

In contrast to these somewhat concentrated zones of residue, good no-tillage requires that the residue be spread evenly over the entire field. There are no-tillage openers that can physically cope with the concentrated windrows and tailings, but this capability is somewhat academic since the effect of surface residues on germination, emergence and crop growth is so vital that an uneven crop will almost certainly result from grossly uneven chaff and straw distribution. Uneven spreading can also affect the efficacy of herbicide applications.

Most combine harvesters have optional straw spreaders. These are different from straw choppers in that spreaders do not chop the straw into shorter lengths. They spread the straw with beaters rather than with wind assistance (see Fig. 10.3). Most straw choppers spread as well as chop. Straw spreaders are not high power-demanding additions and are easily fitted and operated. They are essential standard equipment on all combine harvesters for no-tillage systems, as indeed they already are on some makes and models.

Whether or not a chopper is also needed will depend on the residue-handling capabilities of the no-tillage drill or planter to follow. Straw choppers are unpopular in some respects because they consume up to 20% of the total power requirement of the combine harvester (Green and Eliason, 1999). Chopping damp straw requires more power than chopping dry straw, although the distribution of damp straw on the soil surface may be more even than that of dry straw.

Generally, if the straw needs chopping to avoid the no-tillage openers blocking, this reflects inadequate performance on the part of the openers.

CHAFF.   Another area of concern is the tailings or chaff. With some openers, this thick mat of fine material is more troublesome than thick straw. Fortunately, in recognition of this, many combine harvesters now offer chaff spreaders (or tailings spreaders) as well as straw choppers or spreaders (see Fig. 10.2).

Most straw choppers/spreaders can be adjusted to produce longer or shorter cuts and to spread the residues different distances through adjustments of the deflector, the vertical positions of the knives and the speed of the chopper (Siqueira and Casão, 2004).

Some modern straw choppers use improved cutting principles and blower support for spreading. For example, auger types can be applied to both straw and chaff with spreading widths up to 10 m in either direction without visible separation of different fractions (Lücke and von Hörsten, 2004).

SPREADING AFTER HARVEST.   There are limited residue management options available where it is not possible to spread the residue with the combine harvester. Re-spreading of the residues evenly after harvest has been only partially successful because most straw is light and fluffy, making it difficult to throw or blow any distance. One way of handling the situation after harvesting is to pass the material through a large fan or forage harvester and blow it as high into the air as possible on a mildly windy day. In this manner the wind will spread it reasonably evenly, but it requires a tractor with cab and good air filtration system or an operator who can tolerate dusty conditions. Variations on this have been attached to combine harvesters to create 'straw storms'.

Another way is to use straw harrows, which consist of feely rotating angled spikes that are pulled at an angle and flick the residues more evenly across the field.

Fig. 10.2. A straw and chaff (tailings) spreader on a combine harvester. Note the dust associated with spreading chaff.

Fig. 10.3. A pair of simple beater-type straw spreaders on the rear of a combine harvester. No attempt is made to spread chaff (tailings) with such a device.

They also double as a convenient way to disturb weeds seeds and induce them to germinate so they can be killed with a herbicide before drilling the next crop (referred to as 'chitting' in Europe).

Small-scale no-tillage

The killing of cover crops on a small scale is not as dominated by herbicides as is the case for large-scale no-tillage.

Mechanical destruction is frequently used, or a combination of mechanical and chemical methods. Mechanical destruction is favoured because it results in lower repetitive cash outlays and less exposure by small farmers and their families to chemicals, although chemicals such as glyphosate have a high level of safety associated with their use. But other herbicides (e.g. paraquat) are less safe and more difficult for farmers operating on small fields to take proper protective measures against than in larger operations, where fully enclosed vehicle cabs with filtered air supplies are common. Mechanical methods for cover-crop handling in small-scale agriculture are therefore being widely promoted.

Mechanical destruction of growing plants is achieved by slashing, chopping, crushing, spreading or bending the plants. Each method is suited to different conditions and results in different amounts of plant material being left on the soil surface.

Manual slashing

Manual slashing is a very labour-intensive operation. Schimitz *et al.* (1991) reported that labour requirements of 70 man-days/ha for manual slashing have been measured when managing a 3-year-old grass-residue field yielding 10 t/ha dry matter.

Knife roller

Knife rollers are amongst the more useful residue-management tools to achieve evenly distributed plant material on the soil surface. Figures 10.4, 10.5 and 10.6 show examples of
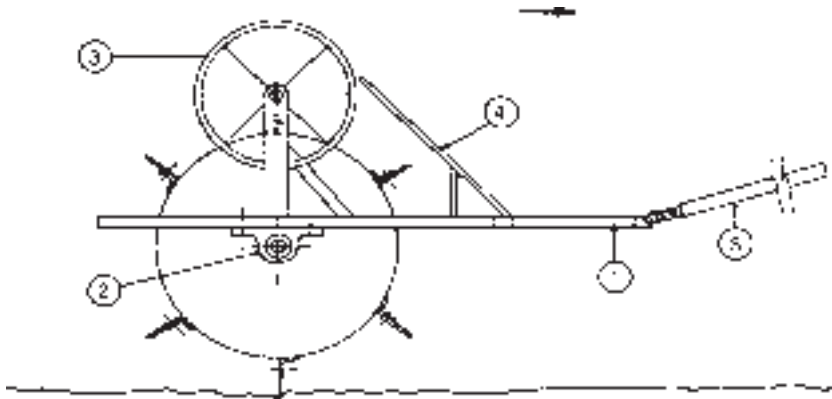

Fig. 10.4.   Side view of a knife roller: (1) frame; (2) bearings; (3) transport wheel; (4) protection structure; (5) shaft (from Araújo, 1993).

Fig. 10.5.   Animal-drawn knife rollers: (left) with full-width knives and (right) with short knives.

Fig. 10.6. A tractor-pulled knife roller operating in oats.

typical knife rollers. They have the advantage of allowing non-chemical organic production methods to be combined with no-tillage. For example, such implements are in common use for no-tilled organic soybeans in southern Brazil (Bernardi and Lazaretti, 2004) and are available for both animal and tractor power.

Knife rollers have flat metal knives mounted on a roller with a frame for support, wheels for transport and a protective structure. The knives are mounted on the roller in various patterns, most commonly perpendicular to the direction of travel. The effect of the knives is to bend, crush and chop off plant material. Their effectiveness depends upon the width, diameter and weight of the roller, the number, height, mounting angle and sharpness of the knives, speed of operation and the fibre and moisture content of the plants (Schimitz *et al.*, 1991; Araújo *et al.*, 1993).

Rollers are constructed from either steel or wood. Steel rollers are often filled with sand, so that their weight can be adjusted according to the condition of the

plant material and the desired result of chopping, crushing or bending. But on slopes the sand can move to one side of the roller and affect the evenness of performance and stability. Monegat (1991) recommended roller widths between 1 and 1.2 m as a compromise between stability on hillsides and an ability to stay in contact with irregular surfaces.

Knives may be the same width as the roller (Fig. 10.5 – left) or in short sections (Fig. 10.5 – right). Shorter sections increase the pressure exerted as each knife impacts the ground and spreads the impact forces more evenly, which is important for draught animals in particular. For a given diameter of roller, the effectiveness decreases as the number of the knives increases because the pressure on each knife is reduced (Schimitz *et al.*, 1991). For the best cutting action, the knives should be perpendicular (i.e. not angled) to the surface of the roller (Siqueira and Araújo, 1999).

Tables 10.1 and 10.2 show recommendations for the construction of knife rollers for draught animals and tractors, respectively (Araújo, 1993).

Table 10.1. Recommendations for the construction of animal-drawn knife rollers (1 m wide) operating at 1 m/s (3.6 km/h) (from Araújo, 1993).

Roller		Diameter (cm)	Height of knives (cm)	Number of knives
Material	Density (kgf/m³)			
Eucalyptus wood	1040	60	5	5
			10	6
			15	6
Steel + sand	2000	40	10	4
		60	5	10
			10	10

Table 10.2. Recommendations for the construction of tractor-mounted knife rollers (1 m wide) (from Araújo, 1993).

Roller		Speed, m/s (km/h)	Diameter (cm)	Height of knives (cm)	Number of knives
Material	Density (kgf/m³)				
Eucalyptus wood	1040	2 (7.2)	40	5	4
				10	4
				15	6
Steel + sand	1500	2 (7.2)	30	15	12
		3 (10.8)	25	8	4

The design, construction and operation of knife rollers must also take safety considerations into account. When working on slopes, it is advisable to use a fixed shaft instead of chains, so that the shaft will work as a brake for the roller. Other considerations are manoeuvrability, including reversing (Schimitz *et al.*, 1991), and the use of protective shields. Figure 10.7 shows a protective shield, which is important to both the draught animal and the operator.

The force required to pull a knife roller in black oats at the milky seed stage (sown at a density of 100 kg/ha) was measured at approximately 3430 N (350 kgf) per metre of width (Araújo, 1993).

Time requirements for handling black oats with a knife roller are about 3 h/ha for animal-drawn and 0.9 h/ha for tractor-pulled (Fundação ABC, 1993; Ribeiro *et al.*, 1993), although Schimitz *et al.* (1991) reported requirements as high as 6 days/ha with animal-drawn units.

The crushing action of knife rollers interrupts the flow of sap through the plant, which will kill many annual plants if the timing is correct (see Fig. 10.8). In this regard, it is best if the cover crop is uniform and rolling is undertaken at the beginning of the reproductive stage, when seeds are not yet viable. This is at full flowering for leguminous species and at the milky stage for cereals (Calegari, 1990). In some environments, such as sub-Saharan Africa, it is desirable that the cover crop remains green as long as possible to avoid burning during the dry season. In this situation, a knife roller should be used at the beginning of the rainy season, prior to planting.

Different methods of cover-crop residue handling will result in different rates of biomass decomposition. Araújo and Rodrigues (2000) compared the decomposition rates of black oats (*Avena strigosa*) as a function of mechanical treatment. They found that after 68 days the residues

Fig. 10.7. A protective structure for the draught animal and operator alike.

Fig. 10.8. Black oats killed with a knife roller.

remaining in relation to the initial amount were 59% for a knife roller, 48% for a flail mower and 39% for herbicide application. A similar study carried out by Gamero *et al.* (1997) indicated that after 75 days the amount of black oat dry matter was 68% for a knife roller and 48% for a flail mower. The authors also found a lower weed

population when the knife roller was used compared with a flail mower.

Yano and Mello (2000) evaluated the distribution of various cut lengths of pigeon peas (*Cajanus cajan*) as a result of different mechanical treatments of cover-crop residues. A flail mower resulted in 70% of the cut lengths being 100 mm or less compared with 45% for a rotary mower and 22% for a knife roller.

Another advantage of mechanical treatment of heavy cover-crop residues is that, if the crop is sprayed with herbicide before mechanical treatment, the main canopy may prevent the herbicide getting to lower-growing weeds beneath the canopy. Alternatively, the cover crop can be treated with a knife roller and then sprayed, provided that sufficient time is allowed for the weeds to appear through the bent-over canopy so that they can be targeted by the spray. This option is best suited to heavy cover crops. Spraying options are most effective where the cover crop is not heavy.

Can a knife roller substitute for herbicides?

Knife rollers are not designed for weed control, even though the mulch they produce may contribute to weed suppression. But one purpose of growing a cover crop is to pre-suppress the weeds with a dominant monoculture, which can itself be killed by a knife roller at the appropriate time prior to planting the main cash crop. If the cover crop is vigorous and the weed incidence is low, a knife roller alone may be sufficient to prepare the field. In Tanzania, for example, Schimitz *et al*. (1991) reported that a knife roller had been effective for weed control in grass up to 3 m high after a fallow. The factors that make such a totally mechanical option viable are:

1. Perform the planting operation as close as possible to the destruction of the cover crop.
2. Use planters with minimal slot disturbance.
3. For planters that create substantial slot disturbance, plant before the cover crop is treated so that the residue will cover the slot opened by the planter.

Management of Residues by Openers, Drills and Planters: Micro-management of Crop Residues

Micro-management refers to how the residues are handled by the openers themselves and the role the residues play in the opener functions. It is a sad fact that the designers of many no-tillage openers still treat residues as an unwanted nuisance. While recognizing the macro-value of residues to no-tillage, these designers often show little sign of recognizing the micro-value of residues for opener function and seeding results. As explained in Chapter 5, the highly desirable Class IV slot cover is only possible if the ground is residue-covered in the first place and then only if the openers are designed in such a way as to retain that residue over the slot itself.

Opener handling of residues

Chopping (strip tillage)

All power till openers chop the surface residues with the soil. There is no practical way to avoid their doing this. Where the surface residues consist of undecomposed accumulated organic matter in colder climates, such incorporation may be of benefit, but, in all other circumstances, some of the value of no-tillage is lost when the residues are incorporated, even on a strip scale. Besides, strip tillage itself defeats some of the objectives of true no-tillage in the planting zone.

Sweeping aside

Hoe, knife, shank, angled flat disc and angled dished disc openers all push soil and some of the surface residues aside as they proceed through the soil. Disc openers may also push some of the residue into the soil to form hairpins in the seeding slot. With hoe- and shank-type openers, if the residue is reasonably thick and of some length, it will accumulate on the shank of the opener rather than be pushed aside, causing opener blockages. Angled disc-type openers do not have this problem, but, in

either case, residue that is pushed aside will have negligible influence on the micro-environment within the slot that is being created.

On the other hand, because the residue is usually heaped to one or both sides of the slot (Fig. 10.9), careful choice and operation of a subsequent covering device may succeed in collecting some of this residue and guiding it back into the slot zones (Class III cover), although it is then likely to be mixed with soil. This process will occur if the soil remains dry and friable. If the soil becomes damp, the covering device is likely to create a smearing effect and the value of the residue will be lost by becoming smeared into the soil alongside but not over the slot.

Pushing down or through

All discs, to a greater or lesser extent, push down through surface residues. Double or triple disc openers mostly push down, whereas angled discs sweep aside as well as push through. The problem with pushing down is that, because it is impossible to cut all of the residue all of the time, a proportion of residue is doubled over and pushed (tucked) down into the slot in the form of a 'hairpin'.

The tendencies of different discs to hairpin depend on several factors:

1. Sharpness of the disc. Sharper discs are more likely to cut than to hairpin, but it is impossible to keep discs sharp all of the time.
2. Brittleness of the straw. Brittle straw is more likely to break than fibrous straw. Brittleness itself is a function of crop species, dampness and stage of decay.
3. Softness of the soil. Firm soil will assist shearing by a disc (the anvil effect) more than soft soil. More hairpinning will occur in soft soils.
4. Speed. Faster operating speeds generally reduce the incidence of hairpinning. The straw has less time to bend because of its inertia and is therefore more likely to be cut or broken.
5. The presence of chaff and tailings. Where straw is lying over a mat of fine tailings, as is often the case, the tailings provide a soft mat beneath the straw, which acts like a soft soil and encourages hairpinning. Worse, a portion of the tailings themselves may be pushed down into the slot, where they make the hairpinning problem worse by coming into contact with the seed.

Fig. 10.9. Residue swept to one side of a no-tillage slot.

6. Diameter of the disc. Smaller-diameter discs, because of their reduced footprint area, will put more pressure on the residue than larger discs and are therefore more likely to cut the residue than to hairpin it. But small discs are also more likely to sledge, since larger discs have a flatter cutting angle at the soil surface.

7. Disc design. Wavy-edged discs, because of their self-sharpening tendencies, will cut better than plain discs. Notched discs do not remain any sharper than plain discs but cut more residue because of the slicing action of the sides of the 'points' and the increased footprint pressure of the 'points'.

Folding up from beneath

The disc version of winged openers manipulates the surface residues by first pushing a notched disc down through the residues and then using the lateral wings of the side blades to fold the residue and soil upwards and outwards while the seed and fertilizer are deposited in the slot. A pair of following press/gauge wheels then fold the material back over the seeded slot. The end result is a horizontal slot covered with soil and residue (Class IV cover) in much the same layering as the soil and residues had been before seeding.

The limited amount of vertical hairpinning caused by the notched disc is of little consequence because, unlike with all other no-tillage openers, the seed is placed to one side of the central disc slot away from any hairpins. In this way the seed is effectively separated from any hairpinned material and instead benefits from the presence of residues over the slot (see Chapter 5).

Row cleaners

One method of assisting no-tillage openers to operate in residues is to clean the row of residues immediately ahead of the openers. The devices designed to achieve this are known as 'row cleaners' or 'residue managers'.

With small-scale no-tillage, it is often not feasible to use disc openers because of the weight required to push them into the ground compared with tine- or shank-type openers. 'Row cleaners' require little additional weight since most of them only work on the surface of the ground. But in such situations they may make the difference between being able to undertake no-tillage or not.

With large-scale no-tillage, where weight is less of a problem, 'row cleaners' are often used in springtime to remove residues from over the immediate row area so as to allow sunlight to warm the soil more quickly after a cold (and often freezing) winter.

Most 'row cleaners' consist of spiked rotating wheels, notched discs or rakes set at an angle to the direction of travel and operating ahead of the openers. The spikes just touch the ground, which causes them to rotate much like a finger-wheel rake for turning hay. In the process, they sweep the residues to one side or both sides while at the same time moving as little soil as possible.

With tougher residues, such as maize stover, two wheels may be set at opposite angles to one another and the spikes are synchronized at their fronts to reduce the side force on the whole device by sweeping residues to both sides of the row rather than to one side. Figure 10.10 shows a 'row cleaner' consisting of a pair of synchronized spiked wheels. Figure 10.11 shows unsynchronized notched discs designed to push residues aside.

Chopping of straw into short lengths

There is a critical length for most straws, above which they will bend and thus wrap around approaching rigid tools (e.g. tines). Chopping all straw into relatively short lengths allows short lengths to fall away from rigid tools rather than wrap around them. Other objectives for chopping straw trace their origins to tillage by making the straw easier to incorporate into the soil and enhancing the decomposition process.

To drill into maize stover with shank-type openers, Green and Eliason (1999)

Fig. 10.10.   A pair of synchronized star wheels (row cleaners) for pushing residues aside.

Fig. 10.11.   A pair of angled, notched, disc row cleaners designed to push residues to either side of the row ahead of the opener.

recommended that the cut lengths should be no longer than the shank spacing of the openers.

Chopped straw may also settle down on to the ground more easily and closely than long straw and may therefore provide a more effective mulch. On the other hand, an effective no-tillage opener will ensure that

even long straw is replaced on the ground after its passage (see Fig. 10.1).

One of the most effective ways to obtain chopped straw is to fit a straw-chopper to the rear of a combine harvester. Such devices are not readily favoured by operators, however, because they consume considerable power and are yet another component

that must be adjusted correctly on an already complicated machine. In any case, they seldom chop every single straw, with the result that the long straws that persist may eventually accumulate on openers not equipped to handle them.

Other methods produce chopped straw with a separate chopper. Some of these machines incorporate the straw into the soil as they chop it, which departs from true no-tillage because of the general soil disturbance. Others simply chop it and redistribute it back on the ground again.

Yet a third approach is 'vertical mulching', where the straw is chopped and then blown into a vertical slit created simultaneously in the soil by a large soil opener on the machine (Hyde *et al.*, 1989; Saxton, 1990). The result is a series of vertical slits filled with straw, thus solving a disposal problem as well as providing an entry zone for water infiltration.

Because no general tillage takes place, vertical mulching complements no-tillage, but the absence of a horizontal surface mulch reduces the options for maximizing the benefits of true no-tillage. Figure 10.12

shows a prototype vertical mulching machine in the USA.

Random cutting of straw in place

The most obvious way of handling long surface residues in place is to cut a pathway through them with some form of sharp tool. Generally, discs are the most commonly used device but other forms of tool have included rigid knives and powered rotating blades.

Rigid knives

These have been known to work for short periods only if their cutting edges remain smooth and very sharp, but extended use is impossible because of random damage and dulling by stones and soil abrasion. Figure 10.13 shows a knife-edge opener where the sweeping action of a tapered front was combined with a sharp edge in an attempt to slide past and/or cut residues. The sliding action was unsuccessful because small imperfections soon developed in the otherwise smooth edge from contact with stones,

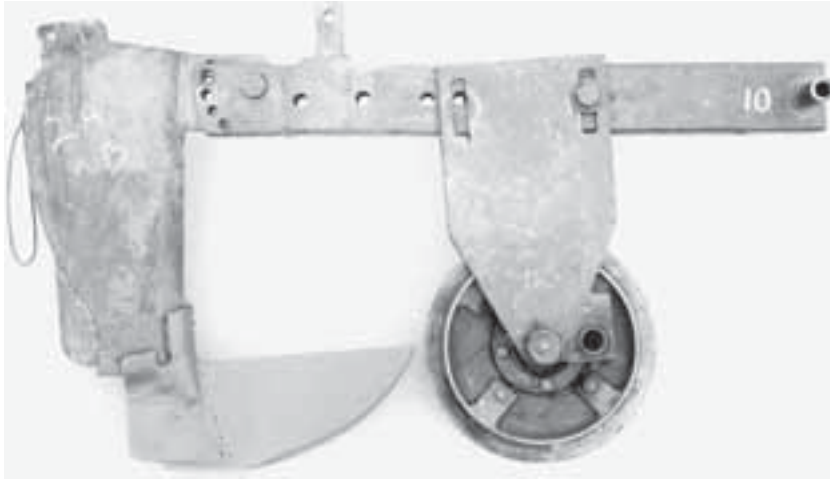**Fig. 10.12.** A prototype vertical mulching machine.

Fig. 10.13. A prototype knife-edge opener designed to sweep and cut residue (from Baker *et al.*, 1979a).

resulting in straw catching as it slid down the face. This led to deterioration of the cutting effect and blockage.

Rotating blades

These, such as on power till openers, are not always successful either. To be most effective as a soil pulverizer, power till blades are usually L-shaped. The horizontal portion of the L is important because it elevates and accelerates the soil upwards and throws it against the surrounding cowling, breaking it into smaller particles. Unfortunately, the horizontal L is also a perfect catch for wrapping of residue. As a consequence, backward-facing C-shaped blades are often used in residue situations because they allow the residue to be brushed off as they rotate. C-shaped blades, however, do not have a truly horizontal portion to the blade and the trade-off is that they are less effective as a soil pulverizer.

Discs

These can be most effective for breaking through or slicing straw, but, as explained previously, their action is highly dependent on the firmness of the background soil against which they must shear the straw and the brittleness of the straw itself. No matter what design of disc is used, no disc will cut all of the residue all of the time.

Cutting damp fibrous straw is particularly difficult. Cutting it against a soft soil background is even more so. One variation that has been tried is to power the disc so that it rotates faster than its peripheral forward speed. The aim is to create a slicing action as the disc presses the residue against the ground. Figure 10.14 shows a prototype powered disc. A further variation is to cause the disc to vibrate as it rotates by using a power drive on the disc hub. Both of the powered disc options, however, are disadvantaged by the cost and complexity of providing individual drives to a multiplicity of openers together with the interruption to residue flow between adjacent openers brought about by the bulkiness of such drives in the vicinity of the disc hubs. Besides, some unpowered designs have managed to achieve comparable results at a fraction of the cost.

The most appropriate diameter of discs for handling agricultural residues is always a matter for debate. Small-diameter discs have a smaller footprint and are therefore easier to push into the soil than larger discs. For this reason they also cut residues better than larger discs. However, the closer the disc axle is to the ground, the easier it is to stop the disc rotation (stall) when the
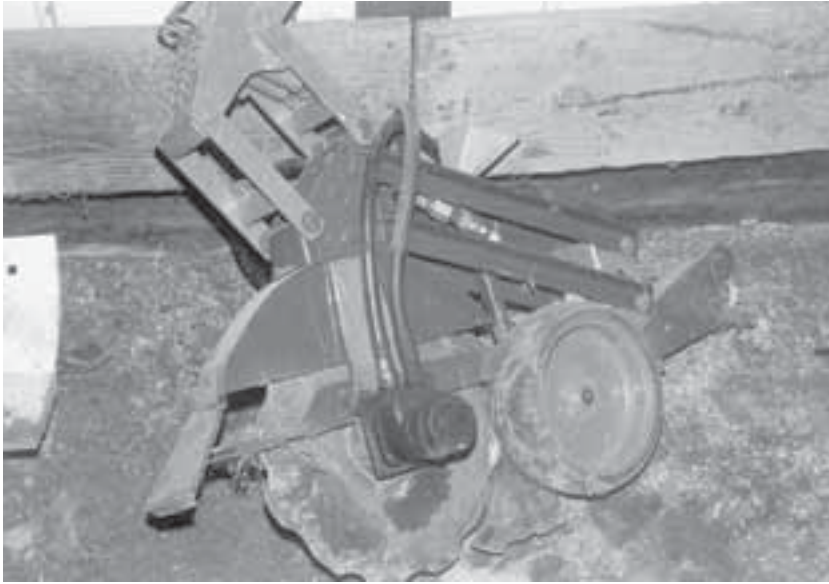
Fig. 10.14. A powered disc opener designed to rotate faster than the speed of travel through the soil.

thickness of residue exceeds the height of the disc axle. Also, a large-diameter disc has a flatter angle of approach between the leading edge of the disc and the ground, making it less likely to push ('bulldoze') the residue ahead of it and more likely to trap it in the 'pinch zone' and then roll over or cut through it. The most appropriate disc size is a compromise between getting sufficient penetration and avoiding disc stall. The most appropriate disc diameters used in agriculture seem to be between 450 mm (18 inches) and 560 mm (22 inches) and are used extensively on no-tillage openers.

DISC DESIGNS. Another debatable aspect is the design of the disc. Essentially discs can be of five designs.

PLAIN FLAT DISCS (FIG. 10.15). These are used on more no-tillage openers than any other form. They are the least expensive option to manufacture and have a sharpened edge, although experiments have shown that sharpening of the edge is not altogether necessary in all situations. They have the least traction of all alternate designs to ensure turning, which is not a disadvantage when used in short

standing residue, but can be a disadvantage in long lying residue. When sharpened, their action is intended to be one of cutting the residue, but as the edge becomes dull they tend to trample rather than cut some of the residue. As such, they have a strong tendency to hairpin when configured as double discs, angled flat discs or a single vertical pre-disc.

One redeeming feature of flat discs is that they are able to handle large woody sticks better than most other discs. The smooth edge tends to push such sticks away, whereas other disc types may slice into and catch on the sticks without actually cutting them, which then prevents the disc from rotating.

WAVY-EDGED 'FLAT' DISCS (FIG. 10.16). T h e s e are designed to gain maximum traction by interrupting the smooth sides of plain discs with a series of ripples. These ripples are designed to 'gear' the disc to the soil, ensuring the disc will rotate in even the heaviest lying residue. For reasons that are not well understood, the ripples also result in the discs being self-sharpening. As such, their action is more one of cutting than with

Fig. 10.15. A plain flat disc.

Fig. 10.16. A wavy-edged 'flat' disc.

plain discs, making them somewhat less likely to hairpin. Penetration forces are similar to those of plain flat discs. Although wavy-edged discs are sharper than plain discs, making penetration easier, their waviness actually increases their footprint area and increases rather than decreases required penetration forces.

Their self-sharpening tendency also results in relatively high wear rates. The ripples also become collection zones for sticky soils, interrupting their effective functioning. Their most common use is as a single pre-disc ahead of rigid components such as hoe openers. They may also have the function of loosening the soil ahead of the double disc openers so as to counter the compacting tendencies of such discs. They are sometimes known as 'turbo-discs' for this reason.

NOTCHED, OR SCALLOPED, FLAT DISCS (FIGS 4.27 AND 8.10).   These have semicircular notches cut from their peripheries, leaving about 50% of the periphery as 'points' (actually they are not points, as such, but simply a portion of the edge of the original plain disc left unaltered) and 50% as gullets. The objective is to reduce the footprint area on the ground, which aids penetration when compared with plain discs, and to 'gear' the disc to the soil to assist traction. The 'points' of the disc penetrate the soil first and present approximately half the footprint area of a plain disc of the same diameter, although the gullet zones of the notches also eventually penetrate the soil to a

shallower depth. The net effect, therefore, is easier penetration than with plain or wavy-edged discs.

Furthermore, as the 'points' penetrate the soil, they change their angle of attack slightly as they progress further around the rolling circle. One important effect of this is that the near-vertical edges from the 'points' to the gullets slide into the soil at a range of angles and thus produce a slicing action against a portion of the residue. This cuts that portion of the residue more effectively than when it is simply pressed on from above, as with all other disc types.

DISHED, OR CONCAVE, DISCS (SEE FIGS 4.10 AND 4.11).   These are nearly always angled to the direction of travel. As such, the friction against them is increased compared with plain discs travelling straight ahead. They therefore have good traction and are less likely to stall in heavy, flat residue than plain discs, but have all of the other attributes of plain discs, including power requirements and a tendency to hairpin residue.

One of the difficulties with all angled discs is delivery of the seed to the U-shaped slot created behind the lee (back) side of the disc. Usually, a boot is positioned close to the disc beneath the ground, but the gap between this boot and the disc is a collection point for random residue when used in no-tillage. Unless this gap is continually adjusted, blockage soon results.

One way of solving the problem is to spring-load the boot so that it rubs on the disc at this point. An advantage of dished discs is that their curvature provides considerable strength, allowing the discs to be made from thinner steel than is common for flat discs of any nature. This in turn has clear advantages as far as penetration and sharpness are concerned. For example, a 3 mm thick disc will require only 60% of the penetration force required for a 5 mm disc, although with dished discs this advantage is offset by the resistance to penetration of the convex (back) side of the disc.

NOTCHED DISHED DISCS.   These combine the attributes of dished discs with those of notched discs. Although such designs have

been used extensively in heavy residues for cultivating new land from native scrub and felled bush, there are no known no-tillage openers that use the principle in a more refined role. Similarly, there are no known no-tillage openers that use a wavy-edged dished disc.

Realigning residue on the ground

A novel approach to avoiding hairpinning with plain discs has been to use realigning fingers ahead of the discs. One drill of US origin had vertical spring tines designed to agitate and jostle the lying straw so as to cause each straw to lie end-to-end with the approaching disc. This was intended to avoid the tendency of discs to pass across straws, the starting point of all hairpinning. The tangled nature of many straw residues, however, ensured that this approach was never wholly successful.

Flicking

Another novel approach to the operation of single plain or wavy-edged discs ahead of rigid tines has been to attempt to flick off any residue that collects on the leading faces of the tines, since a single disc operating ahead of a rigid tine will not allow that tine to pass cleanly through lying residue all of the time. Clean-cutting ahead of a tine can sometimes be achieved with short cut straw and often with anchored residue, but long and lying residues are another problem. Regardless of how well the disc cuts the residue, there will always be some straw remaining uncut and passing the disc to collect on (or wrap around) the tine. Even when the disc is positioned close to, or even touching, the front edge of the tine, residue will collect on this front edge. Besides, it is most difficult to ensure that a disc remains permanently touching a tine when both are subject to normal wear.

Scottish designers created a self-flicking device (Fig. 10.17). Two spring-loaded fingers were attached to the hub of the disc in such a way that, as the disc rotated, the fingers became tensioned against the ground. At a certain point in the rotation, each of the

Fig. 10.17.   A flicking device designed to self-clean stationary tines.

fingers was suddenly released from the ground, whereupon it flicked upwards at high speed past the front edge of the tine and dislodged residue that had collected there. Similar devices have been used by the authors, but these were attached to separate wheels that ran alongside the tine.

While the flicking devices worked in light and dry residues, heavy residues, especially when wet, tended to interfere with the flicking action. Failure to dislodge all of the straw from the tine with any one flick became a cumulative problem, leading eventually to total blockage of the tine.

Treading on residues

To overcome the 'hit-and-miss' nature of flicking, recourse to more predictable treading has been tried with mixed success. To achieve this, wheels are located alongside the tines so that they continuously roll on to one side of the residues wrapped around the leading edges of the tines. The intention is to cause the residue to be pulled off to one side. Even though they may achieve this objective, the presence of the wheels themselves generally interferes with free passage of other lying residue between the openers.

Self-clearance by free fall of residues off tines

Provided that sufficient space can be provided around each tine, most accumulated residue on the front of tines will eventually fall off, simply as a function of its own accumulated weight. Unfortunately, this does not always occur, especially with wet residue, necessitating irregular stops to clear what can become a sizeable mound of accumulated debris. Not only do these mounds of debris on the ground interfere with subsequent operations, their clearing is invariably a source of annoyance for operators at seeding time.

The most serious disadvantage of this principle, however, is the spatial demands on the drill required for clearance between individual tines. Drills of this type are limited to relatively wide row spacing (250 mm or greater) and the extended area occupied by the tines interferes with accurate surface following by individual tines and seed delivery.

Unfortunately, there are some designers and operators who are willing to widen the row spacing of their drills beyond what is agronomically desirable, expressly to

provide more clearance for residue. But, if anything, no-tillage, by conserving soil moisture, should allow closer row spacing to be used than for tilled soils, with resultant higher potential crop yields. An example of a drill with wide row spacing is shown in Fig. 4.15.

Combining rotating and non-rotating components

An important new residue-handling principle was designed in 1979 (Baker *et al.*, 1979b). This involved rubbing the entire leading edge of a rigid component (such as a tine, shank or blade) against the vertical face of a revolving flat disc. For the rubbing action to be self-adjusting (so as to accommodate wear of components), the stationary component needs to be wedge-shaped so that it presents a sharp leading edge against the disc but tapers outwards away from the disc towards the rear. In this way it is held against the disc by lateral soil forces as the soil flows past. If two such rubbing components are positioned one on either side of the disc, all of the soil forces become symmetrical, thus avoiding undesirable side-loading on the discs and their bearings.

The design is illustrated in Figs 4.27 and 8.2. In the design of the disc version of a winged opener, an opportunity was taken to deliver the seed to the base of the slot by directing it to fall between one such stationary blade and the corresponding face of the disc. By directing fertilizer in an identical manner down the other side of the disc, an effective method of horizontal separation of seed and fertilizer in the slot was achieved (see Chapter 9).

There are four important principles involved in the rubbing action:

1. The intimate contact between the stationary blades and the revolving disc allows any residue passing the disc to also pass the whole assembly, thus making openers involving a rigid tine or blade at least as able to handle residues as a pure disc opener. This combination of disc and rigid component has achieved a remarkable residue-handling ability. This is important because all pure disc openers compromise at least some of the slot-shape functions to achieve residue handling. The best micro-environments for seeds in no-tillage are generally created by horizontal slots formed by a rigid tine (see Chapter 4).

2. The contact between the rigid component and the revolving disc is lubricated by a thin film of soil (Brown, 1982). This means that the rigid component can be manufactured from material that is much harder (and therefore more wear-resistant) than the disc, without cutting into the face of the disc to any appreciable extent.

3. There needs to be a small amount of pre-load between the rigid component and the disc, even though, in operation, the soil continually presses the two together. As the device enters the soil, and before the soil forces have pressed the two components together, a single piece of straw may occasionally become wedged between the two components if there is no pre-load between them. This residue will hold them fractionally apart for a short period. Other pieces of straw are then likely to enter the gap, with the result that blockage eventually occurs.

4. There is a disc-braking effect on the disc from the rubbing of the rigid components. For this reason, traction of the disc must be maximized. Notched flat discs are most commonly used for this type of opener, although plain flat discs have also been used. Wavy-edged discs are unsuitable because a flat surface is necessary for the blade and disc contact to be effective.

Wet versus dry straw

The action of most openers is affected by the brittleness of the straw, which is itself a function of dampness or dryness as well as other physical attributes, such as fibre content. After spraying or physical killing of growing material, the residue will lose water and become increasingly 'stringy'. Sometimes best results will come from waiting 10–15 days so that the residues will dry completely and be more easily cut by discs. This also allows root material to begin decaying, which makes the soil more

crumbly and usually leads to better slot formation. In other situations, drilling might be undertaken before or immediately after the residues are killed, provided that competition for soil water does not take place between the crop and the cover crop before the latter is killed.

On the other hand, harvested straw will normally be at its most brittle shortly after harvest. Discs are most effective when operating on brittle straw in warm dry weather and when the background soil is firm. Standing residue often becomes increasingly brittle as it 'ages' over winter, making spring no-tillage seeding more easily accomplished.

The case for and against scrapers

A natural reaction to problems of accumulation of sticky soil and/or residues on rotating components of openers is to strategically place scrapers and deflectors to remove the unwanted material. Such scrapers and deflectors can range from those designed to deflect residue from ever coming near the opener (e.g. Fig. 10.18) to those designed to protect a specific part of the opener. Figure 10.19 shows a circular scraper designed

in Canada to remove soil from the inside of double disc openers.

However, most scrapers create more problems than they solve. Often, they simply present yet another point on which unwanted material can accumulate. While they may remove the original problem from interfering with a critical part of the opener, they seldom result in a total cure from accumulated debris. With the disc version of winged openers, both the side blades and the disc-cleaning scrapers (Fig. 10.20) operate beneath the ground and are therefore self-cleaning.

Clearance between openers

Even if individual openers are designed to freely handle surface residues without blockage, arranging multiples of such openers to handle residues in narrow rows is often a difficult problem in its own right. The main principles generally involve lateral spacing. To provide sufficient lateral space between adjacent openers for residues to pass through, the openers need to have a minimum of 250 mm clearance. Even then, the actions of different openers
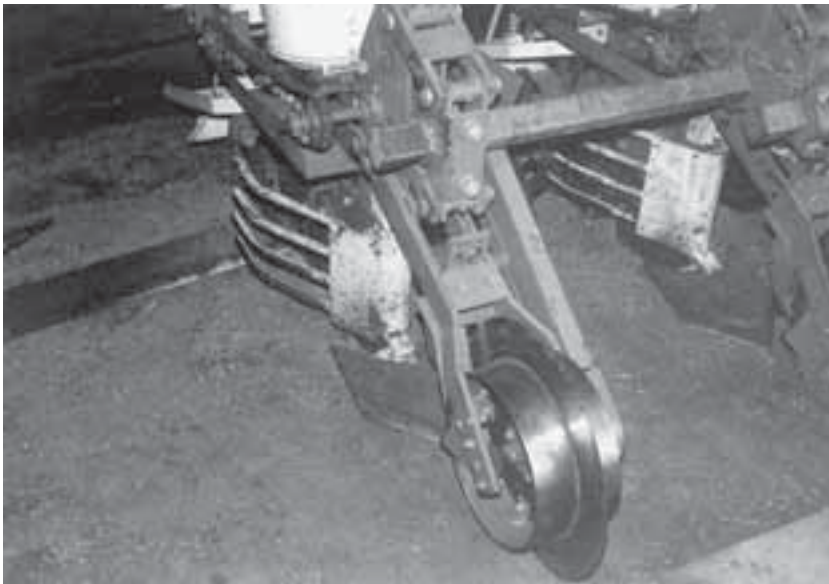

Fig. 10.18.   Residue deflectors on a maize planter.

may interfere with their neighbours and therefore require greater clearance.

For example, while 250 mm might be sufficient for openers that create minimal

Fig. 10.19. Circular scrapers for double disc openers.

disturbance of the soil (e.g. double disc), greater distances may be required for those that either throw the soil (e.g. angled flat discs and angled dished discs), push it aside (hoe) or fold it back (winged). In such circumstances, each alternate opener needs at least to be offset forwards or rearwards of its neighbours so as to give diagonal as well as lateral clearance (referred to as staggering). An alternative to staggering is to create greater lateral distances between openers, but this usually means increasing row spacing, which may be agronomically undesirable.

The problem is further complicated by the greater downforces required for opener penetration under no-tillage, which is usually applied to the drag arm connecting the opener to the drill frame. The strength required of drag arms to transmit these large downforces discourages the use of alternately long and short drag arms to create staggering, especially if such drag arms are also of the parallelogram type with multiple pivots. In contrast, long and short drag arms are common on drills designed for tilled soils because the forces are small in comparison.

One way of overcoming this problem has been to operate the openers from two separate tool bars, one in front of the other.

Fig. 10.20. Underground scrapers on the disc version of a winged no-tillage opener.

This allows the openers on each tool bar to be spaced twice the distance apart as the row spacing. If used, it also allows the longer drag arms for a stagger arrangement to be of robust construction without interfering unduly with the between-opener spacing.

The problem of lateral spacing largely applies to drills and not to planters, because drills may have row spacing as close as 75 mm, while planters seldom require row spacing closer than 375 mm.

Summary of Residue Handling

1. The most serious physical problem relating to the handling of surface residues is mechanical blockage.

2. The most serious biological problem relating to the handling of surface residues is hairpinning (or tucking) of residues into the seed slot.

3. Macro (whole field)-management of surface residues starts with the combine harvester and is important for soil and resource management of no-tillage in general.

4. Macro-management should aim at even spreading of both straw and tailings over the entire field. Chopping of straw is optional.

5. Micro-management of surface residues is a function of no-tillage openers and is important for controlling the micro-environment of the seed slots.

6. Micro-management should strive to return the residue over, but not into, the seed slot (Class IV cover).

7. Large-scale no-tillage almost invariably involves the use of herbicides to kill existing vegetation.

8. Small-scale no-tillage relies predominantly on mechanical or manual residue management.

9. Knife rollers are a useful tool for management of residues in small-scale no-tillage.

10. Residue can be classified as 'short root-anchored'; 'tall root-anchored'; 'short flat'; or 'long flat'.

11. 'Long flat' residue is the most difficult to handle.

12. Relying solely on the cutting of residues is seldom effective. No device will cut all of the residue all of the time.

13. Most pure disc-type openers handle residues well, but also tend to hairpin (or tuck) straw into the slot, which is undesirable.

14. Most rigid component openers (hoe- or shank-type) handle residues poorly with regard to blockage but do not hairpin.

15. Most power till openers handle residues poorly except when the blades are C-shaped.

16. Wavy-edged and notched discs handle residues better than plain discs.

17. Small-diameter discs penetrate soil and residues more easily than larger discs, but are more likely to form blockages in heavy residues.

18. Firm soils provide a better medium for residue handling and cutting by openers than soft soils, thus reducing hairpinning.

19. Small no-tillage machines often have poor performance by having tined openers (due to cost) but benefit from the manual attention that can be given to residue management by operators.

20. Wet soil and/or wet residue are more difficult to handle than dry soil and/or dry residue.

21. Unless operating beneath the ground, most scrapers are of limited value because they accumulate residue on themselves while they are removing it from elsewhere.

22. Vertical mulching consists of disposing of straw into deep vertical slits in the soil.

23. Any rigid opener component, such as a tine or shank, will accumulate residue regardless of the design or positioning of a disc ahead of it.

24. Only when the leading edge of a rigid tine is forced to rub in intimate contact with the side face of a revolving flat disc will a tine/disc combination handle residues as well as a disc alone.

25. The minimum distance between adjacent openers for self-clearance of residues is approximately 250 mm, either laterally or diagonally, or both.

11   Comparing Surface Disturbance and Low-disturbance Disc Openers

C. John Baker

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The surface disturbance of soil and residues often represents the most visible difference between no-tillage openers; yet the real effects may lie underground.

The passage of a seeding drill over a no-tilled field causes a wide variety of soil and residue disturbances, largely depending on the opener design, soil condition and operation speed. These disturbances are quite visible and yet the impacts on crop establishment and subsequent yields may only become obvious in stress conditions.

In the first part of this chapter, we revisit the seeding principles of the previous chapters to relate the disturbance effects to the effectiveness of common no-tillage slot shapes. In the second part, we compare the design features of common disc-type openers, since it is mainly disc openers that create minimum-disturbance slots.

Minimum versus Maximum Slot Disturbance – How Much Disturbance Is Too Much?

The largest concern centres on openers that create significantly different amounts of disturbance, such as a single, straight-running disc versus a broad hoe or chisel opener. These results are recognized as minimum versus maximum opener disturbance drills. Minimum disturbance creates just enough soil movement for the seed insertion with a single cut through the overlying residue while maximum disturbance moves a significant volume of soil to create a seed slot and allows the soil to fall or be moved back over the slot with the residue moved well away from the seed row.

Crop residues are the lifeblood of no-tillage. Indeed, they are the lifeblood of sustainable agriculture itself. In the past, debates about surface residues have mostly centred on their macro-management: the percentage of ground that is covered by residues in relation to erosion control, surface sealing, shading and the ability of machines to physically handle them. Recent emphasis has been to reduce the amount of residue disturbance during drilling for the erosion protection that greater amounts of ground cover offer.

Micro-management of residues centres on the influence that residues have on seed, seedling and plant performance in individual rows, all of which ultimately affect crop yield.

One aspect relates to soil erosion. The other to crop yield. Is one more important than the other?

Unless crop yield is maintained, few will undertake no-tillage and the soil erosion

benefits become irrelevant. Therefore it could be said that micro-management of surface residues should be the first objective in any no-tillage system. But, sadly, history shows that that has seldom been the case.

Then again, minimum slot disturbance means different things to different people. For example, an allowable limit of 30% slot disturbance means that the disturbed zone in 150 mm spaced wheat rows can only be 45 mm wide – a difficult but achievable expectation for many no-tillage openers. But 30% disturbance in rows of maize or cotton sown in 750 mm–1 m rows represents 225–300 mm of disturbance – a much more generous objective.

So the development of no-tillage openers for wheat and other narrow-row crops may take a very different course from that for wide-row crops. But, since there is twice as much wheat sown in the world as the next most common crop, the constraints on openers for narrow-row crops provides the greatest challenge for machinery designers.

Minimum-disturbance no-tillage is created by openers that disturb the surface of the ground as little as possible, retaining at least 70% of the surface residues intact after their passage, with residues evenly distributed over the surface of the ground. Minimum-disturbance openers include double and triple disc (so long as the soil is not sticky); the disc version of winged openers; some narrow knife openers operating in low-residue conditions; and some angled disc openers operating at slow speeds on flat ground and in non-friable soils.

Maximum-disturbance no-tillage is created by openers that either burst the soil aside or deliberately till a strip at least 50 mm wide. Maximum-disturbance openers include most hoe, shank and sweep types; angled discs operated at high speed and/or on hills; double or triple disc openers in sticky soils; dished disc type openers; and powered till-type openers.

Disturbance effects

No-tillage opener design has the biggest influence on the amount of slot disturbance that occurs, and this in turn can have a direct influence on multiple factors directly related to the effectiveness of no-tillage seeding. Each will be discussed using many of the principles previously introduced, but more specifically related to the amount of visual soil and residue disturbance as the seeding is accomplished.

Slot cover

In tilled seedbeds, it is relatively easy to cover the seeds with loose soil. Therefore, aiming to create localized tilled strips during no-tillage has been an obvious objective of some no-tillage machinery designers. But no one has ever advanced a good biological reason for regularly tilling or disturbing the soil in the slot zone other than to compensate for the inadequacies of the openers that place the seed.

Many low-disturbance no-tillage openers cut a vertical slot in the soil. Even though this creates minimal surface disturbance (which is desirable), unless the soil is dry and crumbly at the time, closure of such slots is difficult and is worst in damp and 'plastic' soils. No-tillage slots that remain open dry out and attract birds, insects and slugs, which may cause crop failures even before the plants emerge from the ground. This problem has probably been responsible for more crop failures in no-tillage than any other single factor.

Covering problems can largely be solved while still retaining minimal residue disturbance by creating horizontal or inverted-T-shaped slots (winged openers). The seed is located on a horizontal soil shelf on one side of these slots and with advanced designs fertilizer is banded on an identical shelf on the other side. Horizontal flaps of soil with residue covering the soil are folded back to cover both. Even if the central slit dries and cracks open, as is inevitable in some untilled soils, neither the seed nor the fertilizer becomes exposed.

Viewed from the surface, inverted-T-shaped slots may appear similar to vertical V-shaped slots. Both are usually classified as minimal disturbance. The difference is beneath the ground. Vertical V-shaped slots

may have compacted near-vertical side walls and get narrower towards their bases. It is often difficult to push a finger into them. They usually provide class I or, at best, II cover. On the other hand, inverted-T-shaped slots are loosened beneath the surface, get wider with depth and are usually very easy to push a finger into, providing Class IV cover.

In-slot micro-environment

Minimum slot disturbance does not always equate with a beneficial slot micro-environment. But nor does maximum slot disturbance. In fact, the best in-slot micro-environment that maximum-disturbance slots can provide is seldom better than a tilled soil, but may be better than poorly made and covered V-shaped slots (Class I cover).

Within the various minimally disturbed slots, horizontal slots (inverted-T-shaped with Class IV cover) create about as favourable a micro-environment as possible by trapping vapour-phase soil water in the slot (see Chapter 5). Seeds will germinate on the equilibrium relative humidity (RH) contained within the soil air, so long as this RH remains above 90%. Tilled soils seldom contain an equilibrium RH greater than 90% due to air exchange with the atmosphere, whereas untilled soils nearly always have an equilibrium RH between 99% and 100%. The problem is that unless the seed slot created in an untilled soil has sufficient coverage to trap the air (which usually means residues overlying soil), the potentially superior micro-environment in an untilled soil will be lost and seeds must then rely on a slot micro-environment that is no better than a tilled soil.

Vertical V-shaped slots (Class I or II cover) do not trap in-slot RH and are therefore about the least tolerant of all no-tillage slots of dry conditions.

All slots that involve strip tillage of some nature (Class III cover) fall into the maximum-disturbance category. They are likely to be more tolerant of adverse conditions than vertical V-shaped slots, simply as a function of the friable soil within the slot, but will still be inferior to horizontal inverted-T-shaped slots, which contain RH as well as liquid-phase water.

Slots created by angled discs fall between the extremes. As a general rule of thumb, if a slot made by an angled disc results in minimal surface disturbance, it will contain a better slot micro-environment than where such slots are more disturbed.

Carbon dioxide loss

Slot shape and residue retention may affect the ability of no-tillage slots to retain carbon dioxide. There is no doubt that all no-tillage offers major advantages over tillage in this regard (Reicosky, 1996; Reicosky *et al.*, 1996), but differences in no-tillage slot disturbance may also affect the amount of carbon dioxide that is lost from the slot zone.

In-slot moisture and temperature

Some studies have shown that slot shape and residue retention have only minimal short-term effects on liquid-phase soil water content and temperature within the sown slots, even though they are both affected on a macro-scale by residue retention (Baker, 1976a, b, c). On the other hand, the practice of removing residues from over the slot to raise the soil temperature in the slot zone in spring has a measurable effect.

The objective of this process is to expose the slot zone to direct sunlight when soil is warming up (such as in springtime), which in turn causes drying, thereby raising the soil temperature in the row. This begs the question whether seeds sown shallow beneath a residue canopy (Class IV cover) experience any lower soil temperature regimes than seeds sown deeper in uncovered slots, because the former option provides water for germination at shallow sowing depths and involves minimal-disturbance of the residues.

Seed germination

Chapters 5 and 6 showed that, while most minimum-disturbance slots promote high germination counts in dry soils, not all such slots perform well in wet soils, even though

some do, such as the inverted-T shape. Nor does good germination always translate into good seedling emergence in dry soils (see below).

Maximum-disturbance slots are neither the best nor the worst for promoting germination. They attempt to emulate tilled soils and as a result usually perform similarly to tilled soils.

Seedling survival and emergence

The most critical time for no-tillage seedlings is the time between germination and emergence, as discussed in Chapter 5. Retaining surface residues over the slot (inverted-T-shaped slots, Class IV cover) sustains seedlings beneath the surface of the soil awaiting emergence better than loose soil (Class II–III cover), which is better than no cover (Class I). In addition, the retained residues are desirable from a soil erosion point of view. Not all minimum-disturbance slots create Class IV cover, depending on the residue amount and condition. Some may even be as poor as Class I cover. Most maximum-disturbance slots create Class II–III cover.

Soil-to-seed contact, smearing and compaction

The amount of slot disturbance visible from the ground surface is not always a good indicator of what is taking place beneath the soil in terms of soil-to-seed contact. For example, V-shaped slots in heavy soils (minimal-disturbance) may create neatly cut, smeared (if wet) and even compacted slot walls but still have adequate soil-to-seed contact, even in dry soils, because the seeds become wedged between the near-vertical slot walls. But such seeds may germinate and die (see Chapter 6), even with adequate soil-to-seed contact. In other cases, seeds sown into highly disturbed dry slots may have good soil-to-seed contact but fail to germinate because loose soil conducts liquid-phase soil water poorly.

In inverted-T-shaped slots (minimal-disturbance) without vertical slot walls, soil-to-seed contact may be little different from highly disturbed U-shaped slots, but, because inverted-T-shaped slots are covered with residue (Class IV cover), the presence of water vapour will ensure germination and emergence take place.

Root development

Vertical V-shaped slots create minimal surface disturbance but may restrict root development more than other openers, especially in heavy damp soils. The use of wavy-edged pre-discs with such openers reduces root restrictions but increases surface disturbance.

Most maximum-disturbance openers, together with most winged openers, present little, if any, restrictions to root growth.

Infiltration into the slot zone

Slot disturbance has a direct effect on infiltration. Earthworms and other soil fauna that feed on surface residues create channels that have a positive effect on infiltration. Earthworms, in turn, respond to the positioning of the residues. Minimum-disturbance slots that leave or replace the residues over the slot encourage earthworms to colonize the slot zone, which increases infiltration.

Maximum-disturbance slots may kill earthworms in the immediate vicinity. The wider and more severe the disturbance (especially if a power till mechanism is involved), the greater the earthworm mortality. But nearby earthworms will recolonize the disturbed zone shortly afterwards.

Other factors may also contribute. Minimum-disturbance slots created by vertical double or triple disc openers compact the side walls of the slot. This has a direct negative effect on infiltration from sealing as well as an indirect negative effect because earthworms avoid the compacted zone.

Hairpinning of residues

The most quoted negative effect from residues positioned close to the slot zone has been tucking of residues into the slot, termed 'hairpinning' (see Chapter 6). Decomposing residues in wet (and especially anaerobic) soils produce acetic acid, which can kill seeds or seedlings that are

touching the residue. In dry soils, seeds suspended in hairpins have difficulty accessing liquid-phase water.

All disc-type no-tillage openers hairpin residues at least some of the time. But no one has yet designed an opener that can physically handle surface residues in closely spaced rows without the assistance of discs. The disc version of the winged opener physically separates seeds from direct contact with hairpinned residues and thus avoids the problem. Acetic acid is rapidly broken down in the soil by bacteria, so small separation distances are effective. But all double disc and angled disc openers (whether slanted or upright) experience hairpinning problems because the seeds remain embedded in the residues.

Fertilizer banding

Banding of fertilizer close to, but not touching, the seeds at seeding is vital to maximize crop yields (Baker *et al.*, 1996; Fick, 2000). Some designers achieve this by combining two openers together, which increases inter-row spacing and surface disturbance, or by using 'skip-row' planting (one row of fertilizer between every two rows of seed). Others use altogether separate fertilizer openers, which increase slot disturbance even more. But there are other 'double-shoot' openers (e.g. disc version of winged openers) that have been purpose-designed with no sacrifice of row spacing or surface disturbance (Baker *et al.*, 1979b).

Soil erosion

Since retention of surface residues is the most effective mechanism for controlling soil erosion, the more of the surface that remains covered with residues after seeding, the better.

Pests, diseases and allelopathy

Early predictions of uncontrollable residue-related pest and disease problems attributable to no-tillage and residue retention have proved to be exaggerated and, in most cases, groundless. In early trials with no-tillage, poor crop results were often attributed to toxic exudates from dying residues (allelopathy). But, as scientists have come to understand what really affects seed germination and seedling emergence during no-tillage (particularly the role of residues in improving the slot micro-environment), examples of true allelopathy have become difficult to find.

In any case, the advantages of residue retention are so great that they far outweigh any minor residue-related disease or pest problems that might occur from time to time.

Disc opener feature comparisons

No comparison would be complete without examining the designs of a selection of mainstream openers and/or machines. In this case, we have compared three different designs of disc openers: the disc version of a winged opener; angled vertical discs; and double discs.

Comparisons in Table 3.2 showed that the risk of impaired crop performance with the disc version of the winged opener was rated at 11%, while the angled vertical disc opener was 30% and the double disc opener 53%. Table 11.1 lists the causes of these differences. Shank-, hoe- and tine-type openers were not compared because the designs and performance of such openers vary widely and are affected by soil conditions and operating speed; thus the results are difficult to generalize.

Summary of Comparing Surface Disturbance and Low-disturbance Disc Openers

1. The dual objective of minimizing the amount of disturbance to surface residues while at the same time maximizing seed, seedling and plant performance is possible to achieve with modern no-tillage techniques and equipment.

2. Not all minimum-disturbance openers will create optimum crop yields, but all maximum-disturbance openers will reduce

Table 11.1. Comparison of selected features of three disc-type no-tillage openers.

Opener features	Disc version of winged opener	Angled vertical disc opener	Double disc opener
Risk of impaired performance	11%	30%	53%
Opener description	Opener comprises a vertical notched disc with two blades with horizontal wings and scrapers in intimate contact with either side of the disc	Single-shoot form of opener has a single vertical disc arranged at an angle to the direction of travel. Double-shoot option has duplicate fertilizer-only openers	Single-shoot form has two discs arranged at about 10° vertical angle to one another. Double-shoot option has duplicate fertilizer-only openers
Effects of forward speed	Functions are not greatly affected by forward speed	Functions are affected by forward speed because of the angle (7°) of the disc(s) to the direction of travel	Some functions (e.g. seed flick) can be affected by high forward speeds
Maximum speed	Capable of operating at speeds up to 10 mph (16 kph)	Forward speed is limited by conditions, but maximum is less than 10 mph (16 kph)	With adequate deflectors against seed flick, capable of speeds up to 10 mph (16 kph)
Seed covering	Seed covering (Class IV) is residue layered over soil, which scientific experiments have shown to be superior to all other forms of cover	Seed covering is mostly loose soil but the covering function is very speed-dependent (Classes I–III)	Often covering is very difficult to achieve at all because of the wedged V-shaped slot. Rippled pre-disc helps in this respect (Classes I–III)
Slot compaction	No in-slot compaction occurs	In-slot compaction occurs on one side only	Severe in-slot compaction occurs on both sides
Slot smearing	Any in-slot smearing that occurs remains moist and therefore of no consequence	Most in-slot smearing that occurs remains moist and therefore of no consequence	In-slot smearing is common and difficult to prevent from drying, when it forms in-slot crusting, which is even worse
Surface residues over slot	Retains 70–90% surface residue cover	Tends to push residues aside rather than replacing them. Higher speeds push residues further aside	May retain 70% residue ground cover except in sticky soils, when residue retention declines
Vapour moisture	Retains maximum vapour moisture at seed zone	Medium vapour moisture retention if loose soil covers slot (Class III)	Poor vapour moisture retention
Residue hairpinning	Will create hairpins but the seeds are effectively separated from the hairpins so they are of no consequence	Creates hairpins and, because seeds remain embedded in the hairpins, this affects germination in both dry and wet soils	Creates hairpins and because seeds remain embedded in the hairpins this affects germination in both dry and wet soils
Seedling emergence	High seedling emergence, almost regardless of soil or climatic conditions	Seedling emergence is dependent on favourable soil and climatic conditions	Seedling emergence is highly dependent on favourable soil and climatic conditions
Crop failure	Low crop failure rate	Medium crop failure rate	High crop failure rate

Crop yields	Regularly produces superior crop yields to both tillage and other no-tillage openers	Requires double-shoot version to produce best crop yields, but farmer confidence is not high
Emergence retarding	Seedling emergence is not retarded by soil flaps in wet plastic soils because seedlings follow pathway to the surface provided by the vertical disc slit	Seedling emergence is not affected by soil flaps, but exposure of seeds can be a problem
Banding fertilizer	Simultaneous and separate seed and fertilizer banding occurs on either side of a single disc on the same opener	No separate banding of seed and fertilizer by each opener. Requires duplicate openers for double-shooting
Fertilizer placement	Therefore one compact opener is used to sow both seed and fertilizer	Double-shooting of seed and fertilizer requires either a complex doubled-up opener or duplication of two openers. This increases the complexity and space occupied by each composite opener and encourages farmers to only do half the job by purchasing the cheaper single-shoot option
Row spacing	Can be arranged in close row spacings down to 5.5 inches (140 mm)	Minimum row spacing of double-shoot version is 7.5 inches (190 mm)
Hillside operation	Effective on hillsides	Not effective on hillsides because of the angle of the disc
Prior tillage	Effective in tilled and minimum-tilled soils	Not very effective in tilled and minimum-tilled soils
Service wear	All moving pivots use sealed bearings, leading to long trouble-free service	Most versions use many simple pivot arrangements with limited service life
Penetration force	Individual hydraulic rams on each opener ensure consistent downforce that can be varied infinitely on the move from the driver's seat and automated to adjust to soil hardness on the move	Most have downforce springs with stepwise settings and each setting changes its downforce with elongation and contraction

Third column (far right):

Produces acceptable crops in favourable conditions, but yields are restricted by inability to band fertilizer
Seedling emergence is not restricted, but desiccation and bird damage of exposed seedlings can be a problem
No separate banding of seed and fertilizer by each opener. Requires duplicate openers for double-shooting
No known double-shooting openers exist. Therefore duplicate openers are the only option, with the same problems that angled disc openers have
No double-shoot option. Minimum row spacing of single shoot is 4.72 inches (120 mm)
Effective on hillsides
Effective in tilled and minimum-tilled soils
Most versions use many simple pivot arrangements with limited service life
Most have downforce springs with stepwise settings, and each setting changes its downforce with elongation and contraction

Continued

Table 11.1 *Continued*

Opener features	Disc version of winged opener	Angled vertical disc opener	Double disc opener
Depth gauge	Press/gauge wheels located close to seed zone	On some models gauge wheels located right alongside seed zone	Gauge wheels sometimes behind seed zone, but other versions are right alongside seed zone
Depth control	This results in superb opener depth control and makes drilling over contour banks and variable soils effective	Springs limit opener depth control, especially when drilling over contour banks and surface changes, but good location of gauge wheels helps	Limited opener depth control, especially when drilling over contour banks and surface changes
Downforce control	Electronic monitoring of press wheel footprint allows the downforce to be altered on the move in response to changing soil hardness	Downforce cannot be changed on the move	Downforce cannot be changed on the move
Downforce range	Normal downforce range is 0–500 kg	Most designs have a downforce range 0–250 kg	Most designs have a downforce range 0–250 kg
Maximum downforce	High-downforce rams (1100 kg) are available for openers operating in the wheel tracks of compactable soils	No high-downforce openers available	No high-downforce openers available
Opener adjustments	There are only two operational adjustments with each opener, neither of which changes with wear and one of which is made in the tractor cab	Many operational adjustments are necessary, most of which are affected by wear and require dismounting from the tractor cab	Main operational adjustments are closing wheels, downforce
Disc adjustment for penetration	Disc axle can be located in three different positions, which minimizes the penetration forces required, especially in hard soils and stones	Disc(s) are located in one fixed position	Discs are located in one fixed position
Operation skills	Medium skill and training level required. The electronic monitoring system protects the finished job from the effects of inexperienced operators	Skill level is dependent upon operators gaining experience with every condition likely to be encountered so as to make the correct adjustments. Therefore a good finished job is highly skills-dependent	Medium skills dependency. Simple design creates fewer adjustments than angled disc but also reduces adaptability compared with either other opener
Scientific evaluation	Extensive scientific validation of manufacturer's claims	Little or no scientific validation of manufacturer's claims	Scientific tests have mostly been negative about this opener

the effectiveness of erosion control and soil improvements offered by no-tillage.

3. Minimum slot disturbance is an optimum no-tillage objective, with full consideration given to the several other seeding requirements for stand establishment.

4. Horizontal (inverted-T-shaped) slots provide good slot coverage with minimal residue disturbance (Class IV). V-shaped slots provide poor slot coverage and residue cover (Class I).

5. Minimum-disturbance slots do not necessarily create favourable slot micro-environments unless adequately covered with soil and residue. Horizontal minimum-disturbance slots most readily create favourable slot micro-environments while vertical minimum-disturbance slots do not. Maximum-disturbance slots create slot micro-environments similar to tilled soil.

6. Minimum-disturbance slots are likely to lose somewhat less carbon dioxide than maximum-disturbance slots.

7. The amount of residue cover over the slot has minimal long-term effect on liquid moisture content. Minimum-disturbance slots trap water vapour, while residue-free slots warm more quickly in spring.

8. It is possible to have both minimum residue disturbance and maximum seed germination.

9. It is not always desirable or necessary to sacrifice residue disturbance to encourage seedling emergence. Depending on the design of opener and the climatic condition, it may, in fact, have the opposite effect.

10. Slot disturbance by itself is not necessarily a good indicator of soil-to-seed contact.

The amount of residue disturbance may have little effect on soil-to-seed contact.

11. Some, but not all, maximum-disturbance openers may enhance early root growth. Restrictions by some minimum-disturbance openers may occur with unfavourable soil conditions.

12. Provided that compaction is not a factor, most minimum-disturbance slots encourage earthworm activity, and thus increase infiltration compared with maximum-disturbance slots. In the absence of earthworms, maximum-disturbance slots may have greater infiltration than the best of minimum-disturbance slots.

13. All non-disc openers, especially those associated with maximum residue disturbance, avoid hairpinning problems but experience residue-handling problems. Most disc openers, except those that create horizontal slots, have hairpinning problems.

14. Some no-tillage drills that band fertilizer are less capable of minimizing residue disturbance or close row spacing, or both. But there are notable exceptions, such as the disc version of winged openers.

15. No-tillers should ensure that surface residues are well distributed and minimally disturbed.

16. Disturbing surface residues as little as possible in the slot zone will have more positive effects on seed, seedling and crop performance than harmful effects by pathogens or allelopathy.

17. Disc-type openers vary widely in their specific designs, which in turn affect their biological functions, including slot disturbance.

12 No-tillage for Forage Production

C. John Baker and W. (Bill) R. Ritchie

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The establishment and/or renovation of forage species is a special no-tillage case requiring additional techniques and management.

Pastures and other forage crops provide food for foraging animals in countries, regions or seasons in which animal production is profitable. In some situations animals are grazed outdoors, often all year round. In other situations, forage crops are harvested for storage or transport to the animals housed indoors for at least part of the year. Many of the world's pasture plants are self-sown native species on rangeland, which have survived in the ecosystems to which they are adapted. Most of these species, however, produce relatively poor feed for domestic animals in terms of quality and quantity.

In the improved pastures of temperate countries, genetically superior species have been sown into the rangelands and, together with the judicious use of fertilizers and rotational grazing management, have led to vastly improved animal productive capacity. Over time, however, some of these improved pastures have slowly reverted to the original, less productive species, requiring intermittent renewal or renovation with improved species. In other situations, the continual genetic improvement of pasture species dictates their introduction into

otherwise 'permanent' grazing systems to improve animal performance, regulate seasonal production or repair damage from pests, flood, drought or natural mortality.

We shall discuss the drilling of forage species and pastures separately, although in reality they are as often integrated into a single system as they are dealt with in isolation.

Forage Species

Forage crops are similar to arable crops for their establishment requirements by no-tillage except that small-seeded species are often involved, which require very accurate depth control from the openers. Many brassica species are used for forage cropping, along with grasses, legumes and herbs, all of which require shallow seeding. But a wide range of cereal species are also used, often for whole-crop silage, which have a greater tolerance of the depth of seeding.

One problem is that farmers often value their forage crops lower than arable crops, presumably because the cash returns from forage crops are derived by indirect animal harvesting rather than directly through machine harvesting of seed, fibre or grain. When a forage crop fails, there will often be an alternative forage crop nearby that can be

used to compensate, or, at worst, animals can be sold to reduce demand. In contrast, when an arable crop fails, that source of income is lost for ever and cannot be replaced. For this reason, there seems to be more acceptance by animal farmers of substandard no-tilled forage crops than is the case with arable farmers. Even those people who farm integrated animal and arable systems put less value on the forage crops than on the arable crops, possibly because the latter usually comprise the major part of the farm income.

Further, because pastures are regularly grazed or mowed, differences in individual plant performances are more difficult to detect by eye. As a consequence, rather than attracting greater precision at drilling, much pasture establishment actually attracts less precision.

But this situation is changing. Animal farmers in New Zealand, for example, are finding that a new level of animal intensification is possible using 'fail-safe' no-tillage that rivals arable cropping, in terms of both returns per hectare and risks.

Animals are often grown on 'permanent' forage species (usually pastures), which are characterized by uneven growth cycles during the year. Maximum forage production and quality of feed occur in warm moist months, while minimum production and quality occur in cold and/or dry months. Management of animal systems that rely on such feed supplies is constantly restricted by the lowest-productivity months. Often this involves the use of feed supplements, either purchased in or saved as silage or hay during the more productive months.

But a new level of productivity can be achieved by replacing 'permanent' forage species with highly productive, short-rotation, speciality forage species, which are re-established at least once (and often twice) per year and are chosen according to their suitability for specific growth periods or animal requirements during the year. Some are cold-tolerant; others are dry-tolerant; still others produce a quality of feed suited to particular stages of growth of the animals. The possible combinations are virtually endless and can be regularly changed.

But they all depend on the availability of 'fail-safe' no-tillage techniques and systems. Such systems of forage production cannot be accomplished using tillage because few productive soils can stand being tilled continuously once or twice per year. The soils would quickly deteriorate to unmanageable conditions, and utilization by animals would become almost impossible.

Although the quality and quantity (and therefore productivity) of short-rotation forage species grown under continuous no-tillage regimes are superior to those obtainable from 'permanent' pastures, the new system puts much pressure on the ability of the no-tillage system and equipment to deliver maximum crop yields for each successive crop.

Because the forage crops are established at least once and often twice per year, it is a 'high-input' and 'high-output' system, but some of those practising it have reported tripling the numbers of stock grown to slaughter weight per year on the same area. Outdoor weight gains from lambs and beef cattle in the order of 400 and 1000 g per day, respectively, have been common when the animals are fed *in situ* on a continuing supply of short-rotation no-tilled forage crops.

A variation on this system is to grow continuous short-rotation silage and hay crops for cash sale rather than grazing by animals. In some systems, animals never enter the fields. This restricts the choice of forage species to those that can be converted into hay or silage, but again the system is totally dependent on no-tillage.

Integrated Systems

The optimum diversification is to integrate animal and arable crop production systems. This is a common practice in countries where climate allows animals to graze outdoors all year. Typically one or more arable crops are grown during the most productive time(s) of the year and forage crops are grown between the arable crops and either fed directly to animals or mechanically harvested and fed indirectly to them. Up to

three integrated crops can be grown per year in some climates.

Where no-tillage is not available, such intensive cropping will not sustain soil structure and tillage delays planting. For this reason, typical tillage-based rotations have included a period in permanent pasture with the objective of repairing the damage to the soil structure by previous tillage and readying the soil for further destructive cropping processes to follow.

No-tillage changes all of that by allowing continuous cropping (forage and/or arable) to take place almost indefinitely without significant damage to soil structure. Crop rotations are then not constrained by the need for a remedial pasture phase and can be selected for the relative values of crops at any one time.

Figure 12.1 is an example of where two crops of summer turnips (*Brassica* spp.), one established by tillage and the other by no-tillage on a light organic soil, have been grazed by dairy cattle *in situ*. The difference in soil damage is clear.

Of course, severely wet weather and heavy concentrations of stock will damage even untilled ground eventually. The question then becomes: 'How serious must the damage be before some form of tillage is justified?' Figure 12.2 shows severely damaged soil from repetitive hoof treading in a gateway when the soil was wet. The soil damage in Fig. 12.2 is about the upper limit that winged, hoe or angled disc no-tillage openers can be expected to repair without assistance from tillage tools. Indeed, the result from a single pass with a disc-version winged opener drill can be seen on the left. Double or triple disc openers would not cope well with such surface damage because they have only a minor smoothing effect as they travel through the soil.

Damage beyond that shown in Fig. 12.2 is best repaired with a shallow tined implement or rotating spiked harrow, the actions

Fig. 12.1. Two turnip crops sown with angled disc openers and fed *in situ* to dairy cattle in New Zealand. The upper photograph shows a wide view of the treading damage to the tilled soil on the right compared with the untilled soil on the left. The lower photograph shows close-up views of the respective soil surfaces. Note that the soil surface under no-tillage (left) has not been broken open at all, whereas the tilled soil (right) is heavily scuffed.

Fig. 12.2. Severely hoof-damaged soil that is about the upper limit that can be repaired by a single pass with the disc version of winged openers (seen on left).

of which are to drag or flick surface soil into the hollows rather than invert the soil. More severe treading damage may also compact the surface layers (to about 300 mm) of the soil profile. This is best relieved with a shallow subsoiler with narrow vertical tines or sweeps that leave the soil surface reasonably smooth so that no-tillage may take place again without further smoothing being required.

Where the integration of animal and arable enterprises is practised, it is common for last-minute decisions to be made between the growing of one or more arable crops or forage crops based on expected relative returns. Such flexibility is only possible if last-minute crop-establishment decisions are based on no-tillage. No-tillage provides the flexibility that allows truly integrated animal and arable systems to develop to new heights.

Arable crops are sometimes rotated with pastures where land is retired or 'set aside' to allow it to revert to native grasses and/or scrub for periods of 10 years or more to protect the soil from erosion or reduce agricultural production. With the world's demand for food continuing to expand, however, such land is likely to be returned to arable farming in due course. When it is, it will be more important than ever to retain the sustainability of the soil health, which will, in most cases, have reached

new heights from the retirement process, by adopting no-tillage from the outset. This means learning how to drill or plant into heavy 'unmanaged' sod.

No-tillage of Pasture Species

In some circumstances when drilling pasture species, it is not appropriate to kill all of the competing species. If the competing species are other desirable grasses and not destroyed, this is known as 'pasture renovation'. In other circumstances, it is necessary to kill all of the existing species. If the new species to be sown are also pasture plants, this is known as 'pasture renewal'.

Pasture renewal

One-quarter of the world's surface, some 3000 million hectares, is grassland (Kim, 1971; Brougham and Hodgson, 1992). Renewal and establishment of this valuable resource are a major effort, which can be enhanced with no-tillage practices.

Pastures are traditionally renewed either to improve the productivity of existing vegetation (e.g. bush, scrub, native grasses or introduced swards) or to replace a harvested annual crop with grazable pasture.

The objective can be to establish a long-term 'permanent' sward of monoculture (single species) pasture, including lucerne, or a mixed sward of several grass species and/or compatible legumes, such as clovers or lotus species. A further objective can be to establish a short-term (usually single species) temporary pasture to utilize land between successive arable crops.

Not all pastures will be grazed directly by animals. Many are harvested by machine or hand and fed to animals either directly as grain or as silage or hay, or are regularly mowed to keep them short (e.g. sports turf). This has some importance for the establishment method used. For example, if a pasture is to be directly grazed by cattle, the young plants may be damaged by treading or pulling. No-tillage offers clear advantages over tillage in this respect because the stability of the untilled soil resists treading damage and provides better root anchorage than tilled soils. No differences between no-tillage openers have so far been found in the pulling resistance during grazing (Thom *et al.*, 1986).

Where pasture plants are mechanically cut, pulling damage is minimized. Surface damage to the soil may result from heavy vehicle traffic under wet conditions. In this respect, the improved soil structure by no-tillage offers significant advantages over tillage.

The largest problem with pasture renewal by no-tillage is meeting the requirements of many pasture seeds for depth of sowing and germination micro-environment. The more rapidly establishing grass species, such as ryegrasses, are usually tolerant of sowing depths from 5 to 30 mm, but suffer reduced germination outside this range. The more weakly establishing species, such as lucerne, clovers and some grasses, are much less tolerant of improper depth, preferring the narrower range of 5–15 mm.

In a tilled soil, a narrow depth-tolerance range is relatively easy to achieve because the soil has been previously prepared to a uniform physical consistency and is easily penetrated by drill openers. Accurate sowing depth in a tilled soil favours large flotation-type openers (such as on V-ring roller drills), which are unable to operate in no-tillage because of the more dense untilled soil.

No-tillage openers for pasture renewal therefore need mechanisms for depth control and surface following and to be capable of creating a desirable slot micro-environment within the top 10–15 mm of soil. These are demanding requirements.

The choice of drilling pasture plants in rows compared with random scattering of seeds followed by harrowing has been discussed because the objective is to utilize all the available ground space. With no-tillage, random scattering (oversowing or broadcasting) almost invariably results in poor establishment because untilled soils offer little loose soil or debris to cover undrilled seeds by harrowing. Trampling of the seed into the ground by stock is no substitute for positive placement by a drill opener. None the less, where the operation of drills has been impossible (such as on steep hillsides and on some sports turfs), the practice of oversowing by aircraft, hand or light machine has been undertaken, with acceptable establishment by pelleting the seed and/or increasing the seeding rate to compensate for mortality.

Row spacing

Where no-tillage drilling can be successfully undertaken (i.e. tractors can access the land), the debate shifts to the most desirable row spacing and drilling times. Common design and space limitations of drills provide a narrowest practical row spacing of about 75 mm, with wider spacing up to 300 mm used in dry climates for pasture species with surface creeping habits or for forage seed production.

Research in New Zealand using a rapidly establishing ryegrass species (Inwood, 1990; Thom and Ritchie, 1993; Praat, 1995) showed little or no production differences between: (i) single-pass drilling with winged openers in 150 mm rows; (ii) single-pass drilling with the same openers in 75 mm rows; and (iii) cross-drilling in 150 mm rows with the same openers. In the last case, two passes were made at approximately 30° to

one another, sowing half the intended application rate with each of the two passes (Thom and Ritchie, 1993).

Results in Table 12.1 (Praat, 1995) show that a slowly establishing species (tall fescue, *Festuca arundinacea*) initially benefited from narrow (75 mm) row spacing as a result of reduced weed population. Cross-drilling had no long-term benefits over 150 mm spacing, possibly because the gains of closer plant spacing were offset by greater stimulation of weed seed germination by the second pass of the drill.

Single-pass drilling of tall fescue in 75 mm rows produced greater 5-month growth than single-pass drilling in 150 mm rows, but was not significantly different from the cross-drilling in 150 mm rows. The latter two treatments were themselves not significantly different from one another. The advantage of the 75 mm rows at 5 months was not repeated with ryegrass. By 23 months there were no significant differences among any of the drilling or species treatments.

Since the only differences were during the early stages of pasture growth, and then only with a slowly establishing species, the single-pass 150 mm row option is preferred because it is less expensive, both in terms of drill design and operational costs. An added advantage is that most no-tillage drills can also be used for drilling small-grained cereals, pulse crops, oil seed crops and forage crops.

In mild, wet winter climates, pastures and sports turfs are often renewed by tillage, in autumn because weeds are more easily controlled than in the spring and post-drilling soil moisture levels are likely to be more reliable than in the hotter summer periods. With no-tillage, however, the availability of herbicides and reduction in physical stimulation of dormant weed seeds largely eliminates the disadvantage of spring weed germination.

Further, the moisture conserved with no-tillage reduces the risk to new pasture and turf seedlings in dry summer soils. These factors have led to more spring drilling of new pastures and sports turfs using no-tillage than with tillage, but the majority of such swards are still established in the autumn.

Even in the autumn, the debate about row spacing has centred on the ability of pasture plants to quickly tiller and spread to occupy otherwise bare ground so as to compete with expected natural weed germination between the rows. Data in Table 12.2 (Praat, 1995) show the results of autumn no-tillage drilling of ryegrass and tall fescue into a recent alluvial soil containing a high weed seed population.

Only the two-pass cross-drilling treatment using winged openers increased weed seed germination and growth compared with single-pass drilling in 75 mm and 150 mm rows. Even then, these differences (approximately 20%) occurred only within the first 5 months after sowing. Thereafter there were no significant differences between drilling methods.

On the other hand, data in Table 12.3 (Hamilton-Manns, 1994) show a clear trend of declining weed growth with date of sowing in autumn and early winter, using the same pasture species sown in a single pass with winged no-tillage openers in 150 mm rows in a similar soil.

At the earliest sowing there were twice as many weeds in the tall fescue pasture

Table 12.1. Pasture production from differently spaced no-tillage drill rows, kg/ha dry matter yield at the time of sampling after sowing.

Treatment	5 months after sowing		23 months after sowing	
	Ryegrass	Tall fescue	Ryegrass	Tall fescue
75 mm rows, single pass	1893 a	2066 a	1399 a	1827 a
150 mm rows, single pass	1911 a	1525 b	1449 a	1734 a
150 mm rows, cross-drilled	2196 a	1826 ab	1453 a	1711 a

Unlike letters following data in a column denote significant differences ($P = 0.05$).

Table 12.2.   Effects of no-tillage drilling method on herbage composition of pasture species, kg/ha dry matter at time of sampling.

	5 months after sowing		23 months after sowing	
	Sown grasses and clover	Weeds	Sown grasses and clover	Weeds
75 mm rows, single pass	902 a	531 a	2086 a	119 a
150 mm rows, single pass	835 a	545 a	2146 a	125 a
150 mm rows, cross-drilled	796 a	675 b	2123 a	178 a

Unlike letters following data in a column denote significant differences ($P = 0.05$).

Table 12.3.   The effects of time of sowing on the proportion of weeds in a no-tillage pasture.

Time of sowing	Pasture species sown	% weeds present at 70 days after sowing	Mean % weeds for both species
Early autumn	Ryegrass	4.5 b	7.6 a
	Tall fescue	10.7 a	
Early–mid-autumn	Ryegrass	4.8 b	4.8 b
	Tall fescue	4.9 b	
Mid-autumn	Ryegrass	3.4 b	3.7 b
	Tall fescue	3.6 b	
Late autumn	Ryegrass	0.6 c	1.3 c
	Tall fescue	2.0 c	
Early winter	Ryegrass	1.1 c	1.4 c
	Tall fescue	1.8 c	

Unlike letters following data in a column denote significant differences ($P = 0.05$).

(10.7%) at 70 days after sowing compared with the ryegrass pasture (4.5%), because the more slowly establishing tall fescue pasture took longer to colonize the inter-row spaces. Thereafter there were no differences between these two pasture species in terms of weeds. As the season became colder (from early autumn to early winter), the percentage of weeds in both pastures steadily declined from an average of 7.6% to 1.3–1.4%, reflecting increasingly less favourable conditions for weed seed germination.

For total pasture production in New Zealand, Hamilton-Manns (1994) also found greater yield potential from early autumn sowing (March) than later winter sowing (June) if sufficient soil moisture was available to sustain early seedling development. This held true for both rapidly establishing species (e.g. ryegrasses) and slowly establishing species (e.g. tall fescue). The earlier sowings and warmer temperatures favoured tiller development of the sown species, although there was also an increased (though manageable) weed problem.

The retention of crop residues from a harvested summer crop or the fallowing of ground in the spring by spraying the previous pasture will help offset potential problems of weeds and low soil moisture levels during early autumn no-tillage sowing of new pastures. During winter in temperate climates, the retention of residues may result in increased earthworm populations (Giles, 1994).

In drier climates, improved establishment of new pasture species in the autumn has been achieved by chemical fallowing of fields over the dry summer. Resident species are sprayed out during late spring when they are still actively growing and receptive to herbicides, after which the

fields are left fallow for several dry months. If sufficient residue remains on the surface as a mulch, considerably less soil moisture is lost compared with unsprayed pastures because the spraying reduces moisture loss by transpiration and evaporation. Moisture gains as high as 12-fold have been reported (Anon., 1995).

The potential loss of pasture production over summer in dry climates is small and a more moist soil environment is maintained for early autumn establishment. Control of resident species is enhanced by using a more appropriate time of year for spraying, and there is also the opportunity for an autumn herbicide application prior to drilling, if required.

In climates with adequate summer rainfall, autumn establishment of new pasture species may be enhanced by drilling a forage crop the previous spring. This not only provides the opportunity for a double application of herbicide, but it also provides time and stock trampling to break down the intense root mats that exist with some native pasture species in low-fertility situations.

The emphasis with most of these techniques is to ensure effective long-term control of resident species to provide the greatest opportunity for a competition-free environment into which the new species can vigorously establish.

Pasture renovation

Pasture renovation, where at least partial recovery of the existing vegetation can be expected, adds another requirement to no-tillage seeding. The existing vegetation must be suppressed or managed such that it will not unduly compete with the introduced species. This renovation method is often referred to as overdrilling or sod seeding (see Chapter 1).

The renovation of existing pastures may be undertaken for several reasons:

1. To introduce a more productive long-term pasture species into an existing pasture.
2. To introduce a short-term pasture species that is more suited to a particular time

of the year or animal performance than the existing species.
3. To repair damage from natural mortality, drought, flood, erosion, pests, physical damage or poor drainage.
4. To compensate for management or fertility limitations for particular fields, soils or climates.
5. To capitalize on nitrogen fixation brought about by previously introduced legume species.

No-tillage pasture renovation was accomplished before the modern concept of general no-tillage. Early reports show renovation of animal pastures began in the mid-1950s (Blackmore, 1955; Cross, 1957; Robinson, 1957; Cullen, 1966; Dangol, 1968; Kim, 1971). Sports turf renovation came later (Ritchie, 1988).

In the 1950s the dominant reason for overdrilling was to capitalize on nitrogen fixation (Robinson and Cross, 1957). Low-fertility hilly pastures and pastures sown into bush burns on recent volcanic ash soils tended to become clover-dominant because of their low natural fertility. With time, however, this legume base improved the fertility and organic matter levels of such soils to a stage where they could sustain productive grass growth from pasture plants, mainly ryegrasses. The problem was how best to introduce the new grasses without destroying the clover base, or tilling and burying the organic matter layer of such fragile soils.

Since herbicide use was new at that time and, in any case, all available herbicides had a residual action of several weeks in the soil, early overdrilling machines concentrated on mechanical destruction of existing plants in a limited-width track (up to 50 mm wide) centred on the seed row. The objective was to provide a competition-free habitat for the new seedlings that would remain so until regrowth eventually revegetated the strips. By that time the newly introduced species were expected to be competitive with the resident species.

Even today, several designs of no-tillage openers for pasture renovation, e.g. power till and furrow openers, rely on physical,

rather than chemical destruction or suppression of the resident species to temporarily check the existing competition.

Band spraying

More recent research has shown that physical removal of vegetative matter from the slot cover zone has a negative effect on the micro-environment within the seed slot, thus seeding into less than optimal soil conditions. Fortunately, the advent of non-residual herbicides now permits selective spraying of a strip of existing vegetation (band spraying) at the same time as the seed is sown with openers. This creates a vegetative mulch, while at the same time suppressing the competing vegetation. Figure 12.3 shows an example of a band-sprayed and drilled pasture.

Figure 12.4 shows the trade-off effects of the various options for overdrilling of vegetation in comparison with the various slot shape options for promoting germination and seedling emergence. The top left illustration is of a slot left by a hoe- or shank-type opener without any attempt to cover the seed. The bursting effect of the opener has a positive effect on competition

removal by physically pushing it aside. This is represented by a tick alongside the illustration. But the open (uncovered) slot has a negative effect on seedling survival (represented by a cross alongside the illustration). Therefore there is some risk of failure from this technique.

The centre left illustration shows that covering the slot with loose soil will improve seedling survival (tick and cross) while still having a positive effect on competition removal. The risk of failure is decreased.

The lower left illustration shows that an uncovered V-shaped slot created by a double disc opener has a negative effect on both seedling survival and competition removal. The risk of failure is high. In this case, however, the absence of physical bursting allows band spraying to be used to kill a strip of vegetation over the slot. The top right illustration shows that this has a positive effect on competition removal but does nothing to improve seedling survival. But the risk of failure decreases accordingly.

The centre right illustration shows a slot left by a winged opener. While such an opener might have a positive effect on seedling survival, the absence of physical

Fig. 12.3.   The effects of band spraying and simultaneous drilling of pasture.
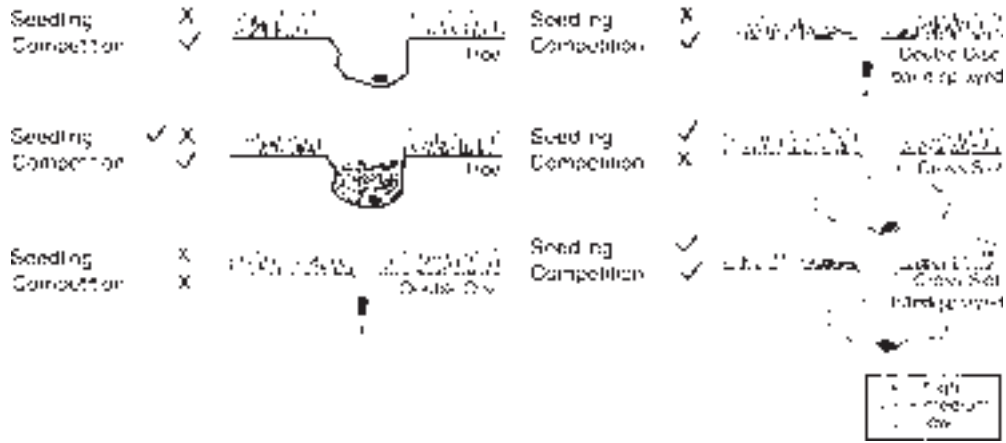
Fig. 12.4. The risk factors of vegetative control and slot micro-environmental control when overdrilling pastures.

bursting has a negative effect on competition removal (the risk of failure is medium).

Only when band spraying is used in conjunction with winged openers does the combination have a positive effect on both seedling survival and competition removal, as shown in the lower right illustration. The risk of failure is low.

There can be debate about how much suppression of existing vegetation is necessary or desirable to bring about the most productive pasture possible as a consequence of overdrilling an improved species into an existing sward. At one end of the scale is complete eradication of all existing species (blanket spraying by herbicide), producing a competition-free environment over the entire field, in which the new species can be expected to express its maximum yield potential. But, during the eradication and establishment period, production from the original sward is lost and must be deducted from the total pasture production for that year or season.

At the other end of the scale is no suppression at all, in which the new species is forced to compete with the existing species from the outset. Lost production from this option is only minor from damage to the existing sward, but the early and continuing competition adversely affects the yield and growth potential of the introduced species.

Between these two extremes is band or strip spraying, where a strip of existing vegetation is sprayed simultaneously as the new seeds are sown, or strip tillage. These are compromises and the loss of yield of the old species and realization of yield potential of the new species both reflect this by falling midway between the other two extremes.

Figures 12.5, 12.6 and 12.7 show the effects of the three spraying options with overdrilled ryegrass. With blanket spraying, the distinct rows of the new species are clear and vigorous. Where no spraying was undertaken, the new rows are less obvious, while band spraying lies in between. On the assumption that the new species has a greater yield potential than the existing species, any pasture that promotes vigorous growth of the new species is likely to have a greater long-term yield potential than the original sward.

To quantify the three options discussed above, scientists in New Zealand measured milk production from the yields of pastures renovated by the three methods (Lane *et al.*, 1993). They also took account of the relative costs of undertaking each practice and expressed their findings in terms of the time taken to recover those costs from the relative milk production figures for each of the options under the prevailing conditions. Their findings are shown in Table 12.4.

Fig. 12.5.   Ryegrass establishment by overdrilling with blanket spraying.

Fig. 12.6.   Ryegrass establishment by overdrilling with band spraying.

The blanket spraying option was the most expensive compared with band spraying and no spraying, but this option also created the best pasture, resulting in greater returns from milk fat per hectare. When the costs were offset against the returns, however, there was little difference between the three options and all repaid themselves within 8 months or a year. After the payback period, however, the extra pasture production becomes clear profit to the farmer, since the establishment costs would not be repeated annually. This clearly favours blanket spraying since returns from that technique are higher than from either of the other two options.

The technique of band spraying was first tried by L.W. Blackmore (1968, personal communication) and later developed by Collins (1970), Baker *et al.* (1979c) and Barr (1980, 1981). The most desirable band width was not obvious because the cost benefits described above suggest that band spraying is somewhat inferior to

blanket spraying. Altering the band width is a simple matter of raising or lowering the spray nozzles. Collins (1970) and Barr (1980) therefore studied different band widths in terms of their effects on yield of both the introduced species and resident species during pasture renovation. Table 12.5 records the results of band spraying during overdrilling with winged openers in 150 mm spaced rows.

Clearly, the wider band (75 mm) reduced the competition from the resident species more than the narrower (50 and 25 mm) bands. This was reflected in lower yield of the resident species with the wider band.

The effects on yield of the introduced species (even at the early stage of 12 weeks) reflected the levels of competition within the bands. The wider band produced the greatest yield of juvenile plants. Since the drilling row spacing was 150 mm, an optimum sprayed band width of 75 mm bands represents 50% removal of the competing vegetation. The results shown in Table 12.4 did not involve bands as wide as 75 mm, so the band spraying treatment may have been

Fig. 12.7. Ryegrass establishment by overdrilling with no spraying.

disadvantaged somewhat in the analysis of Lane *et al.* (1993).

In Barr's (1980) experiments, there was also an effect from fertilizer placement, which at first seemed to be at odds with trends described earlier (see Chapter 9). On closer examination, however, the effects with overdrilling are predictable and logical. It appears that by placing fertilizer with the seed in these circumstances, those resident plants left alive are able to utilize the nutrients before the introduced species because of the mature root systems of the resident species. This disadvantages the young introduced plants through increased competition, as seen in Table 12.6.

The addition of fertilizer at drilling increased the yield of resident species by 25%, which in turn competed with the drilled species and reduced its yield at 12 weeks by 18%. Ryan *et al.* (1979) had earlier illustrated the relative superiority of blanket spraying by comparing blanket spraying, 50 mm band spraying and no spraying. They obtained 1413 kg/ha dry matter yield with blanket spraying, 930 kg/ha

Table 12.4. The cost–benefits of renovating dairy pasture by three different methods.

	Blanket spray	Band spray	No spray
Contract cost of renovation (US$/ha)	113	100	70
Extra pasture production (kg dry matter/ha, first year)	2049	1187	1146
Extra cows/ha able to utilize this pasture	0.43	0.26	0.24
Returns from extra cows (US$/ha)[a]	170	102	96
First-year return on investment (%)	150	98	137
Time to recover renovation costs (years)	0.7	1.0	0.7

[a]Assumes that 25 kg of extra pasture production in New Zealand results in 1 kg of extra milk fat, which sells for US$3.24/kg.

Table 12.5. Effects of spray band width on dry matter (DM) yield of overdrilled ryegrass 12 weeks after drilling (Barr, 1980).

Sprayed band width	DM yield of drilled species (kg/ha)	DM yield of resident species (kg/ha)
25 mm	130	1298
50 mm	143	1184
75 mm	196	776

Table 12.6. Effects of fertilizer application at drilling on overdrilled ryegrass plants 12 weeks after drilling (DM, dry matter).

	DM yield of drilled species (kg/ha)	DM yield of resident species (kg/ha)
With fertilizer	141	1207
Without fertilizer	172	966

with band spraying and 906 kg/ha using no spray at all.

It is recommended, therefore, that, with overdrilling where the resident species have not been totally killed, fertilizer application should be delayed until after emergence (or even after the first grazing) of the drilled species. This is the only no-tillage situation for which such a recommendation is made. If, for example, pasture is being established into an untilled seedbed in which all of the existing competition is dead, the recommendation would be to band fertilizer with the seed at drilling if the openers used are capable of separating the two in the drilled slot.

Although the parameters for optimum results with band spraying are now well defined as above, the practice represents another function from the drill, increasing the opportunity for error. Further, the total yield of the new pasture is seldom as high after 12 months as from blanket spraying (total kill), so the technique is not used as much as drilling into the weed-free environment offered by blanket spraying.

Band spraying represents a realistic option when total kill is not desirable; thus, the techniques and designs of equipment needed to undertake the technique are included. Situations where band spraying is appropriate include:

1. The rejuvenation of lucerne stands where the stand has become thin with age (as is typical) but the surviving plants are healthy and strong, favouring their retention along with newly introduced plants.
2. The temporary balance change of a pasture, e.g. where a legume pasture becomes semi-dormant over the winter months, the temporary injection of an annual ryegrass or winter forage cereal in autumn may increase winter production.

3. The repair of pest-, trampling- or drought-affected pastures where the surviving species are assumed to be resistant to the factors that killed many of the other plants in the pasture and are therefore considered to be a valuable resource worth retaining.
4. The introduction of a new species suited to the habitat created by a resident species, such as in the fertility build-up described earlier in this chapter.

Band spraying equipment

Early designs of band spraying devices centred on placing a spray nozzle ahead of the opener. The option of spraying behind the opener was quickly discarded for two reasons (Collins, 1970):

1. The herbage is often covered by soil after passage of the opener, which tends to deactivate paraquat or glyphosate herbicides.
2. Paraquat is phytotoxic to many seeds, which might be exposed in the slot before covering has had a chance to be completed.

For the nozzle to remain a constant distance above the ground, it has to either be mounted independently on its own height-gauging device (Fig. 12.8), or, if mounted directly on the opener, the latter has to have a positive height control of its own, which is necessary for adequate control of seeding depth anyway.

Even with adequate height control, there are other problems with spray nozzles. The application rates of water that the manufacturers of herbicides recommend be applied per sprayed area are difficult to achieve because the narrow bands mean water application becomes concentrated on to a very small area for each nozzle. This requires very fine nozzles, which require
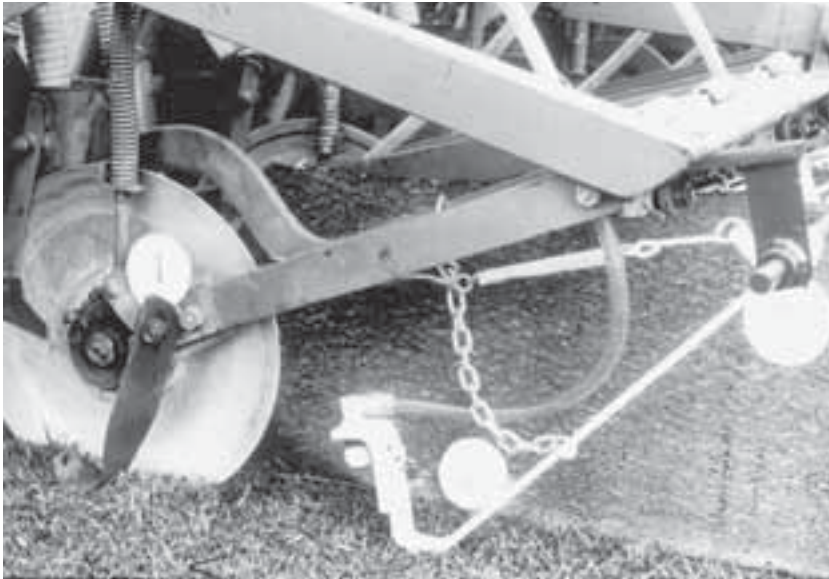
Fig. 12.8. A band spraying nozzle mounted on separate skids to control spraying height.

micro-filtration to avoid blockage by water impurities that would otherwise be acceptable to farm boom sprayers. Further, because these nozzles operate close to the soil (50–75 mm), they are subject to blockage from random soil splash and debris and damage through contact with stones, etc.

Hollow cone nozzles are most suited to single-nozzle band application, although fan-type nozzles have been used successfully, largely because the inherent variations across the band are acceptable when the objective is only to suppress rather than kill all of the target plants. Hollow cone nozzles generally have a more uniform pattern from a single nozzle than fan-type nozzles.

An innovative method of applying banded herbicides has been used with the disc version of winged openers. Because this opener is equipped with two semi-pneumatic rubber gauge/press wheel tyres, the herbicide can be dripped on to the top of the tyres at low pressure and rolled on to the ground in much the same way as a lawn marker (Ritchie, 1986a, b). This avoids problems of blockage, micro-filtration, wind drift, the presence of tall plants and physical damage, common with small nozzles, and introduces the feasibility of ground-metering

of the herbicide. Figure 12.9 shows a drip roller arrangement.

Ground metering involves using a positive displacement pump driven by the ground wheel of the drill in such a way that its output per metre of travel remains largely constant, regardless of travel speed or pressure. Such a system is impractical with pressurized nozzles because inevitable variations in ground speed cause variations in nozzle pressure, which in turn cause variations in band width because the width of the spray pattern from a nozzle is partly dependent on its operating pressure. With the drip roller system, the output pressure is very low and unimportant, since there is no pattern of spray to maintain and, even if there is, this is aimed at the top of the tyre, which then delivers the herbicide to the ground as a wet film on the bottom of the tyres, rather than directly as a jet.

In one respect, the rolling on of herbicide is a disadvantage because the tyres operate behind the opener and inevitably pick up soil, which quickly turns to mud on the wet tyres. Their use for this task is only possible with winged or double disc openers because of the minimal surface soil disturbance each of these openers creates.
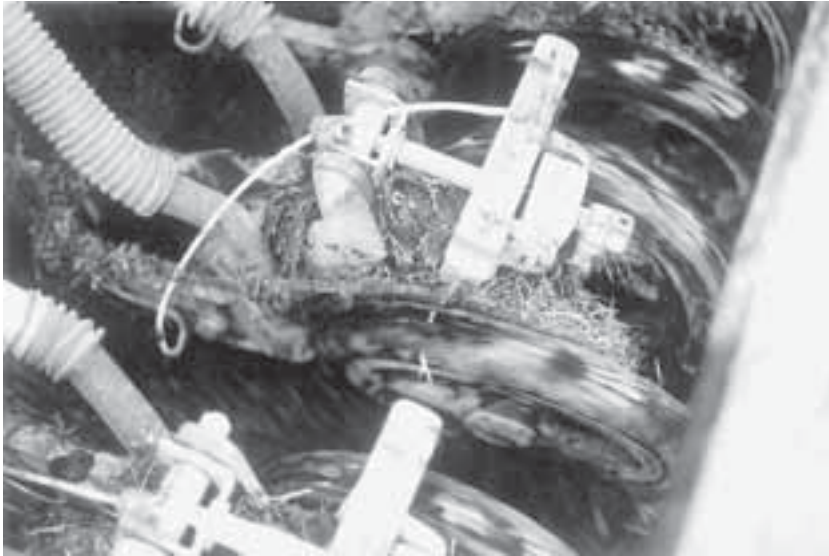
Fig. 12.9.   Herbicide being dripped on to the press/gauge wheels of a no-tillage opener.

Any soil contamination that does occur is countered by the improved efficacy of uptake of most herbicides from being rolled rather than sprayed on to the leaves. The result from many thousands of hectares of field-testing is that the 75 mm wide bands created by rolling on of herbicides works as well as spraying the same width of band and has a greater tolerance of the conditions under which it can be used.

Depth control and slot formation

Control over the drilling depth of pasture, sports turf and many forage crop species is particularly demanding. Most drills designed expressly for pasture renovation have been promoted on a low-cost basis. Because of this, the control mechanisms for depth of seeding are generally primitive and sometimes non-existent.

For example, the simple low-cost drills that dominate the pasture drill markets in Australia and New Zealand are almost all equipped with 'Baker Boot' versions of simple winged openers (inverted-T-shaped slot). While the choice of slot shape is appropriate, the ability of these openers to follow the surface is limited by the simplistic

drill designs to which they are attached, particularly the mechanisms for articulating each opener up and down. This causes the angles of the opener wings to change throughout their arcs of travel (see Chapter 4). To avoid complete loss of wing angle in hollows, the preset angle for level ground is about 10°. This relatively steep wing angle means that the shallowest this opener can drill and still maintain a true inverted-T-shaped slot without breaking through the covering surface mulch is about 25 mm.

In contrast, the more sophisticated disc version of winged openers is mounted on parallelogram drag arms, ensuring that the wing angle never changes. The preset wing angle is reduced to 5° to allow the wings to operate with integrity at depths as shallow as 15 mm. There is a major advantage, therefore, in being able to drill pasture with a machine equipped with similar technology demanded for the more highly valued arable crops.

While many drill designers consider pasture and sports turf to be the most difficult of media to drill, with winged openers the matted roots of pasture and turf plants provide a mulch medium of considerable elasticity and tensile strength, which can

be readily folded back and replaced while retaining the integrity of the inverted-T-shaped slots (Ritchie, 1988).

Seed metering

Most pasture and forage crop seeds are small, light and/or fluffy. Many pasture seeds also have awns attached. This presents several handling and metering problems.

First, they are difficult to meter accurately. Small-grain metering devices that commonly dispense several hundred kilograms of seed per hectare are often not well adapted to dispensing less than 1 kilogram of small seeds per hectare. Further, if the seeds have large awns or are fluffy, they will have a tendency to bridge above the metering device, interrupting the feed. This requires an agitator to be fitted to the drill to continuously avoid bridging. Often, drills for sowing small and/or difficult seeds use an auxiliary hopper designed especially for such seeds.

Many pasture species are sown as blends of two or more species. Common blends are clovers and grasses. Clover seeds are generally round and dense. Grass seeds are generally elongated and often fluffy and light. A previously mixed blend of such different seeds may partially separate into its individual components within the seed hopper of a drill in response to the continual vibration of the machine. To reduce separation and aid metering, the small seeds are often mixed with inert filling material such as sawdust or rice hulls to bulk up the material and reduce settling. Separation can be a problem with these mixes as well, especially if they are metered and dispensed by an air-delivery system. In these circumstances the high-speed airstream may blow some lighter, fluffier seeds out of the seed slot altogether before it has been covered.

Summary of No-tillage for Forage Production

1. Farming systems that depend on an intensive forage supply demand maximum and consistent feed supplies, which favour the use of successive forage crops in preference to more traditional 'permanent' pastures.

2. Establishment of successive forage crops is only sustainable on a long-term basis using no-tillage.

3. The integration of forage and arable cropping systems is desirable in climates that permit economic utilization of forage crops by animals.

4. Farmers generally place lower values on forage crops than on arable crops and will more readily accept inferior results.

5. Drills for pasture and many forage crops need to have more accurate depth control and sow at shallower depths than equivalent machines for arable crops.

6. Drills for pasture and forage crop species need to be able to meter small seeds.

7. Forage crops should generally be treated with the same care and attention as arable crops, but they seldom are.

8. Drills for pasture need to handle tightly root-bound soil and also utilize this covering medium to advantage.

9. With pasture renovation by over-drilling, there may be a trade-off between providing a suitable environment for germination and emergence and reducing competition from the existing sward.

10. Because the drilling time of forage crops and pastures is usually not as critical as with arable crops, there is more opportunity to wait for suitable weather to offset substandard openers.

11. On a cost-recovery basis, blanket spraying of the existing competition will give a greater long-term return than band spraying, which gives a greater return than no spraying.

12. Cross-drilling slowly establishing pasture species may produce greater short-term weed infestation than single-pass drilling.

13. Drilling early in the autumn is likely to produce more pasture production than later drillings, provided adequate soil moisture exists at the time.

14. Early autumn drilling and spring drilling are likely to produce more weed problems than later autumn drilling, especially with slowly establishing pasture species.

15. Single-pass drilling in 75 mm rows may produce a short-term yield advantage with slowly establishing pasture species compared with single-pass drilling in 150 mm rows.

16. Neither single-pass drilling in 75 mm rows nor cross-drilling in 150 mm rows has any long-term agronomic advantage compared with single-pass drilling in 150 mm rows, or any short-term advantage with rapidly establishing pasture species.

17. With band spraying for overdrilling, 75 mm wide bands are preferred with 150 mm spaced rows.

18. With overdrilling for pasture renovation, fertilizer should not be applied at the time of drilling but should instead be applied about 3 weeks post-emergence.

19. With complete pasture renewal, the new pasture should be drilled and fertilizer applied during drilling, similar to an arable or forage crop.