1 The ‘What’ and ‘Why’ of No-tillage Farming

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> No farming technique yet devised by humankind has been anywhere near as effective as no-tillage at halting soil erosion and making food production truly sustainable.

Since the early 1960s farmers have been urged to adopt some form of conservation tillage to save the planet’s soil, to reduce the amount of fossil fuels burnt in growing food, to reduce runoff pollution of our waterways, to reduce wind erosion and air quality degradation and a host of other noble and genuine causes. Charles Little in *Green Fields Forever* (1987) epitomized the genuine enthusiasm most conservationists have for the technique. But early farmer experience, especially with no-tillage, suggested that adopting such techniques would result in greater short-term risk of reduced seedling emergence, crop yield or, worse, crop failure, which they were being asked to accept for the long-term gains outlined above.

Farmers of today were unlikely to see many short-term benefits of their conservation practices. Leaving a legacy of better land for future generations was one thing, but the short-term reality of feeding the present generation and making a living was quite another. Not unreasonably, short-term expediency often took priority. Although some countries already produce 50% or more of their food by no-tillage (e.g. Brazil, Argentina and Paraguay), it is estimated that, worldwide, no-tillage currently accounts for only some 5–10% of food production. We still have a long way to go. Certainly there have been good, and even excellent, no-tillage crops, but there have also been failures. And it is the failures that take prime position in the minds of all but the most forward-looking or innovative farmers.

Tillage has been fundamental to crop production for centuries to clear and soften seedbeds and control weeds. So now we are changing history, not always totally omitting tillage (although that is certainly a laudable objective) but significantly altering the reasons and processes involved. Most people understand tillage to be a process of physically manipulating the soil to achieve weed control, fineness of tilth, smoothness, aeration, artificial porosity, friability and optimum moisture content so as to facilitate the subsequent sowing and covering of the seed. In the process, the undisturbed soil is cut, accelerated, impacted, inverted, squeezed, burst and thrown, in an effort to break the soil physically and bury weeds, expose their roots to drying or to physically destroy them by cutting. The objective of tillage is to create a weed-free, smooth, friable soil material through which

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relatively unsophisticated seed drill openers can travel freely.

During no-tillage, few, if any, of the processes listed above take place. Under no-tillage, other weed-control measures, e.g. chemicals, must substitute for the physical disturbance during tillage to dislodge, bury or expose existing weeds. But part of the tillage objective is also to stimulate new weed seed germination so that fresh weeds get an 'even start' and can therefore be easily killed in their juvenile stages by a single subsequent tillage operation. No-tillage, therefore, must either find another way of stimulating an 'even start' for new weeds, which would then require a subsequent application of herbicide or avoid stimulating new weed growth in the first place.

In his keynote address to the 1994 World Congress of Soil Science, Nobel Prize-winner Norman Borlaug estimated that world cereal production (which accounts for 69% of world food supply) would need to be raised by 24% by the year 2000 and doubled by the year 2025. More importantly, Borlaug estimated that grain yields would need to increase by 80% over the same time span because creating new arable land is severely limited throughout the world. Until now, yield increases have come largely from increased fertilizer and pesticide use and genetic improvement to the species grown. The challenge is for no-tillage to contribute to future increases, while simultaneously achieving resource preservation and environmental goals. But this is only going to happen if no-tillage is practised at advanced technology levels.

The notion of sowing seeds into untilled soils is very old. The ancient Egyptians practised it by creating a hole in untilled soil with a stick, dropping seeds into the hole and then closing it again by pressing the sides together with their feet. But it was not until the 1960s, when the herbicides paraquat and diquat were released by the then Imperial Chemical Industries Ltd (now Syngenta) in England, that the modern concept of no-tillage was born because now weeds could be effectively controlled without tillage.

For the preceding decade it had been recognized that, for no-tillage to be viable, weeds had to be controlled by some other method than tillage. But the range of agricultural chemicals then available was limited because of their residual effects in the soil. A delay of several weeks was necessary after spraying before the new crop could be safely sown, which partly negated saving of time, one of the more noteworthy advantages of no-tillage compared with tillage. Paraquat and diquat are almost instantly deactivated upon contact with soil. When sprayed onto susceptible living weeds, the soil beneath is almost instantly ready to accept new seeds, without the risk of injury.

This breakthrough in chemical weed control spawned the birth of true no-tillage. Since then, there have been other broader-spectrum translocated non-residual chemicals, such as glyphosate, which was first introduced as Roundup by Monsanto. Other generic compounds, such as glyphosate trimesium (Touchdown) and glufosinate ammonium (Buster), were later marketed by other companies, which have expanded the concept even further.

In other circumstances non-chemical weed control measures have been used. These include flame weeding, steam weeding, knife rolling and mechanical hand weeding. None of the alternative measures has yet proved as effective as spraying with a translocated non-residual herbicide. These chemicals are translocated to the roots of the plant thereby affecting a total kill of the plant. Killing the aerial parts alone often allows regeneration of non-affected plant parts.

The application of any chemicals within agricultural food production correctly raises the question of human and biological safety. Indeed, many chemicals must be very carefully applied under very specific conditions for specific results, just like any of the modern pharmaceuticals that assist in cures and controls. Through careful science, and perhaps some good fortune, glyphosate has been found to be non-toxic to any biological species other than green plants and has been safely used for many years with virtually no known effects other than the control of undesired plants.

An even more recent development using genetic modification of the crops themselves has made selected plant varieties immune to very specific herbicides such as glyphosate. This unique trait permits planting the crop without weed concerns until the crop is well established and then spraying both the crop and the weeds with a single pass. The susceptible weeds are eliminated and the immune crop thrives, making a full canopy that competes with any subsequent weed growth, usually through to harvest. Only selected crops such as maize and soybean are currently commonly used in this fashion, but they have already attained a very significant percentage of the world's acreage. With this success, other important food and fibre crops are being modified for this capability.

What is No-tillage?

As soon as the modern concept of no-tillage based on non-residual (and mostly translocated) herbicides was recognized, everyone, it seems, invented a new name to describe the process. 'No-tillage', 'direct drilling' or 'direct seeding' are all terms describing the sowing of seeds into soil that has not been previously tilled in any way to form a 'seedbed'. 'Direct drilling' was the first term used, mainly in England, where the modern concept of the technique originated in the 1960s. The term 'no-tillage' began in North America soon after, but there has been recent support for the term 'direct seeding' because of the apparent ambiguity that a negative word like 'no' causes when it is used to describe a positive process. The terms are used synonymously in most parts of the world, as we do in this book.

Some of these names are listed below with their rationales, some only for historical interest. After all, it's the process, not the name, that's important.

Chemical fallow, or *chem-fallow*, describes a field currently not cropped in which the weeds have been suppressed by chemical means.

Chemical ploughing attempted to indicate that the weed control function usually attributed to ploughing was being done by chemicals. The anti-chemical lobby soon de-popularized such a restrictive name, which is little used today.

Conservation tillage and *conservation agriculture* are the collective umbrella terms commonly given to no-tillage, minimum tillage and/or ridge tillage, to denote that the inclusive practices have a conservation goal of some nature. Usually, the retention of at least 30% ground cover by residues after seeding characterizes the lower limit of classification for conservation tillage or conservation agriculture, but other conservation objectives include conservation of money, labour, time, fuel, earthworms, soil water, soil structure and nutrients. Thus, residue levels alone do not adequately describe all conservation tillage or conservation agricultural practices and benefits.

Disc-drilling reflects the early perception that no-tillage or direct drilling could only be achieved with disc drills (a perception that proved to be erroneous); thus some started referring to the practice as disc-drilling. Fortunately the term has not persisted. Besides, disc drills are also used in tilled soils.

Drillage was a play on words that suggested that under no-tillage the seed drill was in fact tilling the soil and drilling the seed at the same time. It is not commonly used.

Minimum tillage, *min-till* and *reduced tillage* all describe the practice of restricting the amount of general tillage of the soil to the minimum possible to establish a new crop and/or effect weed control or fertilization. The practice lies somewhere between no-tillage and conventional tillage. Modern practice emphasizes the amount of surface residue retention as an important aim of minimum or reduced tillage.

No-till is a shortening of no-tillage and is not encouraged by purists, for grammatical reasons.

Residue farming describes conservation tillage practices in which residue retention is the primary objective, even though many of the 'conservation tillage' benefits previously mentioned may also accrue.

Ridge tillage, or *ridge-till*, describes the practice of forming ridges from tilled soil into which widely spaced row crops are drilled. Such ridges may remain in place for several seasons while successive crops are no-tilled into the ridges, or they might be re-formed annually.

Sod-seeding, *undersowing*, *oversowing*, *overdrilling* and *underdrilling* all refer to the specific no-tillage practice of drilling new pasture seeds into existing pasture swards, collectively referred to as pasture renovation. The correct use of the term oversowing does not involve drilling at all, but rather is the broadcasting of seed on to the surface of the ground. Each of the other listed terms involves drilling of the seed.

Stale seedbed describes an untilled seedbed that has undergone a period of fallow, usually (but not exclusively) with periodic chemical weed control.

Strip tillage, or *zone tillage*, refers to the practice of tilling a narrow strip ahead of (or with) the drill openers, so the seed is sown into a strip of tilled soil but the soil between the sown rows remains undisturbed. 'Strip tillage' also refers to the general tilling of much wider strips of land (100 or more metres wide) on the contour, separated by wide fallowed strips, as an erosion-control measure based on tillage.

Sustainable farming is the end product of applying no-tillage practices continuously. Continuous cropping based on tillage is now considered to be unsustainable because of resource degradation and farming inefficiencies, while continuous cropping based on no-tillage is much more likely to be sustainable on a long-term basis under most agricultural conditions. Some discussions of 'sustainability' include broader considerations beyond the preservation of natural resources and food production, such as economics, energy and quality of life.

Zero-tillage was synonymous with no-tillage and is still used to a limited extent today.

The most commonly identified feature of no-tillage is that as much as possible of the surface residue from the previous crop is left intact on the surface of the ground, whether this be the flattened or standing stubble of an arable crop that has been harvested or a sprayed dense sward of grass. In the USA, where the broad category of conservation tillage is generally practised as an erosion-control measure, the accepted minimum amount of surface covered by residue after passage of the drill is 30%. Most practitioners of the more demanding option of no-tillage or direct seeding aim for residue-coverage levels of at least 70%.

Of course, some crops, such as cotton, soybean and lupin, leave so little residue after harvest that less than 70% of the ground is likely to be covered by residue even before drilling. Such a soil, however, can be equally well direct drilled as a fully residue-covered soil in the course of establishing the next crop. Thus it is also regarded as true no-tillage. What is no-tillage to one observer may not be no-tillage to another, depending upon the terms of reference and expectations of each observer.

The most fundamental criterion common to all no-tillage is not the amount of residue remaining on the soil after drilling, but whether or not that soil has been disturbed in any way prior to drilling. Even then, during drilling, as will be explained later, such a seemingly unambiguous definition becomes confused when you consider the actions of different drills and openers in the soil. Some literally till a strip as they go, while others leave all of the soil almost undisturbed. So the untilled soil prior to drilling might well become something quite different after drilling.

This book is focused on the subject of 'no-tillage' in which no prior disturbance or manipulation of the soil has occurred other than possibly minimal disturbance by operations such as shallow weed control, fertilization or loosening of subsurface compacted layers. Such objectives are entirely compatible with true no-tillage. Any disturbance before seeding is expected to have had very minimal surface disturbance of soil or residues.

Depending on the field cropping history and the available seeding machine capability, it may be necessary to perform one or more very minimal-disturbance functions for best crop performance. The most common of these needs is the application of fertilizer when that function can not be made part of the seeding operation. Early no-tillage seeding trials often simply broadcast the fertilizer over the soil surface expecting it to be carried into the soil profile by precipitation, but two things became readily apparent. First, only the nitrogen component was moved by water, leaving the remaining forms, such as phosphorus and potassium, on or near the soil surface. And even then preferential flow of soluble nitrogen down earthworm and old root channels often meant that much of it bypassed the juvenile roots of the newly sown crop (see Chapter 9).

Secondly, emerging weeds between the crop plants readily helped themselves as the first consumers of this fertilizer and 'outgrew' the crop. Subsurface placement is now the only recommended procedure, often banded near the seeding furrow or emerging crop row.

Where herbicides are less available, it may prove more economical to perform a weeding pass prior to seeding to reduce the weed pressures on the emerging crop. If used in conservation agriculture, this operation must be very shallow and leave the soil surface and residues nearly intact ready for the seeding operation. Typical implements that can achieve this quality of weed control are shallow-running V-shaped chisels or careful hand hoeing.

Historical compaction arising from many years of repetitive tillage often cannot be undone 'overnight' by switching to no-tillage. While soil microbes are rebuilding their numbers and improving soil structure, a process that may take several years even in the most favourable of climates, historical compaction may still exist. Temporary relief can often be achieved by using a subsoiling machine that cracks and bursts subsurface zones while causing only minor disturbance at the surface.

But sometimes overly aggressive subsoilers cause so much surface disturbance that full tillage is then required to smooth the surface again. This seemingly endless negative spiral must be broken if the benefits of no-tillage are to be gained. All that is required is a less aggressive or shallow-acting subsoiler that allows no-tillage to take place after its passage without any further 'working' of the soil surface layer.

Another effective method is to sow a grass or pasture species in the compacted field and either graze this with light stocking or leave it ungrazed as a 'set-aside' area for a number of years before embarking on a no-tillage programme thereafter without tillage. A rule of thumb for how many years of pasture are required to restore soil organic carbon (SOC) and ultimately the structural damage done by tillage was established by Shepherd *et al.* (2006) for a gley soil (Kairanga silty clay loam) under maize in New Zealand soils as:

> Where tillage has been undertaken for up to 4 consecutive years, it takes approximately 1½ years of pasture to restore SOC levels for each year of tillage.
>
> Where tillage has been undertaken for more than 4 consecutive years, it takes up to 3 years of pasture to restore SOC levels for each year of tillage.

The rate of recovery of soil structure lags behind the recovery rate of SOC. The more degraded the soil, the greater the lag time.

Why No-tillage?

It is not the purpose of this book to explore in detail the advantages and disadvantages of either no-tillage or conservation tillage. Numerous authors have undertaken this task since Edward Faulkner and Alsiter Bevin questioned the wisdom of ploughing in *Ploughman's Folly* (Faulkner, 1943) and *The Awakening* (Bevin, 1944). Although neither of these authors actually advocated no-tillage, it is interesting to note that Faulkner made the now prophetic observation that 'no one has ever advanced a scientific reason for ploughing'. In fact, long before Faulkner's and Bevin's time, the ancient Peruvians, Scots, North American Indians and Pacific Polynesians are all reported to have practised a form of conservation tillage (Graves, 1994).

None the less, to realistically focus on the methods and mechanization of no-tillage technologies, it is useful to compare the advantages and disadvantages of the technique in general as measured against commonly practised tillage farming. The more common of these are summarized below with no particular order or priority. Those followed by an * can be either an advantage or a disadvantage in differing circumstances.

In Chapter 2 we shall expand on the advantages (benefits) of no-tillage, particularly those derived either directly or indirectly from enhancement of SOC levels, and in Chapter 3 we shall examine the risks of no-tillage in more detail.

Advantages

Fuel conservation. Up to 80% of fuel used to establish a crop is conserved by converting from tillage to no-tillage.

Time conservation. The one to three trips over a field with no-tillage (spraying, drilling and perhaps subsoiling) results in a huge saving in time to establish a crop compared with the five to ten trips for tillage plus fallow periods during the tillage process.

Labour conservation. Up to 60% fewer person-hours are used per hectare compared with tillage.

Time flexibility. No-tillage allows late decisions to be made about growing crops in a given field and/or season.

Increased soil organic matter. By leaving the previous crop residues on the soil surface to decay, soil organic matter near the surface is increased, which in turn provides food for the soil microbes that are the builders of soil structure. Tillage oxidizes organic matter, resulting in a cumulative reduction, often more than is gained from incorporation.

Increased soil nitrogen. All tillage mineralizes soil nitrogen, which may provide a short-term boost to plant growth, but such nitrogen is 'mined' from the soil organic matter, further reducing total soil organic matter levels.

Preservation of soil structure. All tillage destroys natural soil structure while no-tillage minimizes structural breakdown and increases organic matter and humus to begin the rebuilding process.

Preservation of earthworms and other soil fauna. As with soil structure, tillage destroys humans' most valuable soil-borne ally, earthworms, while no-tillage encourages their multiplication.

Improved aeration. Contrary to early predictions, the improvement in earthworm numbers, organic matter and soil structure usually result in improved soil aeration and porosity over time. Soils do not become progressively harder and more compact. Quite the reverse occurs, usually after 2–4 years of no-tillage.

Improved infiltration. The same factors that aerate the soil result in improved infiltration into the soil. Plus residues reduce surface sealing by raindrop impact and slow down the velocity of runoff water.

Preventing soil erosion. The sum of preserving soil structure, earthworms and organic matter, together with leaving the surface residues to protect the soil surface and increase infiltration, is to reduce wind and water soil erosion more than any other crop-production technique yet devised by humans.

Soil moisture conservation. Every physical disturbance of the soil exposes it to drying, whereas no-tillage and surface residues greatly reduce drying. In addition, accumulation of soil organic matter greatly improves the water-holding capacity of soils.

Reduced irrigation requirements. Improved water-holding capacity and reduced evaporation from soils lessen the need for irrigation, especially at early stages of growth when irrigation efficiency is at its lowest.

*Moderating soil temperatures.** Under no-tillage soil temperatures in summer stay lower than under tillage. Winter temperatures are higher where snow retention by residue is a factor, but spring temperatures may rise more slowly.

Reduced germination of weeds. The absence of physical soil disturbance under no-tillage reduces stimulation of new weed seed germination, but the in-row effect of this factor is highly dependent on the amount of disturbance caused by the no-tillage openers themselves.

Improved internal drainage. Improved structure, organic matter, aeration and earthworm activity increase natural drainage within most soils.

Reduced pollution of waterways. The decreased runoff of water from soil and the chemicals it transports reduces pollution of streams and rivers.

Improved trafficability. Untilled soils are capable of withstanding vehicle and animal traffic with less compaction and structural damage than tilled soils.

Lower costs. The total capital and/or operating costs of all machinery required to establish tillage crops are reduced by up to 50% when no-tillage substitutes for tillage.

*Longer replacement intervals for machinery.** Because of reduced hours per hectare per year, tractors and advanced no-tillage drills are replaced less often and reduce capital costs over time. Some lighter no-tillage drills, however, may wear out more quickly than their tillage counterparts because of the greater stresses involved in operating them in untilled soils.

*Reduced skills level.** While achieving successful no-tillage is a skilful task in itself, the total range of skills required is smaller than the many sequential tasks needed to complete successful tillage.

Natural mixing of soil potassium and phosphorus. Earthworms mix large quantities of soil potassium and phosphorus in the root zone, which favours no-tillage because it sustains earthworm numbers and increases plant nutrient availability.

Less damage of new pastures. The more stable soil structure of untilled soils allows quicker utilization of new pastures by stock with less plant disruption during early grazing than where tillage has been employed.

More recreation and management time. The time otherwise devoted to tillage can be used to advantage for further management inputs (including the farming of more land) or for family and recreation.

Increased crop yields. All of the above factors are capable of improving crop yields to levels well above those attained by tillage – but only if the no-tillage system and processes are fully practised without short cuts or deficiencies.

Future improvements expected. Modern advanced no-tillage systems and equipment have removed earlier expectations of depressed crop yields in the short term to gain the longer-term benefits of no-tillage. Ongoing research and experience have developed systems that eliminate short-term depressed yields while at the same time raising the expectation and magnitudes of yield increases in the medium to longer term.

Disadvantages

*Risk of crop failure.** Where inappropriate no-tillage tools and weed- or pest-control measures are used, there will be a greater risk of crop yield reductions or failure than for tillage. But where more sophisticated no-tillage tools and correct weed- and pest-control measures are used, the risks will be less than for tillage.

*Larger tractors required.** Although the total energy input is significantly reduced by changing to no-tillage, most of that input is applied in one single operation, drilling, which may require a larger tractor or more animal power, or conversely a narrower drill.

New machinery required. Because no-tillage is a relatively new technique, new and different equipment has to be purchased, leased or hired.

*New pest and disease problems.** The absence of physical disturbance and retention of surface residues encourages some pests and diseases and changes the habitats of others. But such conditions also encourage their predators. To date, no pest or disease problems have proved to be insurmountable or untreatable in long-term no-tillage systems.

Fields are not smoothed. The absence of physical disturbance prevents soil movement by machines for smoothing and levelling purposes. This puts pressure on no-tillage drill designers to create machines that can cope with uneven soil surfaces. Some do this better than others.

Soil strength may vary across fields. Tillage serves to create a consistently low soil strength across each field. Long-term no-tillage requires machines to be capable of adjusting to natural variations in soil strength that occur across every field. Since soil strength dictates the penetration forces required to be applied to each no-tillage opener, variable soil strength places particular demands on drill designs if consistent seeding depths and seed coverage are to be attained.

*Fertilizers are more difficult to incorporate.** General incorporation of fertilizers is more difficult in the absence of physical burial by machines, but specific incorporation at the time of drilling is possible and desirable, using special designs of no-tillage openers.

Pesticides are more difficult to incorporate. As with fertilizers, general incorporation of pesticides (especially those that require pre-plant soil incorporation) is not readily possible with no-tillage, requiring different pest-control strategies and formulations.

*Altered root systems.** The root systems of no-tillage crops may occupy smaller volumes of soil than under tillage, but the total biomass and function of the roots are seldom different and anchorage may in fact be improved.

*Altered availability of nitrogen.** There are three factors that affect nitrogen availability during early plant development under no-tillage:

The decomposition of organic matter by soil microbes often temporarily 'locks up' nitrogen, making it less plant-available under no-tillage.

No-tillage reduces mineralization of soil organic nitrogen that tillage otherwise releases.

The development of bio-channels in the soil from earthworms and roots causes preferential flow of surface-applied nitrogenous fertilizers into the soil, which may bypass shallow, young crop roots.

Each (or all) of these factors may create a nitrogen deficiency for seedlings, which encourages placing nitrogen with drilling. Fortunately some advanced no-tillage drills have separate nitrogen banding capabilities that overcome this problem.

*Use of agricultural chemicals.** The reliance of no-tillage on herbicides for weed control is a cost and environmental negative but is offset by the reduction in surface runoff of other chemical pollutants (including surface-applied fertilizers) and the fact that most of the primary chemicals used in no-tillage are 'environmentally friendly'. Small-scale agriculture may require more hand weeding, but with greater ease than with tilled soils.

*Shift in dominant weed species.** Chemical weed control tends to be selective towards weeds that are resistant to the range of available formulations, requiring more diligent use of crop rotations by farmers and commitment by the agricultural chemical industry to researching new formulations.

*Restricted distribution of soil phosphorus.** Relatively immobile soil phosphorus tends to become distributed in a narrower band within the upper soil layers under no-tillage because of the absence of physical mixing. Improved earthworm populations help reduce this effect and also cycle nutrient sources situated below normal tillage levels.

*New skills are required.** No-tillage is a more exacting farming method, requiring the learning and implementation of new skills, and these are not always compatible with existing tillage-related skills or attitudes.

Increased management and machine performance. There is only one opportunity with each crop to 'get it right' under a no-tillage regime. Because no-tillage drilling is literally a once-over operation, there is less room for error compared with the sequential operations involved in tillage. This places emphasis on the tolerance of no-tillage drills to varying operator skill levels and their ability to function effectively in suboptimal conditions.

*No-tillage drill selection is critical.** Few farmers can afford to own several different no-tillage drills awaiting the most suitable conditions before selecting which one to use. Fortunately more advanced no-tillage drills are capable of functioning consistently in a wider range of conditions than most tillage tools, making reliance on a single no-tillage drill for widely varying conditions both feasible and a practical reality.

Availability of expertise. Until the many specific requirements of successful no-tillage are fully understood by 'experts', the quality of advice to practitioners from consultants will remain, at best, variable. Local, successful no-tillage farmers often become the best advisers.

*Untidy field appearance.** Farmers who have become used to the appearance of neat, 'clean', tilled seedbeds often find the retention of surface residues ('trash') 'untidy'. But, as they come to appreciate the economic advantages of true no-tillage, many such farmers gradually come to see residues as an important resource rather than 'trash' requiring disposal.

*Elimination of 'recreational tillage'.** Some farmers find driving big tractors and tilling on a large scale to be recreational. Others regard it as a chore and health-damaging. Farmers in developing countries regard tillage as burdensome or impossible.

Figure 1.1 shows some of the likely short- and long-term trends that might arise as a result of converting from tillage to no-tillage.

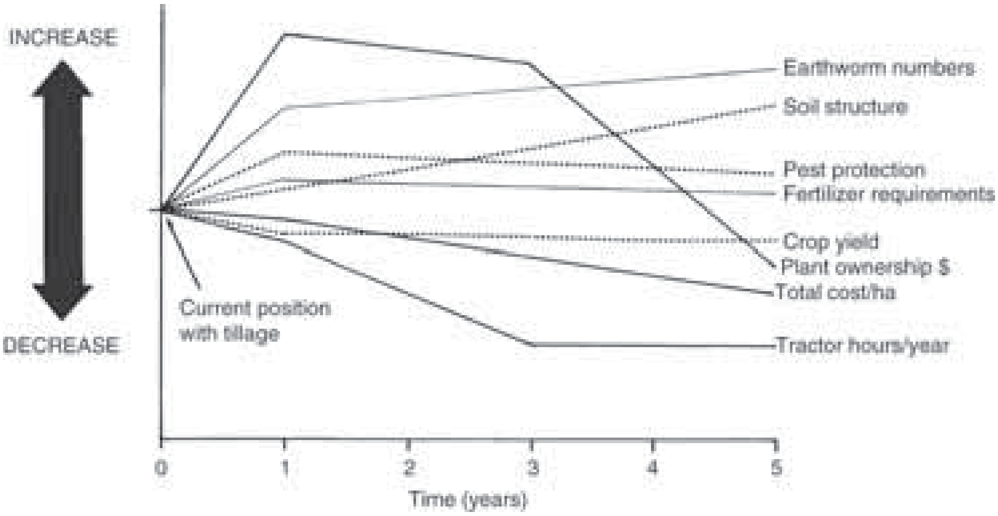

Fig. 1.1. The likely short- and long-term trends that might arise as a result of converting from tillage to no-tillage (from Carter, 1994).

Each identified item or process progresses over the years from stopping tillage as the effects of no-tillage take precedent. The realization is that the effects of no-tillage are developed as the soil and its physical and biological characteristics change. The result of these combined processes has been observed and documented in nearly every soil and climate worldwide, to the point of becoming common knowledge. It is in this transition stage that many who convert to no-tillage farming become disillusioned and sceptical that the benefits will in fact occur.

Summary of the 'What' and 'Why' of No-tillage

No-tillage farming is a significant methodology shift in production farming as performed over the past 100 years of mechanized agriculture. It intuitively requires new thinking by the producers of the 'what' and 'why' to change the processes. Only by encompassing the full scope of 'why' we should change from an enormously successful food production system shall we move forward with confidence to develop 'what' a modern no-tillage farming system should incorporate. The short-term advantages far outweigh the disadvantages, and in the longer term it involves no less than making world food production sustainable for the first time in history.

2 The Benefits of No-tillage

Don C. Reicosky and Keith E. Saxton

Intensive tillage farming reduces soil organic matter and degrades soil quality – no-tillage farming enhances soil quality and sustains long-term agriculture.

Introduction

Sustainable food and fibre production of any given field and region requires that the farming methods be economically competitive and environmentally friendly. To achieve this result requires adopting a farming technology that not only benefits production but provides an environmental benefit to the long-term maintenance of the soil and water resources upon which it is based. We must reduce pollution and use our resources in line with the earth's carrying capacity for sustainable production of food and fibre.

The responsibility of sustainable agriculture lies on the shoulders of farmers to maintain a delicate balance between the economic implications of farming practices and the environmental consequences of using the wrong practices. This responsibility entails producing food and fibre to meet the increasing population while maintaining the environment for a sustained high quality of life. The social value of an agricultural community is not just in production, but in producing in harmony with nature for improved soil, water and air quality and biological diversity.

Sustainable agriculture is a broad concept that requires interpretation at the regional and local level. The principles are captured in the definition reported by El-Swaify (1999) as: 'Sustainable agriculture involves the successful management of resources for agriculture to satisfy changing human needs, while maintaining or enhancing the quality of the environment and conserving natural resources.'

Conservation agriculture, especially no-tillage (direct seeding), has been proved to provide sustainable farming in many agricultural environments virtually around the world. The conditions and farming scales vary from humid to arid and vegetable plots to large prairie enterprises. All employ and adapt very similar principles but with a wide variety of machines, methods and economics.

The benefits of performing crop production with a no-tillage farming system are manyfold. Broad subjects discussed here only begin to provide the science and results learned over recent decades of exploring and developing this farming method. In addition to improved production and soil and water resource protection, many other benefits accrue. For example, it saves time and money, improves timing of planting

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and harvesting, increases the potential for double cropping, conserves soil water through decreased evaporation and increased infiltration, reduces fuel, labour and machinery requirements and enhances the global environment.

Principles of Conservation Agriculture

Conservation agriculture requires implementing three principles, or pillars, as illustrated in Fig. 2.1. These are: (i) minimum soil tillage disturbance; (ii) diverse crop rotations and cover crops; and (iii) continuous plant residue cover. The main direct benefit of conservation agriculture and direct seeding is increased soil organic matter and its impact on the many processes that determine soil quality. The foundation underlying the three principles is their contribution and interactions with soil carbon, the primary determinant of long-term sustainable soil quality and crop production.

Conservation tillage includes the concepts of no-tillage, zero-tillage and direct seeding as the ultimate form of conservation agriculture. These terms are often used interchangeably to denote minimum soil disturbance. Reduced tillage methods, sometimes referred to as conservation tillage, such as strip tillage, ridge tillage and mulch tillage, disturb a small volume of soil and partially mix the residue with the soil and are intermediate in their soil quality effects. These terms define the tillage equipment and operation characteristics as they relate to the soil volume disturbed and the degree of soil–residue mixing. Intensive inversion tillage, such as that from mouldboard-ploughing, disc-harrowing and certain types of powered rotary tillage, is not a form of conservation tillage. No-tillage and direct seeding are the primary methods of conservation tillage to apply the three pillars of conservation agriculture for enhanced soil carbon and its associated environmental benefits.

True soil conservation is largely related to organic matter, i.e. carbon, management.

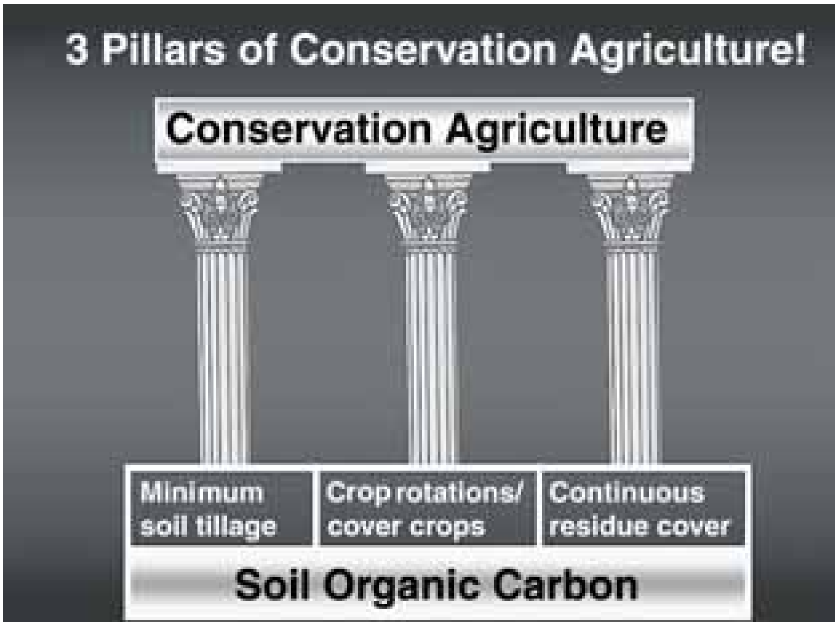


Fig. 2.1. Schematic representation of the three pillars or principles of conservation agriculture supported by a foundation of soil carbon.

By nothing more than properly managing the carbon in our agricultural ecosystems, we can have less erosion, less pollution, clean water, fresh air, healthy soil, natural fertility, higher productivity, carbon credits, beautiful landscapes and sustainability. Dynamic soil quality encompasses those properties that can change over relatively short time periods, such as soil organic matter, soil structure and macroporosity. These can readily be influenced by the actions of human use and management within the chosen agronomic practices. Soil organic matter is particularly dynamic, with inputs of plant materials and losses by decomposition.

Crop Production Benefits

Producing a crop and making an economic profit are universal goals of global farming. Production by applying no-tillage methods is no different in these goals, but there are definite benefits for the achievement, which we outline in this chapter. But these benefits only occur with fully successful no-tillage farming. There are certainly obstacles and risks in moving from traditional tillage farming, which has been the foundation technology for centuries, as outlined in Chapter 3.

Acceptable crop production requires an adequate plant stand, good nutrition and moisture with proper protection from weed, insect or disease competition. Achieving the plant stand in untilled, residue-covered soils is the first major obstacle, a particular challenge in modern mechanized agriculture, but certainly surmountable, as explained in the core of this text. Providing adequate nutrition and water for full crop potentials is readily achieved with the benefits of no-tillage, as discussed below.

Weed-control methods, by necessity, shift to dependence on chemicals, flame-weeding, mechanical crushing or hand picking for full no-tillage farming to stay within the goal of minimum soil disturbance. Chemical developments in recent decades have made great strides in their effectiveness, environmental friendliness and economic feasibility. Supplemental techniques of mowing, rolling and crushing without soil disturbance are showing significant promise to reduce weed presence and increase the benefit of cover crops and residues. Experience has shown that controlling insects and diseases has generally been less of a problem with no-tillage, even though there are often dire predictions about the potential impact of surface residues harbouring undesirables. As with weeds, crop health and pest problems are not likely to be avoided but may well shift to new varieties and species with the change in the field environment.

As a result of these developments and skilled applications, it has been repeatedly shown that crop production can be equalled and exceeded by no-tillage farming compared with traditional tillage methods. Because many soils have been tilled for many years, it is not uncommon to experience some yield reduction in the first few no-tillage years, largely because, as discussed later, it takes time for the soil to rebuild into a higher quality. This ‘transition period reduction’ can often be overcome or even averted with increased fertility, strategic fertilizer banding with drill openers and careful crop selection.

The full benefit of no-tillage comes in the reduced inputs. Most notable are the reduced inputs by minimizing labour and machine hours spent establishing and maintaining the crop. Reduced machine costs alone are significant, since all tillage equipment is dispensable. True no-tillage farming requires only an effective chemical sprayer, seeding–fertilizing drill and harvester.

With no seedbed preparation of the soil by tillage, seed drilling has become the major limitation to many efforts to successfully change to no-tillage farming. Modifying drills used in tillage farming has generally not been very successful, resulting in undesirable crop stands for optimum production. Many were not equipped to provide simultaneous fertilizer banding; thus it had to be provided by a supplemental minimum-tillage machine or, in the worst case, surface-applied, where it was very ineffective and stimulated weed growth.

Fortunately, drill development has progressed to now provide acceptable seeding in many cases, but, as described in later chapters, many still do not fully meet all desirable attributes, especially in relation to the amount of soil disturbance they create.

As a result of science and technique developments of recent years, no-tillage crop production now not only is feasible but has significant economic benefits. Combining and multiplying this result by the further benefits of soil and environmental qualities make no-tillage farming a highly desirable method of crop production. Further, many are now finding personal and social benefits from the reduced labour inputs, which remove much of the demanded time and drudgery often associated with traditional farm life. A common remark by successful no-tillage farmers is 'It has brought back the fun of farming.'

Increased organic matter

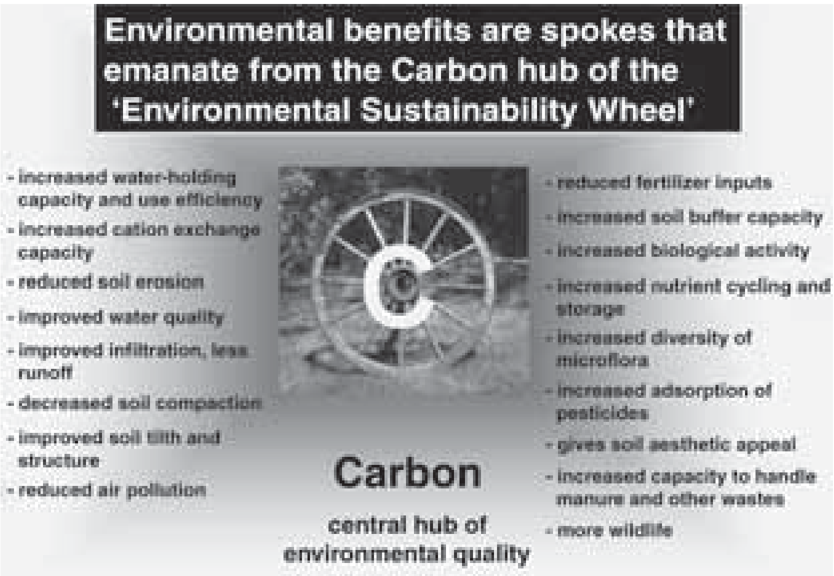
Understanding the role of soil organic matter and biodiversity in agricultural ecosystems has highlighted the value and importance of a range of processes that maintain and fulfil human needs. Soil organic matter is so valuable for its influence on soil organisms and properties that it can be referred to as 'black gold' because of its vital role in physical, chemical and biological properties and processes within the soil system.

The changes of these basic soil properties, called 'ecosystem services', are the processes by which the environment produces resources that sustain life and which we often take for granted. An ecosystem is a community of animals and plants interacting with one another within their physical environment. Ecosystems include physical, chemical and biological components such as soils, water and nutrients that support the biological organisms living within them, including people. Agricultural ecosystem services include production of food, fibre and biological fuels, provision of clean air and water, natural fertilization, nutrient cycling in soils and many other fundamental life support services. These services may be enhanced by increasing the amount of carbon stored in soils.

Conservation agriculture through its impact on soil carbon is the best way to enhance ecosystem services. Recent analyses have estimated national and global economic benefits from ecosystem services of soil formation, nitrogen fixation, organic matter decomposition, pest biocontrol, pollination and many others. Intensive agricultural management practices cause damage or loss of ecosystem services, by changing such processes as nutrient cycling, productivity and species diversity (Smith *et al.*, 2000). Soil carbon plays a critical role in the harmony of our ecosystems providing these services.

Soil carbon is a principal factor in maintaining a balance between economic and environmental factors. Its importance can be represented by the central hub of a wagon wheel, a symbol of strength, unity and progress (Reicosky, 2001a). The 'spokes' of this wheel in Fig. 2.2 represent incremental links to soil carbon that lead to the environmental improvement that supports total soil resource sustainability. Many spokes make a strong wheel. Each of the secondary benefits that emanate from soil carbon contributes to environmental enhancement through improved soil carbon management. Soane (1990) discussed several practical aspects of soil carbon important in soil management. Some of the 'spokes' of the environmental sustainability wheel are described in the following paragraphs.

Based on soil carbon losses with intensive agriculture, reversing the decreasing soil carbon trend with less tillage intensity benefits a sustainable agriculture and the global population by gaining better control of the global carbon balance. The literature holds considerable evidence that intensive tillage decreases soil carbon and supports increased adoption of new and improved forms of no-tillage to preserve or increase storage of soil organic matter (Paustian *et al.*, 1997a, b; Lal *et al.*, 1998). The environmental and economic benefits of conservation agriculture and no-tillage demand their consideration in the development of improved soil carbon storage practices for sustainable production.



Environmental benefits are spokes that emanate from the Carbon hub of the 'Environmental Sustainability Wheel'

- increased water-holding capacity and use efficiency
- increased cation exchange capacity
- reduced soil erosion
- improved water quality
- improved infiltration, less runoff
- decreased soil compaction
- improved soil tilth and structure
- reduced air pollution

Carbon

central hub of environmental quality

- reduced fertilizer inputs
- increased soil buffer capacity
- increased biological activity
- increased nutrient cycling and storage
- increased diversity of microflora
- increased adsorption of pesticides
- gives soil aesthetic appeal
- increased capacity to handle manure and other wastes
- more wildlife

Fig. 2.2. Environmental sustainability wheel with benefits emanating from the soil carbon hub.

Increased available soil water

Increased soil organic matter has a significant effect on soil water management because of increased infiltration and water-holding capacity. Enhanced soil water-holding capacity is a result of increased soil organic matter, which more readily absorbs water and releases it slowly over the season to minimize the impacts of short-term drought. Hudson (1994) showed that, for some soil textures, for each 1% weight increase in soil organic matter, the available water-holding capacity in the soil increased by 3.7% volume. Other factors being equal, soils containing more organic matter can retain more water from each rainfall event and make more of it available to plants. This factor and the increased infiltration with higher organic matter and the decreased evaporation with crop residues on the soil surface all contribute to improved water use efficiency.

Increased organic matter is known to increase soil infiltration and water-holding capacity, which significantly affect soil water management. Under these situations, crop residues slow runoff water and increase infiltration by earthworm channels, macropores and plant root holes (Edwards *et al.*, 1988). Water infiltration is two to ten times faster in soils with earthworms than in soils without earthworms (Lee, 1985).

Soil organic matter contributes to soil particle aggregation, which makes it easier for water to move through the soil and enables plants to use less energy to establish root systems (Chaney and Swift, 1984). Intensive tillage breaks up soil structure and results in a dense soil, making it more difficult for plants to fully access the nutrients and water required for their growth and production. No-tillage and minimum-tillage farming allows the soil to restructure and accumulate organic matter for improved plant water and nutrient availability.

Reduced soil erosion

Crop residue management practices have included many agricultural practices to reduce soil erosion runoff and off-site sedimentation. Soils relatively high in C, particularly with crop residues on the soil surface, very effectively increase soil organic matter and reduce soil erosion loss. The primary role of soil organic matter to reduce soil erodibility is to stabilize the surface aggregates through reduced crust formation and surface sealing, resulting in less runoff (Le Bissonnais, 1990). Reducing or eliminating runoff that carries sediment from fields to rivers and streams is a major enhancement of environmental quality. Under these situations, crop residues act as tiny dams that slow down water runoff from fields, allowing the water more time to soak into the soil.

Crop residues on the surface not only help hold soil particles in place but keep associated nutrients and pesticides on the field. The surface layer of organic matter minimizes herbicide runoff and, with conservation tillage, herbicide leaching can be reduced by as much as half (Braverman *et al.*, 1990).

Increased soil organic matter and crop residues on the surface will significantly reduce wind erosion (Skidmore *et al.*, 1979). Depending on the amount of crop residues left on the soil surface, soil erosion can be reduced to near zero as compared with that from an unprotected, intensively tilled field. Wind or water soil erosion causes soil degradation and variability to the extent of a resulting crop yield decline.

Papendick *et al.* (1983) reported that the original topsoil on most hilltops had been removed by tillage erosion in the Palouse region of the Pacific Northwest of the USA. Mouldboard ploughs were identified as the primary cause, but all tillage implements will contribute to this problem (Groves *et al.*, 1994; Lobb and Kachanoski, 1999). Soil translocation from mouldboard plough-based tillage can be greater than soil loss tolerance levels (Lindstrom *et al.*, 1992; Groves *et al.*, 1994; Lobb *et al.*, 1995, 2000; Poesen *et al.*, 1997). Soil is not directly lost from the fields by tillage translocation; rather, it is moved away from the convex slopes and deposited on concave slope positions.

Lindstrom *et al.* (1992) showed that soil movement on a convex slope in southwestern Minnesota, USA, could result in a sustained soil loss level of approximately 30 t/ha/year from annual mouldboard-ploughing. Lobb *et al.* (1995) estimated soil loss in southwestern Ontario, Canada, from a shoulder position to be 54 t/ha/year from a tillage sequence of mouldboard-ploughing, tandem-discing and C-tine cultivating. In this case, tillage erosion, as estimated through resident caesium-137, accounted for at least 70% of the total soil loss. The net effect of soil translocation from the combined effects of tillage and water erosion is an increase in spatial variability of crop yield and a likely decline in soil carbon, related to lower soil productivity (Schumacher *et al.*, 1999).

Enhanced soil quality

Soil quality is the fundamental foundation of environmental quality. Soil quality is largely governed by soil organic matter (SOM) content, which is dynamic and responds effectively to changes in soil management, tillage and plant production. Maintaining soil quality can reduce the problems of land degradation, decreasing soil fertility and rapidly declining production levels that occur in large parts of the world needing the basic principles of good farming practice.

Soil compaction in conservation tillage farming is significantly reduced by the reduction of traffic and increased SOM (Angers and Simard, 1986; Avnimelech and Cohen, 1988). Soane (1990) presented several mechanisms by which soil ‘compactibility’ can be affected by SOM:

1. Improved internal and external binding of soil aggregates.
2. Increased soil elasticity and rebounding capabilities.
3. Reduced bulk density due to mixing organic residues with the soil matrix.
4. Temporary or permanent existence of root networks.
5. Localized change of electrical charge of soil particle surfaces.
6. Change in soil internal friction.

While most soil compaction occurs during the first vehicle trip over the tilled field, reduced weight and horsepower requirements associated with no-tillage can also help minimize compaction. Additional field traffic required by intensive tillage compounds the problem by breaking down soil structure. Maintenance of SOM contributes to the formation and stabilization of soil structure. The combined physical and biological benefits of SOM can minimize the effect of traffic compaction and result in improved soil tilth.

While it is commonly known that tillage produces a well-fractured soil, sometimes requiring several tillage passes, it is a misconception that this is a well-aggregated, healthy soil. These soils never fare well when judged against modern knowledge of high ‘soil quality’. A tilled soil is poorly structured, is void of many microorganisms and has poor water characteristics, just to name a few characteristics. As soils are farmed without tillage and supplied with residues, they naturally improve in overall quality, again support many microorganisms and become ‘mellow’ to the point of being easily penetrated by roots and earthworms. This transition takes several years to accomplish but invariably occurs given the opportunity.

Many traditional experienced farmers will often ask, ‘How many years of no-tillage are possible before the soil becomes so compact as to require tillage?’ No-tillage experience has shown exactly the opposite effect: once a no-tilled soil has regained its quality, it will continue to resist compaction and any subsequent tillage will cause undue damage. Most soils will continue to build organic matter and improve in quality criteria for years into the practice of no-tillage farming if the sequence is not broken by the thunderous effect of tillage.

Improved nutrient cycles

Improved soil tilth, structure and aggregate stability enhance the gas exchange and aeration required for nutrient cycling (Chaney and Swift, 1984). Critical management of soil airflow, with improved soil tilth and structure, is required for optimum plant function. It is the combination of many factors that results in comprehensive environmental benefits from SOM management. The many attributes suggest new concepts on how we should manage the soil for long-term aggregate stability and sustainability.

Ion adsorption or exchange is one of the most significant nutrient cycling functions of soils. Cation exchange capacity (CEC) is the quantity of exchange sites that can absorb and release nutrient cations. SOM can increase this capacity of the soil from 20 to 70% over that of the clay minerals and metal oxides present. In fact, Crovetto (1996) showed that the contribution of organic matter to the cation exchange capacity exceeded that of the kaolinite clay mineral in the surface 5 cm of his soils. Robert (1996) showed that there was a strong linear relationship between organic carbon and the cation exchange capacity of his experimental soil. The capacity was increased fourfold with an organic carbon increase from 1 to 4%. The toxicity of other elements can be inhibited by SOM, which has the ability to adsorb soluble chemicals. Adsorption by clay minerals and SOM is an important means by which plant nutrients are retained in crop rooting zones.

Increased infiltration and concerns over the use of nitrogen in no-tillage agriculture require an understanding of the biological, chemical and physical factors controlling nitrogen losses and the relative impacts of contrasting crop production practices on nitrate leaching from agroecosystems. Domínguez *et al.* (2004) evaluated the leaching of water and nitrogen in plots with varying earthworm populations in a maize system. They found that the total flux of nitrogen in soil leachates was 2.5-fold greater in plots with increased earthworm populations than in those with lower populations. Their results are dependent on rainfall amounts, but do indicate that earthworms can increase the leaching of water and inorganic nitrogen to greater depths in the profile, potentially increasing nitrogen leaching from the system. Leaching losses were lower on the organically fertilized plots, attributed to higher immobilization potential.

Reduced energy requirements

Energy is required for all agricultural operations. Modern, intensive agriculture requires much more energy input than traditional farming methods since it relies on the use of fossil fuels for tillage, transportation, grain drying and the manufacture of fertilizers, pesticides and equipment used to apply agricultural inputs and for generating electricity used on farms (Frye, 1984). Reduced labour and machinery costs are economic considerations that are frequently given as additional reasons to use conservation tillage practices.

Practices that require lower energy inputs, such as no-tillage versus conventional tillage, generally result in lower inputs of fuel and a consequent decreases of CO_2-carbon emissions into the atmosphere per unit of land area under cultivation. Emissions of CO_2 from agriculture are generated from four primary sources: manufacture and use of machinery for cultivation, production and application of fertilizers and pesticides, the soil organic carbon that is oxidized following soil disturbance (which is largely dependent on tillage practices) and energy required for irrigation and grain drying.

A dynamic part of soil carbon cycling in conservation agriculture is directly related to the ‘biological carbon’ cycle, which is differentiated from the ‘fossil carbon’ cycle. Fossil carbon sequestration entails the capture and storage of fossil-fuel carbon prior to its release to the atmosphere. Biological carbon sequestration entails the capture of carbon from the atmosphere by plants. Fossil fuels (fossil carbon) are very old geologically, as much as 200 million years. Biofuels (bio-carbon) are very young geologically and can vary from 1 to 10 years in age and as a result can be effectively managed for improved carbon cycling. One example of biological carbon cycling is the agricultural production of biomass for fuel. The major strength of biofuels is the potential to reduce net CO_2 emissions to the atmosphere. Enhanced carbon management in conservation agriculture may make it possible to take CO_2 released from the fossil carbon cycle and transfer it to the biological carbon cycle to enhance food, fibre and biofuel production, for example, using natural gas fertilizer for plant production.

West and Marland (2002) conducted a carbon and energy analysis for agricultural inputs, resulting in estimates of net carbon flux for three crop types across three tillage intensities. The analysis included estimates of energy use and carbon emissions for primary fuels, electricity, fertilizers, lime, pesticides, irrigation, seed production and farm machinery. They estimated that net CO_2-carbon emissions for crop production with conservation, reduced and no-tillage practices were 72, 45 and 23 kg carbon/ha/year, respectively.

Total carbon emission values were used in conjunction with carbon sequestration estimates to model net carbon flux to the atmosphere over time. Based on US average crop inputs, no-tillage emitted less CO_2 from agricultural operations than did conventional tillage, with 137 and 168 kg of carbon/ha/year, respectively. The effect of changes in fossil-fuel use was the dominant factor 40 years after conversion to no-tillage.

This analysis of US data suggests that, on average, a change from conventional tillage to no-tillage will result in carbon sequestration in soil, plus a saving in CO_2 emissions from energy use in agriculture. While the enhanced carbon sequestration will continue for a finite time until a new equilibrium is reached, the reduction in net CO_2 flux to the atmosphere, caused by the reduced fossil-fuel use, can continue indefinitely, as long as the alternative practices are continued.

Lal (2004) recently provided a synthesis of energy use in farm operations and its conversion into carbon equivalents (CE). The principal advantage of expressing energy use in terms of carbon emission as kg CE lies in its direct relation to the rate of enrichment of atmospheric CO_2 concentration. The operations analysed were carbon-intensive agricultural practices that included tillage, spraying chemicals, seeding, harvesting, fertilizer nutrients, lime, pesticide manufacture and irrigation. The emissions for different tillage methods were 35.3, 7.9 and 5.8 kg CE/ha for conventional tillage, chisel tillage or minimum tillage and no-tillage methods of seedbed preparation, respectively.

Tillage and harvest operations account for the greatest proportion of fuel consumption within intensive agricultural systems.

Frye (1984) found fuel requirements using reduced tillage or no-tillage systems were 55 and 78%, respectively, of those used for conventional systems that included mouldboard-ploughing. On an area basis, savings of 23 kg/ha/year in energy carbon resulted from the conversion of conventional tillage to no-tillage. For the 186 million ha of cropland in the USA, this translates to a potential reduction in carbon emissions of 4.3 million metric tonnes carbon equivalent (MMTCE)/year.

These results further support the energy efficiencies and benefits of no-tillage. Conversion of ploughed tillage to no-tillage, using integrated nutrient management and pest management practices, and enhancing water use efficiency can save carbon emissions and at the same time increase the soil carbon pool. Thus, adopting conservation agriculture techniques is a holistic approach to management of soil and water resources. Conservation agriculture improves efficiency and enhances productivity per unit of carbon-based energy consumed and is a sustainable strategy.

Carbon Emissions and Sequestration

Tillage or soil preparation has been an integral part of traditional agricultural production. Tillage fragments the soil, triggers the release of soil nutrients for crop growth, kills weeds and modifies the circulation of water and air within the soil. Intensive tillage accelerates soil carbon loss and greenhouse gas emissions, which have an impact on environmental quality.

By minimizing soil tillage and its associated (CO_2) emissions, global increases of atmospheric carbon dioxide can be reduced while at the same time increasing soil carbon deposits (sequestration) and enhancing soil quality. The best soil management systems involve minimal soil disturbance and focus on residue management appropriate to the geographical location, given the economic and environmental considerations. Experiments and field trials are required for each region to develop proper knowledge and methods for optimum application of conservation agriculture.

Since CO_2 is the final decomposition product of SOM, intensive tillage, particularly the mouldboard plough, releases large amounts of CO_2 as a result of physical disruption and enhanced biological oxidation (Reicosky *et al.*, 1995). With conservation tillage, crop residues are left more naturally on the surface to protect the soil and control the conversion of plant carbon to SOM and humus. Intensive tillage releases soil carbon to the atmosphere as CO_2, where it can combine with other gases to contribute to the greenhouse effect.

Soils store carbon for long periods of time as stable organic matter. Natural systems reach an equilibrium carbon level determined by climate, soil texture and vegetation. When native soils are disturbed by agricultural tillage, fallow or residue burning, large amounts of carbon are oxidized and released as CO_2 (Allmaras *et al.*, 2000). Duxbury *et al.* (1993) estimated that agriculture has contributed 25% of the historical human-made emissions of CO_2 during the past two centuries. However, a significant portion of this carbon can be stored, or sequestered, by soils managed with no-tillage and other low-disturbance techniques. Increased plant production greater than that of native soil levels by the addition of fertilizers or irrigation can enhance carbon sequestration.

Carbon is a valuable environmental natural resource throughout the world's industrial applications of production and fossil energy consumption. Releasing carbon to the atmosphere by energy processes may be offset by capturing carbon with plant biomass and subsequently soil carbon sequestration in the form of organic matter. Energy consumers may at some time be required to compensate for their atmospheric carbon emissions by contracting with those who can sequester atmospheric carbon. Conservation agriculture may be able to provide this sequestration benefit and thus be compensated for its role in maintaining low net carbon emissions. While this 'carbon trading' mechanism is still in the discussion stage, it provides an important potential benefit.

A more detailed explanation of carbon dioxide emissions and sequestration is given in Chapter 17, together with comments on how these interact with nitrous oxide and methane emissions and the potential for carbon trading.

Summary of the Benefits of No-tillage

Conservation tillage, and particularly no-tillage, agriculture has universal appeal because of numerous benefits. Improved production with fewer inputs and reduced time and energy are often cited as the highlights. Conservation agriculture techniques benefit the farmers and the whole of society, and can be viewed as both ‘feeding and greening the world’ for global sustainability. Agricultural policies are needed to encourage farmers to improve soil quality by storing carbon as SOM, which will also lead to enhanced air quality, water quality and productivity and help to mitigate the greenhouse effect.

Some of the more important benefits of conservation tillage farming are:

1. Improved crop production economics.
2. Increased SOM.
3. Improved soil quality.
4. Reduced labour requirements.
5. Reduced machinery costs.
6. Reduced fossil-fuel inputs.
7. Less runoff and increased available plant water.
8. Reduced soil erosion.
9. Increased available plant nutrients.
10. Improved global environment.

3 The Nature of Risk in No-tillage

C. John Baker, W. (Bill) R. Ritchie and Keith E. Saxton

The ultimate decision to adopt a no-tillage
system will have more to do with how farmers
perceive it altering their business risks
than anything else.

The risks associated with no-tillage are those that result in reduced income to the farmer through impaired crop performance and/or increased costs. To be a sustainable technique, the failure rate for no-tillage must be no more, and preferably less, than that for tillage (Baker, 1995).

While early sceptics of the no-tillage concept forecast many and varied problems that would ultimately lead to the downfall of the practice, experience has shown that there are no insurmountable obstacles in most circumstances. The fact remains, however, that many farmers are still reluctant to attempt the new technique, fearing that it may increase their risks of crop failure or reduced yield.

The perception of risk is probably the single biggest factor governing the rate of adoption of no-tillage, and it is likely to remain so for a long time. Only education and personal experiences will finally put risk into perspective. Recent results convincingly show that no-tillage is not inherently more risky than conventional tillage, even in the short term. Indeed, it can reduce the risk factor during crop establishment if it is undertaken and managed correctly. Of course, tillage is also subject to increased risk under poor management. It is therefore pertinent to explore the concept of risk during crop establishment and growth, and to explain how this is affected by sound no-tillage practices.

What is the Nature of Risk in No-tillage?

To plant and grow a crop with no-tillage, a farmer undertakes an economic risk that is affected by three functional risk categories: (i) biological; (ii) physical; and (iii) chemical. These risks are comparable between tillage and no-tillage systems because almost all of them are the everyday risks of cropping either way. Only their relative levels and remedies differ between the two techniques. The combined effects of the functional risks result in economic risks. The results and associated implications are sometimes surprising and are examined at the end of this chapter.

Biological risks

Biological risks arise from pests, toxins, diseases, seed vigour, seedling vigour, nutrient stress and, ultimately, crop yield.

No-tillage Seeding in Conservation Agriculture, 2nd edn. (eds C.J. Baker and K.E. Saxton)

The change to residue farming in general, which is the cornerstone of no-tillage, can have a marked effect on the incidence of diseases and pests, both positively and negatively. Seed placement and soil and residue disturbance by various drill or opener designs can influence all of these factors.

Pests

The change in earthworm and slug populations creates the most common pest problems in no-tillage. Slugs are particularly prone to proliferate in residue in high-humidity climates and must often be controlled by chemical means. Earthworms, on the other hand, can be either beneficial or damaging, depending on type. Earthworms generally provide positive effects that help aerate, drain and cycle nutrients. All of the effects of earthworms are not yet known but some of their benefits in wet soils are explained in detail in Chapter 7. While tillage destroys earthworms, no-tilled soil nearly always has a significant and important increase in populations, and they are a great 'indicator' organism for other beneficial biota developments. Other damaging worms, such as wireworms, are generally not different regarding crop risks.

Slugs (*Deroceras reticulatum*) (Follas, 1981, 1982) find shelter beneath the soil in many types of seed slots and feed on sown seeds and establishing seedlings. Clearly, slugs increase the biological risks of no-tillage. But they are relatively cheaply countered by the application of a suitable molluscicide.

Other pests can increase their damage risk because of increased surface residues or decreased physical destruction by tillage machines. But then so too do many of their predators.

An example of pest–drill interaction is that experienced with inverted T-shaped slots (see Chapter 4), which create subsurface soil-slot environments that are higher in soil humidity than either tilled soils or other no-tillage slots. Soil fauna that are sensitive to soil humidity, such as slugs and earthworms, tend to congregate in such slots. These may have both positive and negative effects for the sown crop (Carpenter *et al.*, 1978; Chaudhry, 1985; Baker *et al.*, 1987; Basker *et al.*, 1993).

Diseases

The most common soil disease that no-tillage appears to encourage is *Rhizoctonia*. Disturbance of the soil during tillage appears to partly destroy the fungal mycelia. Other fungal diseases are carried over in cereal residue and decaying organic matter in root channels, requiring diligent use of crop rotations or application of appropriate fungicides. On the other hand, the soil disease take-all (*Gaeumannomyces graminis*) appears to become more confined under no-tillage because of reduced soil movement.

A concept called 'green bridge' was identified by Cook and Veseth (1993), in which certain root bacteria from recent chemically killed plants can readily transfer to new seedlings if no-tillage seeding is undertaken within 14–21 days after the green crop begins dying. The specific pathogen has not yet been identified, but some delay after spraying and before no-tillage seeding appears to be an advantage where these bacteria exist, particularly in instances of continuous cereal cropping.

Toxins

The risks arising from toxins relate mainly to contact between seeds and decaying residue within the sown slot under persistently wet conditions (see Chapter 7). This risk, which is peculiar to no-tillage in cold wet soils, is eliminated by the use of no-tillage openers that effectively separate seed from the residues (Chaudhry, 1985) or the use of neutralizing agents sown with the seed (Lynch, 1977, 1978; Lynch *et al.*, 1980).

The most common occurrence of residue effects has been experienced with double-disc drills seeding into wet, soft soils with surface residues. The residues tend to be folded and 'tucked' or 'hairpinned' into the seed slot with the seed dropped in the same location, which results in both the seed and residue experiencing decaying conditions and poor plant stands.

Some explanations for early no-tillage failures assumed that allelopathic exudates from dying plants may have killed newly sown seeds. But later detailed explanations for the causes of seedling emergence failures pointed to other (largely physical) factors and it has been hard to find any confirmed cases of allelopathy having played any role at all.

Nutrient stress

Without soil tillage to stir and mix applied fertilizer applications, careful attention must be paid to placing the fertilizer in untilled soils to optimize crop uptake and yield. Bands of fertilizer to the side and below the seed have proved to be very effective, sometimes utilizing one fertilizer band for each pair of seed rows. While it is important to place fertilizers far enough away from seeds and seedlings to avoid toxicity problems (see 'Chemical Risks'), it also appears that separation distances can (and indeed should) be much closer than those commonly accepted for tilled soils (see Chapter 9). Fertilizer banding has been found to be optimally accomplished by simultaneously seeding and fertilizing with a combination direct seed drill and fertilizer dispenser, and which is now common practice.

Again, the risk under no-tillage increases only if inappropriate equipment is used. On the other hand, there is voluminous evidence to show that, when fertilizers are placed correctly, no-tillage crop yields may be greater than those obtained from tilled soils (see Chapter 9). Thus, while the risk of nutrient stress under no-tillage may increase with inappropriate equipment, it may decrease compared with tillage if improved designs of no-tillage drills and planters are utilized.

Physiological stress

It has been stated that untilled seedbeds are not as 'forgiving' as their tilled counterparts (Baker, 1976a). This is often true because seedlings have to emerge through covering material that is physically more resistant than friable tilled soils. If the seeds are sown into mellow soils that have been no-tilled for several years or with scientifically designed furrow openers, such as inverted-T-shaped slots, the micro-environment of the slots will actually place less physiological stress on the seedlings than will a tilled soil. Thus physiological stress at the time of seedling emergence need not increase the biological risks. It may actually decrease the risk (see Chapter 5). Figure 3.1 shows the difference in growth between seedlings established within contrasting no-tillage slots resulting from physiological stress.

Seed quality

International seed testing authorities throughout the world test mainly for purity and optimally wetted germination as the main indicators of seed quality. But there are also agreed voluntary tests that describe other aspects of seed quality. One such test, the 'accelerated ageing' or 'vigour' test, examines a seed's ability to germinate after experiencing a period of stress (usually high or low temperature). It is possible for a given seed line to record a high-percentage germination but a low-percentage vigour. Therefore final germinations counts give no real indication of the vigour of a seed line although interim counts might be helpful in this respect.

There is an important interaction between seed vigour and drill opener designs, which can have important impacts on biological risk, and operators need to understand this interaction. No-tillage openers that create inverted-T-shaped slots produce about as favourable a micro-environment as it is possible to create for seeds, in either tilled or untilled soils. The main attribute is the availability of both vapour-phase and liquid-phase water. This ensures that even low-vigour seeds will germinate, almost regardless of the soil conditions.

In contrast, seeds sown into tilled soils or less favourable no-tillage slots that only provide liquid-phase water for germination of seeds are less likely to germinate. Farmers usually attribute such failures to a variety of reasons, but seldom test the vigour of

Fig. 3.1. Growth responses of wheat seedlings as a result of physiological stress when sown by a winged opener (left) and double disc (right) no-tillage openers.

the seed they had sown. When germination of low-vigour seeds does occur in tilled soils and open no-tillage slots, emergence of the seedlings is seldom restricted because of the friable nature of tilled soils and the open nature of vertical no-tillage slots. But the ensuing crop is likely to perform poorly.

Extensive field experience with inverted-T-shaped no-tillage slots, where even low-vigour seeds will often germinate under unfavourable conditions, have shown that the seedlings often did not have the vigour to emerge and were instead found twisted, weak and un-emerged beneath the soil surface. Observers at first attributed such twisting to fertilizer burn, but it is now known that fertilizer burn causes shrivelling and premature death of seedlings, not twisting. When vigour tests were carried out over a 3-year period on some 40 lines of seeds that had shown symptoms of sub-surface seedling twisting in inverted-T no-tillage slots, all seed lines were found to be of low vigour (some as low as 18%).

The question is: What can be done about the problem? The responsibility rests with both the seed industry and individual no-tillage farmers. The seed industry needs to improve the quality of the seeds it offers for sale or at least be prepared to disclose information on seed vigour to farmers. Some companies already do this. No-tillage farmers, for their part, need to seek information from the seed industry about the vigour of particular seed lines and to be prepared to pay more for high-vigour lines. Those drill manufacturers that market advanced no-tillage seed drills need to advise purchasers that the weakest part of the system may now be seed quality, whereas previously it had been drill quality.

Physical risks

Weather

Weather is likely to be the most variable and uncontrollable element in farming, and performing no-tillage won't change that. However, no-tillage does have the opportunity to significantly modify the impact by several means, some already mentioned or obvious. Increased available plant water is often the first noticeable effect, since residues and minimal soil disturbance reduce evaporation and increase infiltration.

Improved trafficability in wet soil is often a surprising no-tillage effect. With only one or two no-tillage crop years, the 'fabric' of the soil strengthens (mainly through improved soil structure) and animal or machine treading causes much less compaction with fewer surface depressions. It is common knowledge that no-tilled fields are accessible for seeding or spraying several days sooner following rainfall than tilled soils, with less damage by surface compaction. No-tilled soils are not more dense or compact than tilled soils; they just have more resistance to down pressures as a result of the increased organic matter and structure.

No-tillage also moderates excessive weather effects, such as extreme rainfalls and temperatures. With the surface residues protecting the surface against raindrop impact, runoff and erosion, rills and gullies don't form. Residues minimize the high wind profiles from having an impact on the soil surface and significantly reduce wind erosion. And very subtle dampening of soil temperature variations often prevents freezing of overwintering plants. No-tillage seeding into standing residues has allowed successful winter wheat crops in far more northerly climates in the northern hemisphere than previously possible, with increased yields compared with spring-seeded crops.

Young *et al.* (1994) showed how seasonal weather variations could affect the risk of altering the profitability of conservation tillage (which includes a component of no-tillage) compared with conventional tillage (Fig. 3.2). They pointed out that the period 1986 to 1988 was particularly dry in the Palouse area of Washington State, which favoured the profitability of conservation tillage. The 1990/91 winter was particularly cold, which also favoured conservation tillage. At other times (1989 and 1990) the weather did not favour either technique. In this manner the relative risks of changing profitability are clearly illustrated. Such risks cannot be predicted with any accuracy, but they can be minimized by selecting conservation tillage techniques and/or machines with the widest possible tolerance of changing weather patterns.

It is obvious that no-tillage machines cannot control the weather. But it has been repeatedly noted that when no-tillage is undertaken with appropriate residue manipulation and seeding machines designed with proper seeding slots, seeds and seedlings have considerably better protection from weather variations (e.g. too hot, cold, dry, windy or wet) than when that soil is either tilled or drilled with inappropriate

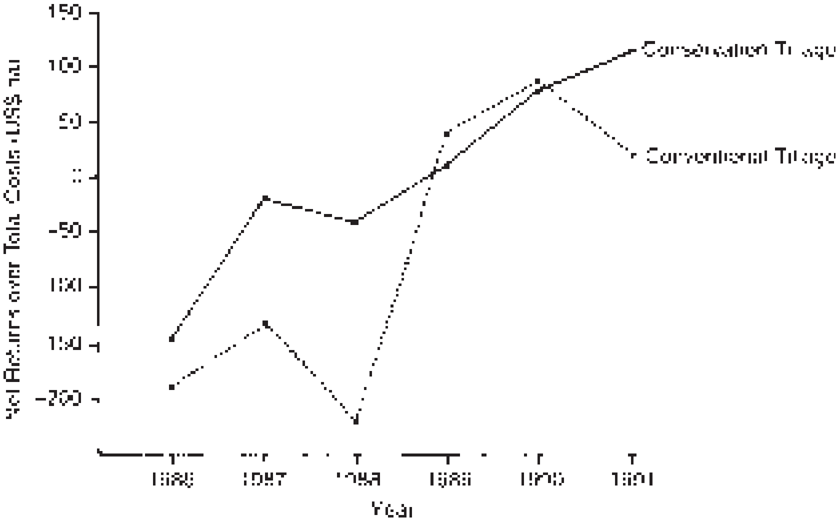


Fig. 3.2. The relative profitability of two crop establishment systems in Washington State over 5 years (from Young *et al.*, 1994).

no-tillage equipment. Thus, risks arising from inclement weather have the potential to be reduced under no-tillage if appropriate methods and equipment are used.

Machine function

Many of the physical risks arise from how well no-tillage machines perform their intended functions. The machine's designers must understand and incorporate the required capabilities to perform its intended functions in a wide variety of soil types, residues and weather conditions. These variations can change widely even within a single field or on a single day. There is much risk inserted into the farming system from a machine that operates at different levels of performance on different days in different parts of a field. A successful no-tillage drill must have a wide tolerance of changing, sometimes even hostile, conditions.

There are few more important physical functions than creating the correct micro-environment for the seeds within the soil. Different drill openers differ markedly in their abilities to do this (see Chapter 4) and this affects the level of risk associated with different machines. To reduce machine-related risks, the openers of no-tillage drills must follow ground surface variations and move through significant surface residues without blockage. Seeding depth can only be maintained by careful tracking of the soil surface by the seed opener.

Maintaining surface residues is the main long-term benefit from no-tillage, especially for reducing erosion and temperature fluctuations and increasing soil fauna and infiltration. Residues are an equally important ingredient in short-term biological performance of seedling emergence and vigour. No-tillage does not offer the option to ‘till out’ last season’s mistakes of vehicle ruts, animal paths, washed gullies, hardpans, etc. It is critically important to avoid creating field surfaces that are not mechanically manageable the following cropping season.

No-tillage seeding machines not only must physically handle residues consistently without blockage but must also have the ability to micro-manage those residues close to the slot and to utilize them for the benefit of the sown seeds and plants (Baker and Choudhary, 1988). Conversely, the inability of any opener to do these things significantly increases the risks from no-tillage, since the residues themselves are an important ingredient in creating a favourable habitat for seeds and seedlings. A positive utilization of crop residues in no-tillage is considerably different from tillage farming in that residues are seen as beneficial rather than a hindrance to machine performance. Since tilled soils, almost by definition, have minimal surface residues, they do not benefit in comparison with good utilization of residues by no-tillage openers, but they may compare well with no-tillage where residues are not utilized.

Similarly, the ability to uniformly track the untilled soil surface for uniform seeding by no-tillage drills will greatly determine the biological risks associated with poor seedling stands and vigour. These aspects are discussed in greater detail in Chapter 8, but in summary it should be acknowledged that there is a need for no-tillage openers to follow the surface better than their tillage counterparts, or the risk of poor crop stands will increase.

No-tillage drills encounter much higher forces and wear of components than their tillage counterparts. Since some of the critical functions, such as residue handling and slot formation, are often dependent on the mechanical wear remaining within narrow limits, maintenance of no-tillage machines is more important than for conventional drills. To put it another way, the absence of adequate maintenance on no-tillage drills may increase the risk of malfunction disproportionately.

None of the physical functions described above, however, has any relevance to risk unless its successful implementation has an identifiable biological function with regard to the sown seeds and emerging plants. Somewhat surprisingly, many of the early ‘desirable functions’ listed for no-tillage openers (e.g. Karonka, 1973) failed to define any biological objectives at all. Failure to recognize these biological-engineering linkages alone probably increased the level of risk of early no-tillage and accounted for much of the 'hit-and-miss' reputation the technique acquired in its early days.

Ritchie *et al.* (2000) summarized the biological risks associated with six critical functions that no-tillage drill openers must perform. Their modified chart is shown in Fig. 3.3. Each criterion was assigned a risk rating of 1 to 10 (1 being low-risk and 10 being high-risk) according to published scientific data and engineering principles.

Several commonly used drill openers were ranked using the criteria of Fig. 3.3 and are shown in Table 3.1. The risk-assessment of the disc version of winged openers closely matches actual field surveys of users in New Zealand, which have consistently found a 90–95% success rate over several years and hundreds of thousands of hectares of field drilling (Baker *et al.*, 2001). But the most commonly used opener throughout the world (vertical double disc) ranks poorly. This helps explain the many no-tillage failures associated with this opener.

Chemical risks

Chemical risks have many of the same implications as physical risks. They are linked to the resultant biological risks that arise from them. Two stand-alone chemical risks are the effectiveness of weed control by herbicide application and the risk of toxicity or 'seed burn' from inappropriate placement of fertilizer in the seed slot relative to the seed placement.

Weed control

Weed control with herbicides must be as effective as that with mechanical means or the risk of impaired crop performance will increase. The principal variables determining herbicide effectiveness are as follows.

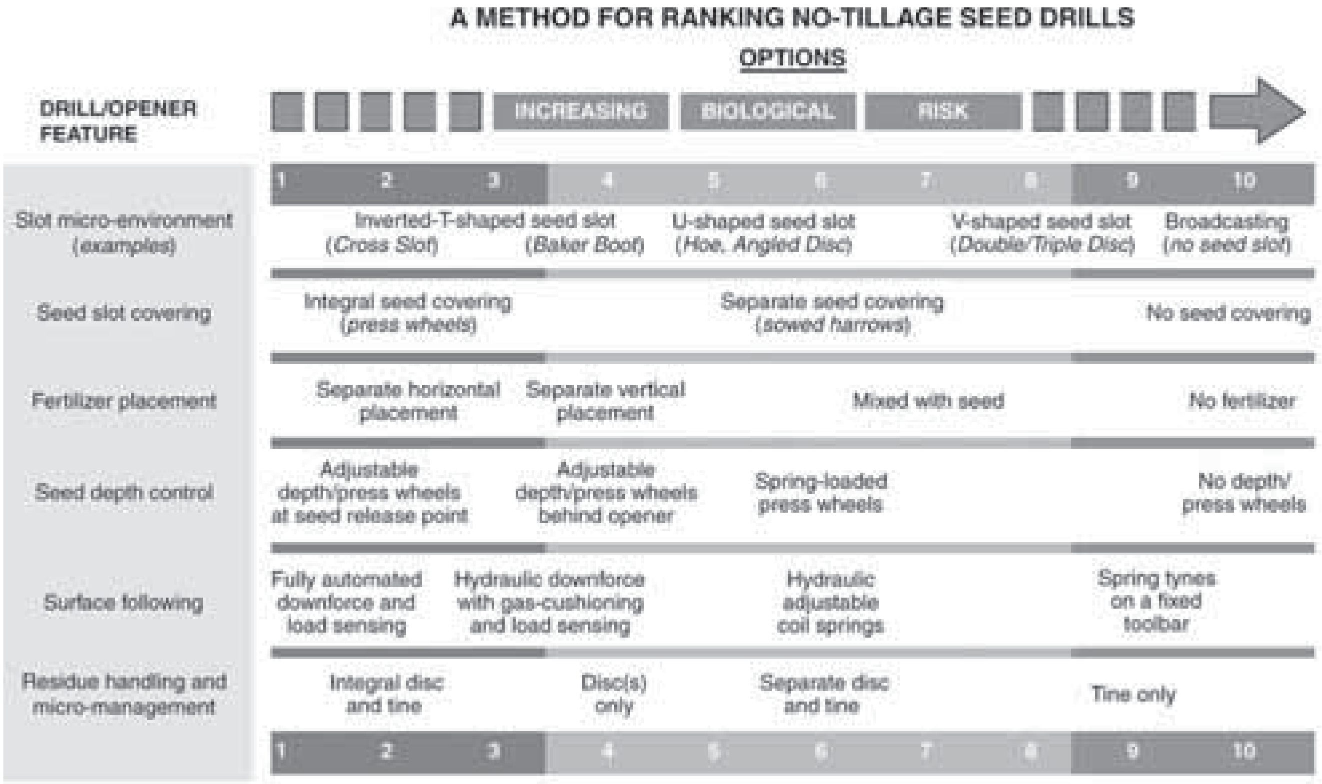
APPLICATION OF ACTIVE INGREDIENT. The ability of operators to properly interpret the labels and literature supplied with various herbicides and pesticides has much to do with the success of applications. In addition, operators need to be able to recognize weed species and to be able to reliably calibrate their spraying machines. All of these operator choices are more risky than corresponding tillage operations. Nor are spraying mistakes as forgiving as tillage mistakes, which can often be 'repaired' the next day.

SELECTION OF APPROPRIATE CHEMICAL. The selection of tillage tools can follow a trial-and-error routine where: (i) the non-performance of one implement becomes obvious within a short time; (ii) the consequences are seldom of great magnitude; and (iii) rectification using an alternative implement is accomplished quickly. Few, if any, of these flexibilities are available when choosing appropriate chemicals for a given weed or pest situation. Occasionally a mistaken choice can be rectified by the application of another chemical, but the options are fewer than with tillage and the risks are therefore greater.

WEATHER. Some chemicals require several hours without rain to be fully effective, while others are virtually 'rain-fast'. Since most chemicals involve a significant outlay of cash and, unlike tillage tools, are not reusable, the risk from untimely rain and wind is greater than with tillage.

WATER QUALITY. Some foliage-applied herbicides, especially those that are inactivated upon contact with soil, such as glyphosate, have their efficacy altered by impurities in the mixing water. Of particular concern is water derived from storage dams or underground bores that is contaminated with particles or iron and carbonates. Some chemical effectiveness is quite variable with water acidity levels. Similarly, impurities on the leaves of target foliage, such as mud and dust from stock or vehicle traffic or recently applied lime, may inactivate some herbicides.

VIGOUR OF WEEDS. The vigour of the target weeds at application time is important. Some herbicides (e.g. glyphosate) work best when sprayed on to healthy, actively growing plants. Others (e.g. paraquat) work best



How to use this chart: Assess each of the six drill/opener features listed down the left-hand side of the chart. Assign a score from the colour bars that relates to the option the drill or opener exhibits. A high total score indicates a higher level of risk (Example: A hypothetical drill may have inverted-T openers (3), require towed harrows (6), have no fertilizer capability (10), no press/depth wheels (10), hydraulically adjustable coil springs (6) and separate disc and tine (6) = Total 41/60).

Fig. 3.3. A biological risk-assessment chart of drill opener designs (after Ritchie *et al.*, 2000).

Table 3.1. Examples of how some common no-tillage openers rank in terms of biological risk.

	Disc version of winged opener	Vertical angled disc	Slanted angled disc	Shank and sweep openers	Vertical double disc	Simple winged tine[a]
Slot micro-environment	1	4	4	3	7	2
Slot covering	1	3	2	2	7	4
Fertilizer placement	1	3	3	2	7	7
Seed depth control	2	1	1	9	3	8
Surface following	1	4	4	9	5	9
Residue handling	1	3	3	7	3	10
Total out of max. 60	7	18	17	32	32	40
Chance of impaired biological performance[b]	11%	30%	28%	53%	53%	67%

[a] Simple winged tine openers are designed to be used predominantly in smooth pasture. Comparing these openers for all no-tillage (including arable) penalizes them unfairly but they are nevertheless included here to illustrate how Fig. 3.3 exposes the limitations of such openers.

[b] The figures represent the chances of obtaining an impaired biological performance from using any of these openers. For example, the table suggests that use of the disc version of winged openers will result in an 11% chance of a poor crop, whereas use of shank and sweep openers will result in a 53% chance of a poor crop unless there is little residue present and the fields are smooth and flat.

Put another way, the table suggests that in heavy residues on less-than-smooth ground there would be about five times as much chance of getting an impaired crop using shank and sweep type openers as compared with the disc version of winged openers.

when the target plants are already stressed. Knowledge of these requirements is essential if effective weed control is to take place.

OPERATOR ERROR. During tillage, driving errors by an operator are seen immediately but they are seldom sufficiently serious to show up in the subsequent crop as an area of impaired yield. With once-over spraying, errors do not show up immediately. Paraquat is the most rapid to take effect but even then it is days before mistakes become visible. Most other herbicides take at least a week to show any visible effect, by which time the crop may have been sown, making remedial action virtually impossible without adversely affecting the sown crop.

Toxicity of fertilizers

There are two risks from inappropriate fertilizer placement at sowing. If fertilizer is broadcast on to the ground surface rather than placed in the soil at the time of drilling, there is a serious risk of impaired crop performance and yield as a result of limited plant availability (see Chapter 9). On the other hand, when fertilizer is sown with the seed there is a danger of the fertilizer damaging or ‘burning’ the seed under no-tillage unless the two are effectively separated in the soil. The latter risk increases with increased soil dryness. Separation is more difficult to achieve in no-tillage than in tilled soils, but it has been shown to be quite possible with the correct equipment without increased risk.

Economic risk

All forms of risk during no-tillage are finally measured as economic risk. But economic risk should not be centred on cost savings alone. Indeed, focusing on cost savings may increase rather than decrease both real and imagined economic risks. This is for two reasons:

1. Where farmers already own tillage equipment, they see the acquisition of no-tillage equipment or even the use of contractors (custom drillers) – no matter how cheap – as duplication of an existing cost.
2. Purchasing inferior no-tillage equipment for cost savings may well result in lowered crop yields, even if only temporarily. Such a result may indeed be less cost-effective than either tillage or no-tillage undertaken with more expensive (and probably superior) equipment that maintains or even improves crop yields.

We shall examine both scenarios below.

The costs of tillage versus no-tillage

The costs of several alternatives for adopting no-tillage under a double cropping system (two crops per year, e.g. wheat followed by a winter forage crop for animal consumption) in New Zealand were analysed and compared with the costs of tillage (C.J. Baker, 2001, unpublished data).

These were:

1. Engaging a tillage contractor (custom driller) versus engaging a no-tillage contractor.
2. Purchasing new tillage equipment versus purchasing new no-tillage equipment.
3. Retaining ownership of used tillage equipment versus purchasing used no-tillage equipment.
4. Retaining ownership of used tillage equipment versus purchasing new no-tillage equipment.
5. Retaining ownership of used tillage equipment versus engaging a no-tillage contractor.

Fixed costs were included, such as interest on the investment, depreciation, insurance and housing, and expressed as a per-hour cost of annual machine use. Drills and planters are used for a shorter period each year to plant the same area under no-tillage than under a tillage regime. Thus the per-hour costs increase even though the per-hectare and per-year costs decrease. The analysis also assumed that a single large tractor and driver would be required for no-tillage compared with two or more smaller tractors and drivers for tillage.

For simplicity, the study assumed that the no-tillage drill being compared was of an advanced design, which ensured that crop yields would remain unchanged regardless of which option was chosen. Such an assumption is reasonable when applied to advanced no-tillage drills (which cost more anyway) but is unrealistic for inferior drills (see below).

The cost analysis did not account for taxation issues, subsidies or other purchase incentives of any nature. These could otherwise be expected to favour no-tillage since many countries have incentives to encourage the practice because of its conservation value. Thus the results could be considered conservative in terms of the benefits recorded for no-tillage.

A more detailed account of the economic analysis is given in Chapter 18.

Operating costs strongly favoured no-tillage. In all of the above options (1) to (5), the costs favoured no-tillage by between US$16 and US$40/ha/year.

The greatest advantage (US$40/ha/year) was shown by option (2) – purchasing new tillage equipment versus purchasing new no-tillage equipment. This was mainly because of reduced running costs of the no-tillage equipment since the total capital outlays in each case were very similar.

The least advantage (US$16/ha/year) was shown by option (4) – retaining ownership of used tillage equipment versus purchasing new no-tillage equipment. Clearly the advantage would increase for this option when and if a decision was eventually taken to sell the existing tillage equipment, provided that a market for such equipment still existed. But realistically, the costs of purchasing no-tillage equipment would probably remain additional to the costs of retaining ownership of existing tillage equipment for a period.

Farmers often see retention of their existing tillage equipment as ‘insurance’ while they gain the knowledge and skills necessary to master the new no-tillage technique to a stage where they can abandon tillage altogether. Other farmers claim that by going 'cold turkey' (i.e. selling the tillage equipment at the same time as they purchase the no-tillage equipment) the learning process is achieved faster and more effectively. This study took the conservative approach.

The advantage for no-tillage from option 1 – engaging a no-tillage versus tillage contractor – was US$36/ha/year. The advantage for no-tillage from option 3 – retaining ownership of used tillage equipment versus purchasing used no-tillage equipment – was US$30/ha/year and for option 5 – retaining ownership of used tillage equipment versus engaging a no-tillage contractor – was US$34/ha/year. Cost advantages for no-tillage would be expected to increase when sale of the existing tillage equipment became feasible.

Machine impacts on crop yields and economic risk

The effect of any one no-tillage drill design on crop yield and risk (and therefore economic returns) will be more important than its initial cost, when compared with either tillage or cheaper no-tillage alternatives. This belief has caused the research and development of improved no-tillage machines and systems as a means to reduce the risks associated with the practice, almost regardless of cost. The following analyses of machine capability versus expected crop yields and the resulting economics clarifies this belief.

The per-hectare charges that no-tillage contractors (custom drillers) make for their services are a good barometer of the relative costs associated with different no-tillage machines and systems. If we take New Zealand contractors as an example, we find that those with advanced (expensive) no-tillage drills in 2004 charged between US$72 and US$96/ha for their services, whereas those with lesser (cheaper) drills charged between US$36 and US$60/ha.

Differences between the ranges of charges are attributable mainly to differences in the initial costs of the two classes of machines and the different sizes of tractors needed to operate them. Differences within both ranges of costs reflect differences in the costs of competing options (such as tillage) together with differences in work rates and maintenance costs brought about by different field sizes, shapes, topographies and soil types (including abrasiveness).

Taking the midpoint of each scale, the premium a farmer therefore paid in New Zealand in 2004 for access to a more advanced drill was about US$36/ha. Actual contractor charges in other countries will differ from these figures but the relativity between the costs associated with advanced machines and lesser machines is likely to be similar.

So a key question is: How much does an advanced no-tillage drill have to increase crop yields in order to justify the US$36/ha premium paid for the better technology under 2004 price conditions?

Wheat sold in New Zealand in 2004 for approximately US$170/t. The average yield of spring-sown wheat in New Zealand in 2004 was 5.7 t/ha and the average autumn-sown wheat yield was 7.4 t/ha (N. Pyke, Foundation for Arable Research, 2004, personal communication). Gross returns for average spring- and autumn-sown wheat crops in 2004 were therefore US$969/ha and US$1258/ha, respectively.

To recover an additional US$36/ha in the costs of no-tillage drilling would require an increase in yield of 0.21 t/ha (or 210 kg/ha). This represented a 3.7% increase in yield of a spring-sown wheat crop or a 2.9% increase in an autumn-sown wheat crop.

Such yield increases have been common. For example, the US Department of Agriculture obtained an average of 13% wheat yield increase in seven separate experiments over a 3-year period in Washington State by switching to a more advanced no-tillage drill compared with the best 'other' no-tillage drill that was then available (Saxton and Baker, 1990). Similarly, the New South Wales Department of Agriculture

(Australia) recorded an 11-year average of 27% yield advantage from soybean sown annually after oats using the same advanced no-tillage openers, compared with tillage (Grabski *et al.*, 1995).

Commercial field experience over a 9-year period in New Zealand, the USA and Australia suggests that such research-plot measurements have been a realistic reflection of field expectations. Wheat and other crop yields approaching twice the national averages have become common from no-tillage practised at its most advanced level.

Conclusions

It can be said that, when comparing the economic risks of tillage and no-tillage, more management and more sophisticated machinery are needed to undertake no-tillage correctly and successfully. But, if the appropriate management and machinery are used and the reasons for these choices are understood, there will be no more and often less economic risk with no-tillage than with tillage. All of the various forms of risk come together in the multiple-year rotations required of modern farming in an integrated management system. Figure 3.4 illustrates the results of a comprehensive assessment of financial risk made during 6 consecutive years of experiments by Young *et al.* (1994) in Washington State, USA.

These experiments compared the combined results of conservation tillage, which included several consecutive years of no-tillage, versus conventional tillage, the effects of maximum, moderate and minimum weed control and crop rotations, all under a high level of agronomic management. Considering all treatments and 6 years of variable weather factors, conservation tillage had the smallest economic risk due to conserved moisture, good yields and low inputs. They concluded that the winter wheat–spring barley–spring peas rotation at maximum or moderate weed management

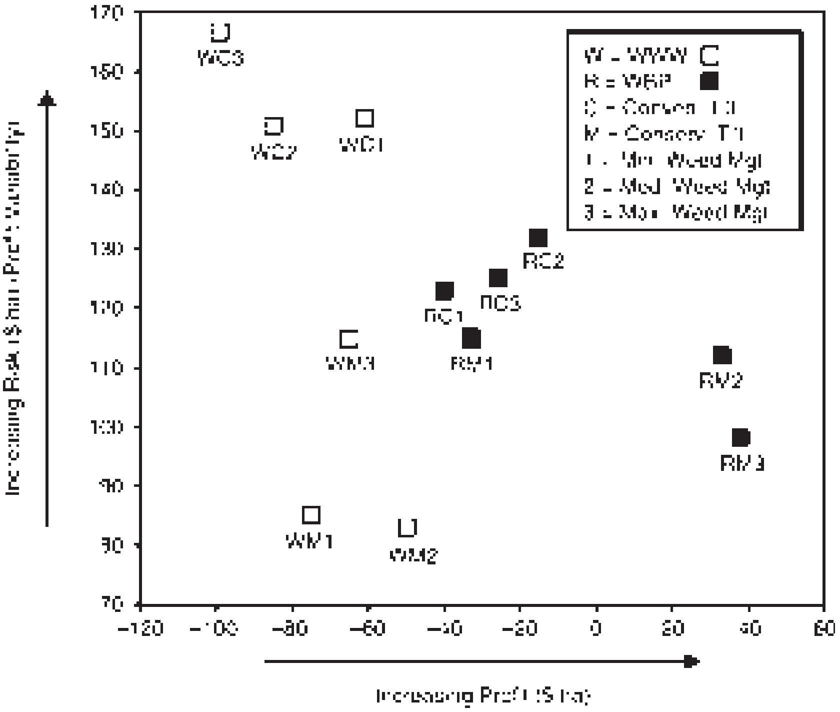


Fig. 3.4. Profit and risk analyses for 12 cropping systems in the Palouse area, Washington, 1986–1991 (from Young *et al.*, 1994). WWW, wheat, wheat, wheat rotation; WBP, wheat, barley, peas rotation.

levels (RM3 or RM2) dominated all other systems in profitability (profit of $30–40/ha) and had the lowest economic risk or 'profit variability'.

Summary of the Nature of Risk in No-tillage

1. The perception that no-tillage involves greater risk than tillage is one of the greatest impediments to its more widespread adoption.
2. The combination of all the components of risk manifests them as economic risk.
3. The components of risks in no-tillage are biological, physical and chemical.
4. Biological risks relate to pests, toxins, nutrient stress, seed vigour, seedling vigour, disease and impaired crop yield.
5. Physical risks relate to weather, slot micro-environment and machine performance and reliability.
6. Chemical risks relate to the supply and availability of plant nutrients, seed 'burn' from fertilizers and the effectiveness of application of chemical herbicides and pesticides.
7. The function and design of no-tillage seed drills can have an influence on pests, toxins, nutrient stress, diseases, fertilizer 'burn', slot micro-environment, machine performance and durability and the supply and availability of plant nutrients.
8. Performed correctly with appropriate equipment, no-tillage has no more, and often less, total risk than tillage, even in the short term.
9. Performed incorrectly with inappropriate equipment, no-tillage has greater associated risk than tillage.
10. It is often 'false economy' to cut costs in no-tillage, particularly in machine effectiveness, as the savings in cost may be much less than the reductions in crop yield that are likely to result.

4 Seeding Openers and Slot Shape

C. John Baker

Very few no-tillage openers were originally designed for untilled soils. Most are adaptations of conventional openers for tilled soils.

A seeding opener is the soil-engaging machine component that creates a ‘slot’, ‘furrow’ or ‘opening’ in the soil into which seed and perhaps fertilizer and insecticide are placed. Different shapes of soil slots may be created by conventional and no-tillage openers. The most important feature is the cross-sectional shape, as if you had cut across the opener path after its passage with a knife and were looking at the vertical exposed face.

Openers are the only components of a no-tillage drill or planter that actually break the soil surface. In no-tillage seeding, they are required to perform all of the functions necessary to physically prepare a seedbed as well as sow the seed and perhaps fertilizer. In contrast, in conventional tillage a succession of separate tillage tools are used to prepare the seedbed, and the seed drill then only has the relatively simple task of implanting the seed and perhaps fertilizer into a pre-prepared medium.

A large amount of scientific evidence shows that the most important aspect of the mechanics of different no-tillage opener designs is the shape of the slots they create in the soil and their interaction with seed placement and seedling emergence and growth. Generally, there are three basic slot shapes created by no-tillage openers and two other ways of sowing seed that do not involve creating a continuous soil slot at all: (i) V-shaped slots; (ii) U-shaped slots; (iii) inverted-T-shaped slots; (iv) punch planting (making discrete holes in the ground and sowing one or more seeds per hole); and (v) surface broadcasting (seeds randomly scattered). Only one slot shape, the inverted-T slot, is used in no-tillage that has not been an adaptation of a slot shape already used for tilled soils.

Figure 4.1 is a diagrammatic representation of slot shapes i–iii as created in a silt loam soil at three different moisture contents (Dixon, 1972). The mechanics of each of these seeding methods and the resulting characteristics will be further discussed in detail in the following sections.

Several authors (e.g. Morrison *et al.*, 1988; Bligh, 1991) have compiled lists and diagrams of openers and in some cases compared observations of field performance. But few detailed scientific studies have been made in which all but the important variables being studied have been controlled or accurately monitored. Such studies (which also included some new and innovative designs) are reported below.

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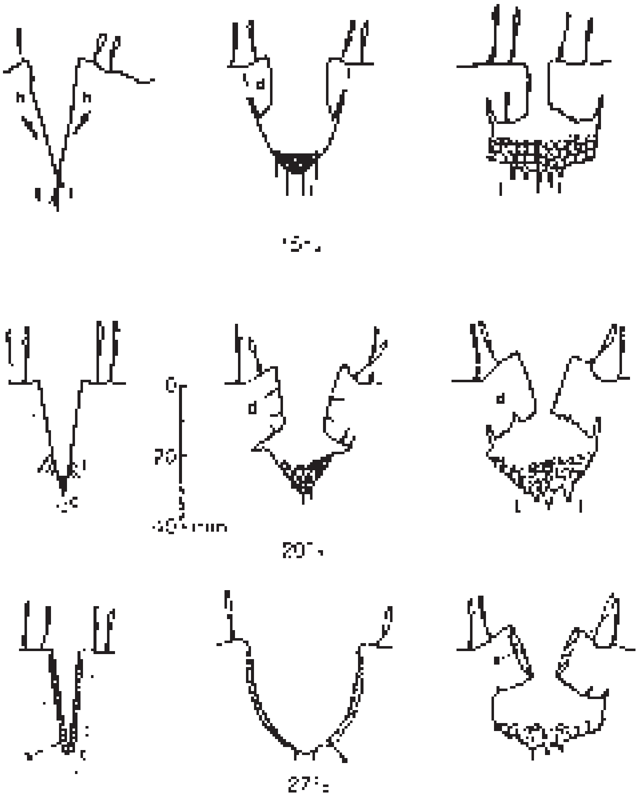

Fig. 4.1. Typical profiles of vertical V- (left), U- (centre) and inverted-T- (right) shaped no-tillage seed slots in a silt loam soil at 15%, 20% and 27% moisture contents (from Dixon, 1972).

Vertical Slots

V-shaped slots

In untilled soils, V-shaped slots are almost invariably created by two discs that touch (either at their bases or behind this position) and are angled outwards towards their tops. The two discs are not always of equal diameter. The included angle (the angle of the V) is usually about 10°, but this is not critical. Seed is delivered into the gap between the two discs, preferably rearwards of the centre 'pinch point', so as to prevent the seed from being crushed as the discs come together.

When arranged so that both discs are at the same angle to the vertical, the slot has a vertical V shape and is created by each of the angled discs pushing roughly equal amounts of soil sideways. The front edges of the two discs at the ground-surface level are apart from one another, which can cause a problem if residues enter the gap. To avoid this they are usually configured in one of the following three forms.

Double disc: offset (Fig. 4.2)

In this form one of the two angled discs (there is no third leading disc) is positioned forward of the other so as to present a single leading cutting edge and deflect residue. The second disc still forms the other side of a vertical V but its leading edge is nestled behind that of the first disc, thus avoiding residue blockage and reducing the magnitude of downforce required for penetration.

Double disc: unequal size (Fig. 4.3)

By placing the smaller of the two discs alongside its larger neighbour, the leading edge of the larger disc becomes the leading edge of the whole assembly in much the

Fig. 4.2. Typical offset double disc no-tillage openers that create vertical V-shaped slots.

Fig. 4.3. Typical unequal-sized double disc no-tillage openers that create vertical V-shaped slots.

same way as for the offset design. Often, the smaller disc is also offset.

Triple disc (Fig. 4.4)

In this form a third vertical disc is placed ahead of, or between, the two angled discs. This additional disc cuts the residue sufficiently for the two following discs to deflect it sideways. The third disc, however, adds to the amount of downforce required for penetration.

All forms of double disc and triple disc openers create vertical V-shaped slots since the actual slot shape is created by the two angled discs, regardless of their sizes or offsets. The third (leading) disc in the triple disc configuration mainly cuts the residue and influences the slot in a minor way. The triple disc design with the leading disc operating slightly below the bases of the two angled discs reduces some of the detrimental effects of 'hairpinning' (see Chapter 7, 'Drilling into Wet Soils') and root penetration problems common to both double and triple disc configurations. Similarly, by using a wavy-edged leading disc (sometimes referred to as a 'turbo disc'), a degree of soil loosening will usually be achieved ahead of the two angled discs and this helps offset the compacting tendencies of the following double discs.

The action of vertical double disc openers in the soil is to wedge the soil sideways and downwards in a V formation. They do not normally heave or raise the soil upwards. In some very sticky soils that cling to the outsides of the discs, some of that soil will be torn away and carried upwards, leaving a disrupted slot (Fig. 4.5).

Figure 4.6 shows the zones of compaction created by a vertical triple disc opener operating in a normal manner in a silt-loam soil (Mitchell, 1983).

From a dry soil perspective, the most distinguishing feature of the slot is the neatness of the vertical V-shaped cut, unless the soil is friable, in which case this neat cut may collapse. But even friable soils progressively become more structured and less friable (as organic matter levels and microbial action increase under no-tillage). Thus, with time, most vertical V-shaped slots become more clearly defined and less likely to collapse of their own accord after passage of the opener.

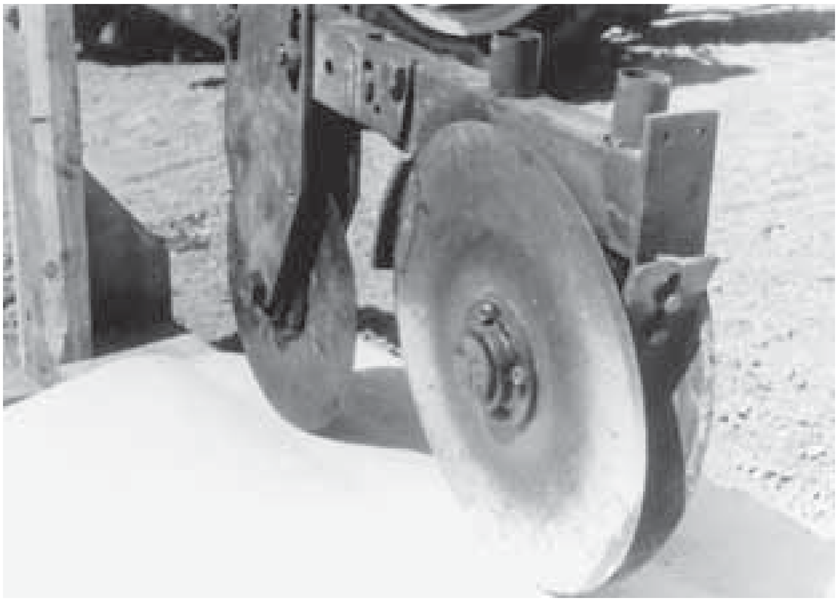

Fig. 4.4. A typical triple disc no-tillage opener that forms a V-shaped slot (from Baker, 1976b).

Fig. 4.5. A slot created by a vertical double disc opener in wet sticky soil in which the soil has stuck to the outside of the disc and been pulled up from the slot zone.

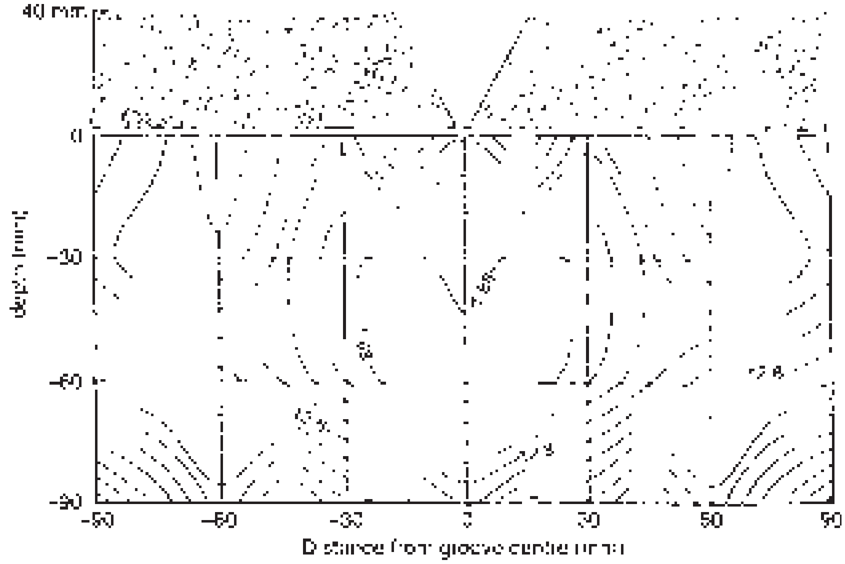

Fig. 4.6. The pattern of soil strength around a vertical V-shaped no-tillage slot as created by a triple disc opener in a damp silt loam soil (from Baker *et al.*, 1996).

Because of its wedging action, there is often little or no covering material available to cover seeds placed into the bottom of the V slot. This is even more of a problem when the opener is used in a moist, non-friable soil. Figure 5.1 illustrates such a situation. The plastic nature of the moist soil prevents the formation of loose soil crumbs, which might otherwise fall back over the seed as covering material (see Chapter 5).

The usual recourse is to follow vertical double disc openers with some configuration of V-shaped press wheels arranged so that they squeeze the soil in the opposite direction to the discs after the seed has been deposited (Fig. 4.7). Unfortunately, this action is also one of compaction, albeit in the opposite direction to the original forces. In an untilled soil, the wedging action of vertical double disc openers does little, if anything, to create a favourable environment for seeds.

The greatest advantages of vertical double disc openers are: (i) their construction is relatively simple and maintenance-free, although the latter attribute depends on the use of good bearings and seals; and (ii) their ability to pass through surface residues without blockage.

The most important disadvantages are: (i) the high penetration forces required; (ii) their poor performance in suboptimal soil conditions; (iii) their tendency to tuck (or ‘hairpin’) residue into the slot, which in dry soils interferes with seed–soil contact and in wet soils results in fatty acid fermentation that kills germinating seeds (Lynch, 1977); and (iv) the inability of individual openers to separate seed from fertilizer in the slot. Indeed, due to the shape of the slot, vertical double disc openers tend to concentrate the seed and fertilizer together at the base of the slot more than other openers (Baker and Saxton, 1988; Baker, 1993a, b).

Despite these shortcomings, vertical double disc openers have been included on more no-tillage drill designs than any other opener design to date. Unfortunately, however, because of their dependence on favourable soil conditions to achieve acceptable seeding results (or, more correctly, their intolerance of unfavourable conditions), they have also been responsible for much of the perception that risk increases with the practice of no-tillage.

It is important to emphasize the distinction between tilled and untilled soils and to illustrate the dangers inherent in deriving designs of no-tillage machines from those that had been successful in tilled soils. Tilled soils are naturally soft before seeding and the wedging action of vertical double disc openers is generally beneficial,

Fig. 4.7. Press wheels arranged in a V configuration for closing no-tillage slots created by vertical double disc openers (from Baker, 1981a, b).

especially when the soil is dry. It consolidates the soil alongside and beneath the seed, which results in increased capillary movement of water to the seed zone. Covering is seldom a problem in tilled soils, because the entire seedbed is comprised of loosened soil. Thus, in many ways, V-shaped openers are an advantage in tilled soils, whereas they have serious shortcomings in untilled soils.

Other mechanical forms of vertical V-shaped openers for tilled soils simply do not work in untilled soils because they will not penetrate in the less friable conditions. These include sliding shoe-type openers and V-ring roller openers (Baker, 1969b). Further consideration of these designs is not justified since they simply cannot effectively seed no-tilled soils.

Slanted V-shaped slots

To reduce the compaction tendencies of vertical V-shaped slots, some designers have slanted double or triple disc openers at an angle to the vertical, and sometimes also angled to the direction of travel. When they are slanted vertically, the uppermost disc pushes the soil partially upwards, thus reducing the compaction that otherwise results from the soil being displaced only sideways by vertical double disc openers. The lowermost disc on slanted double disc openers, however, is then forced to displace soil in a more downward direction, adding to its compaction tendency. Since roots mainly travel in a downward direction, it is debatable whether or not the slanting of double or triple disc openers overcomes the disadvantages inherent from their tendency to compact the slot in the root zone. On the other hand, slanting of V-shaped slots undoubtedly makes them easier to cover, since a near-vertical press wheel is required to shift soil more in a downward direction than sideways.

Two slanting double discs can be combined in such a way that the front pair of discs (which are angled vertically in one direction) sow fertilizer and the rear pair of discs (which are angled vertically in the opposite direction) sow seed at a shallower depth. Not only does this effectively separate seed and fertilizer in the vertical plane, but additionally the zone that would normally be compacted below the seed by the lowermost disc of the rear opener is pre-loosened by the uppermost disc of the front opener, thus partly negating the undesirable compaction effect of the seeding opener. Figure 4.8 shows a pair of slanted double disc openers.

Single discs that are angled in relation to the direction of travel (and sometimes also slanted vertically) are discussed below.

U-shaped slots

There is a wide range of opener designs that form U-shaped slots (Baker, 1981a, b): (i) angled disc-type openers; (ii) hoe openers; (iii) power till openers; and (iv) furrowers.

The slots made by all of these designs are distinguishable from V-shaped slots by the slot bases being broad rather than pointed like a V. The slot-making action of

Fig. 4.8. A pair of slanted discs at opposing angles. The front discs place fertilizer and the rear discs place seed at a shallower depth. (From Baker *et al.*, 1996.)

each of these openers is quite different, even though they all result in a similarly shaped slot, but none of the openers has the downward wedging action of double disc openers. Thus there is less soil compaction associated with all U-shaped slots than with V-shaped slots.

Angled disc-type openers mostly scrape soil away from the centre of the slot; hoe- and furrow-type openers burst the soil upwards and outwards; power till openers chop the soil with a set of rotating blades; and furrow-type openers scoop the soil out from the slot zone. Further, all of the designs produce some loose soil on the surface near the slot, which can be used to cover the slot again, although in all cases this usually requires a separate operation to drag this soil back over the slot (see Chapter 5) and its effectiveness is soil-moisture-dependent.

Angled disc-type openers

The action of angled discs is mostly (although not entirely) one of scuffing. Vertical angled discs are angled slightly to the direction of travel (normally about 5–10 degrees). Seed is delivered to a boot located at or below ground level, close to the rear (lee) side of the discs where it is largely protected from blockage by residue because of the angle of the disc. There are two forms of angled vertical disc opener.

ANGLED FLAT DISCS (FIG. 4.9). This type uses a vertical flat disc (i.e. it has no undercutting action) angled to the direction of travel. The disc and supporting bearings need to have considerable inherent strength since the side forces are quite large, especially when operating at some speed and/or in plastic soils that resist sideways movement. Because the discs continually have a sideways force, they are often configured in pairs with each pair of discs at opposite angles so that the side forces of the entire machine cancel (see Fig. 4.9).

Where the discs are not arranged in pairs, difficulty is sometimes experienced in turning corners in one direction with the drill, while turning in the other direction poses no problem. This is another example in which the requirements of no-tillage are different from tillage, since the soil forces in tilled soils are sufficiently low to not cause problems when cornering with angled disc-type openers.

Fig. 4.9. A pair of angled flat disc no-tillage openers (from Baker *et al.*, 1996).

Relatively steep side-slope drilling causes machine 'tailing', in which the whole machine pulls at an angle to the direction of travel because of gravity pulling the drill sideways. This poses a problem for drills arranged with half of the openers angled in each direction. That part of the drill in which the openers are caused to travel with no angle creates very small, ineffective seed slots, while the other openers double their angle and create extra wide slots that are difficult to cover.

ANGLED CONCAVE DISCS. This type uses a slightly concave, near-vertical disc set at an angle to the direction of travel (Fig. 4.10). The strength derived from the curvature of the disc allows thinner steel to be used in its construction, assisting in soil penetration. The axle of angled dished discs can be either horizontal or slightly tilted from the horizontal in either direction.

If the axle is tilted downwards on the convex (back) side of the disc, the action of the disc will be to undercut the soil like a disc plough. The benefits of this action are that the displaced soil is not thrown to one side where it is otherwise often difficult to retrieve again for covering purposes, as it is lifted, hinged and inverted. The disadvantages are that, in soils that are held together by plant roots (e.g. pasture), a soil flap is produced, which falls back over the seed. Since the seed is placed under the 'hinged' end of this flap, this can restrict seedling emergence. Figure 4.11 shows an angled dished disc that has had a small scraper added to attempt to slice this flap off.

If the axle is tilted upwards on the convex (back) side of the disc, it has the effect of confining the disc action to one of scuffing only, with little or no undercutting. Because of the disadvantages of undercutting, this has become the most commonly preferred option with concave disc openers for no-tillage, along with arranging them with the disc axle horizontal.

TILTED AND ANGLED FLAT DISCS. Some designers have tilted as well as angled the flat discs on their openers (Fig. 4.11). This has mainly been to reduce the throwing action of angled discs so that there is less soil disturbance and also to provide more of a mulch cover than where the discs stand vertically upright. Tilting the discs may also help

Fig. 4.10. An angled dished disc no-tillage opener (from Baker *et al.*, 1996).

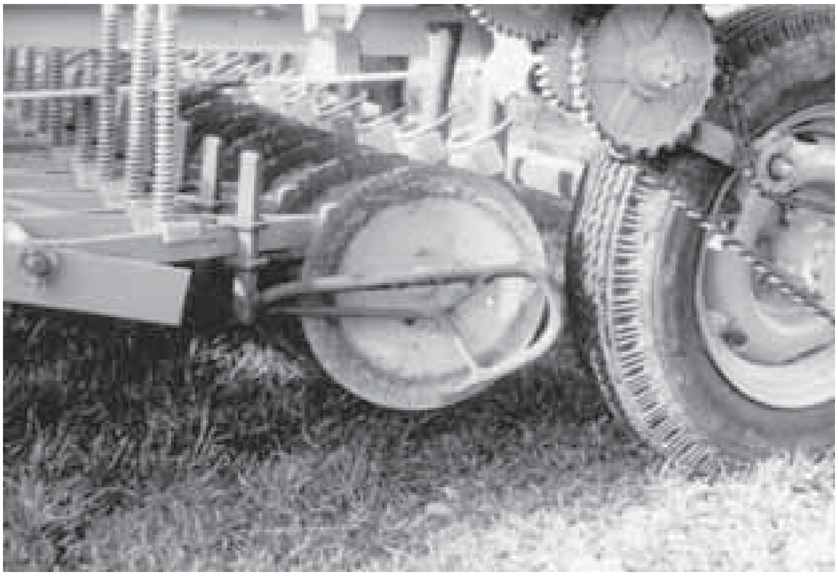

Fig. 4.11. An angled dished disc no-tillage opener with both vertical and horizontal angle. This opener also features a scraper to cut and remove the turf slice. (From Baker *et al.*, 1996.)

penetration and reduce the hillside operation problem discussed above. But it does nothing to reduce the tendency of such openers to hairpin residues into the slot, which interferes with seed germination and/or seedling emergence. Nor do such openers solve the problem of fertilizer placement, since no more opportunity exists to separate fertilizer from seed than with any other configuration of angled disc.

The actions of all angled discs (flat or concave, upright or tilted) are very much dependent on their operating speed. Because all variations depend on at least angulation to the direction of travel (if not also angulation to the vertical) for much of their slot-creating actions, the speed with which they approach the soil has a marked effect on the amount of soil throw and therefore the width and shape of the resulting slot. At higher speeds, the slots tend to be wider and shallower than at slower speeds and the loose soil available for covering tends to be thrown further to one side, where it is more difficult to retrieve. In common with discs that travel straight ahead, the penetration of angled discs is also reduced with increasing speed, but this can be countered by simply increasing the downforce to achieve penetration.

The two biggest advantages of all angled discs are their ability to handle surface residues without blockage and their avoidance of compaction or smearing of the slot at the base and on at least one side wall. They are also relatively cheap, simple and maintenance-free.

The biggest disadvantages of angled disc openers are: (i) they tuck or hairpin residues into the slot in a similar manner to double disc openers; (ii) they make U-shaped slots, which, especially if wide at the top, dry easily despite the presence of loose soil; (iii) they are often difficult to set for correct operation; (iv) they may angle and operate poorly on hillsides; (v) they are not able to separate seed from fertilizer in the slot; (vi) they are affected by the speed of travel; and (vii) they wear rapidly.

Hoe- or shank-type openers

The term hoe or shank describes any shaped tine or near-vertical leg that is designed to penetrate the soil. Seed is delivered either down the inside of the hollow tine itself or down a tube attached to its back.

The shapes of hoe or shank openers range from winged (Fig. 4.26, p. 54), which are often also designed to separate seed and fertilizer simultaneously in the slot, through blunt bursting openers (Fig. 4.12) to sharp undercut points, which are designed to make a relatively narrow slot and penetrate the soil easily (Fig. 4.13). Sometimes a pair of narrow shanks is arranged with horizontal offset to separately place seed

Fig. 4.12. A blunt hoe-type no-tillage opener (from Baker *et al*., 1996).

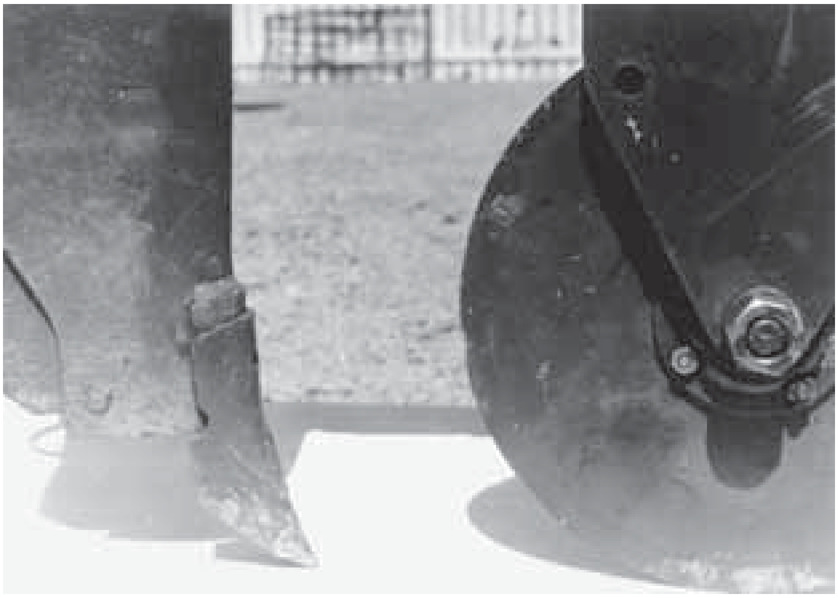

Fig. 4.13. A sharp hoe-type no-tillage opener (from Baker, 1976b).

and fertilizer (Fig. 4.14). One of the problems with hoe-type openers is that they wear rapidly; thus, the original shape seldom lasts long. Because of this they may take on several new shapes during their lifetime, making it difficult to generalize on the basis of slot shape.

Generally, all hoes scrape out a roughly U-shaped slot by bursting the soil upwards from beneath. In moist conditions they tend to smear the base and sometimes the side walls of the slot, but this only affects seedling root systems if the soil is allowed to dry and thus become an internal crust (see Chapter 5).

The bursting action produces considerable loose soil alongside the slot, which may be helpful when covering but can also leave severe ridging between rows. Because of this latter problem most shank-type openers are operated at low speeds (maximum 6–9 kph, 4–6 mph).

The nature and extent of the loose soil alongside the slot is also dependent on soil moisture content. Often, in damp plastic soils, no loose soil will be produced at all, while at other times a few hours of drying after drilling will produce crusty edges to the slots, which can then be brushed with a suitable harrow or dragged to at least partially fill the slot with loose soil. The most appropriate covering action after passage of hoe-type openers is therefore a matter of judgement at the time, which is one of their inherent disadvantages.

The biggest disadvantage of hoe or shank openers, however, is the fact that they can only handle modest levels of residues without blockage (also see Chapter 10), especially when arranged in narrow rows. The placement of a leading disc ahead of a hoe or shank opener, regardless of how or in what position it is placed relative to the hoe, cannot make a group of such openers arranged in narrow rows able to handle residues satisfactorily.

The most successful hoe or shank drill configurations for residue clearance have been to space the openers widely apart in multiple rows (ranks) in the direction of travel. This is based on the observation that, unless the residue is particularly heavy or damp or becomes wedged between adjacent openers, the inevitable accumulation of residue on each tine will usually fall off to one side, as a function of its own weight. If sufficient clearance is built into the spacing between adjacent tines, the falling off of clumps of residue will not block the machine – at least, not as often. These

Fig. 4.14. A pair of shank openers with horizontal offset. The front shank applies fertilizer while the rear shank applies seed offset to one side and sometimes shallower.

clumps of residue can cause problems for seedling emergence and later at harvesting, so it is questionable whether this action can be described as handling residue at all. Unfortunately, wide spacing demands undesirable dimensions from the whole drill, which compromises other functions such as the ability to follow the ground surface and seed delivery. Figure 4.15 shows a shank-type no-tillage drill with widely spaced openers.

Hoe or shank openers have several advantages: (i) they are relatively inexpensive; (ii) they can be made to 'double-shoot' seed and fertilizer relatively simply; (iii) they do not tuck (or hairpin) residues into the slot; in fact, they brush the residue aside, although this is a disadvantage for controlling the microclimate within the sown slot, as described in Chapter 5.

Their major disadvantages are: (i) a high wear rate; (ii) their poor residue handling ability; and (iii) their inability to separate seed from fertilizer in the slot (see Chapter 9).

Power till openers

Power till openers are an enigma in no-tillage. Because most people had become accustomed to tilling the soil before planting seeds, it seemed natural to till the soil in strips for no-tillage. Thus, power till openers consist of miniature rotary cultivators that are power-driven from a common source and literally till a series of narrow strips for the seed. While the tillage ensures that seeds will become well covered with loose soil, it has long been known that rotary tillage is one of the least desirable ways of tilling soil. Its main disadvantages, when applied either to general seedbed preparation or discretely in strips, is that it stimulates weed seed germination, is very destructive of soil structure and is power-demanding (Hughes, 1975; Hughes and Baker, 1977).

The actual placement of seed varies with design. With some, the seed is scattered into the pathway of the rotating blades and thus becomes thoroughly mixed with the soil, but depth of placement becomes random. With others, separate conventional openers for tilled soils (shoe, hoe or disc type) operate behind the rotating blades as if they were drilling into a fully tilled seedbed.

The advantages of power till openers are that the downforces required for penetration are little more than those commonly

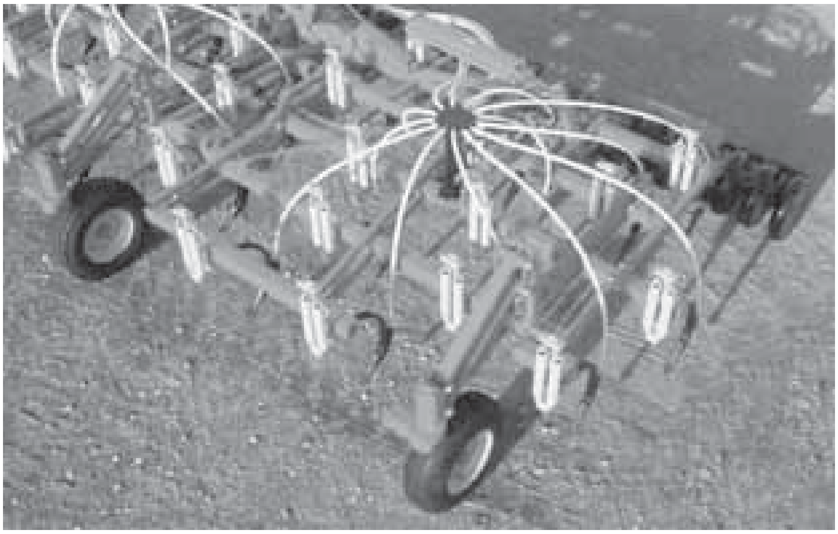

Fig. 4.15. A no-tillage drill with widely spaced shank-type openers designed to 'clear' residues.

required for tilled soils. Power till openers substitute power applied through the tractor power take-off (PTO) shaft to the rotors for the downforces and draft forces more common to other non-rotating types of no-tillage openers. They create U-shaped slots, they do not tuck residue into the slot, they generally cover the seed well and, in cold climates, where there might otherwise be a disadvantage from the slow decomposition of surface residues, they chop up this residue and incorporate it into the soil.

On the other hand, because they physically dispose of the surface residues in this manner, power till openers do little to micro-manage the residues close to the seed, which is one of the most important functions that successful no-tillage openers should perform. Further, few of them separate the seed from the fertilizer in the slot, although, because of the amount of loose soil in the slot, there is more mixing of fertilizer with soil, which provides partial separation from the seed.

Power till openers are relatively complex mechanical devices when compared with other opener designs. They have a particular problem with wear, surface following and damage from stones and other obstructions.

Early designs were adaptations of conventional field rotary cultivators. The normal wide L-shaped blades, which were mounted on a common axle driven by the tractor PTO, were replaced with sets of narrow L blades corresponding to the desired row width and spacing. These created the discrete rows of tilled soil. The width of the tilled strips varied from about 20 mm to 200 mm, depending on the objectives. Figure 4.16 shows the effects from a narrow set of blades, while Fig. 4.17 shows wider tilled strips.

In early designs each set of blades was mounted on a common axle, so it was impossible for each tilled strip to maintain a constant depth while traversing the normal undulations of the ground. Even the use of independently articulated seed-depositing openers, which followed in the tilled strips, could not fully compensate for areas of soil that had missed being tilled altogether because the machine had traversed a small hollow, for example. Figure 4.16 shows a common-axle-type power till drill with independently mounted seed-depositing openers.

Fig. 4.16. Narrow tilled strips left by a power till ‘no-tillage’ opener (from Baker *et al.*, 1996).

Fig. 4.17. Wide tilled strips left by a strip-tillage machine (from Baker *et al.*, 1996).

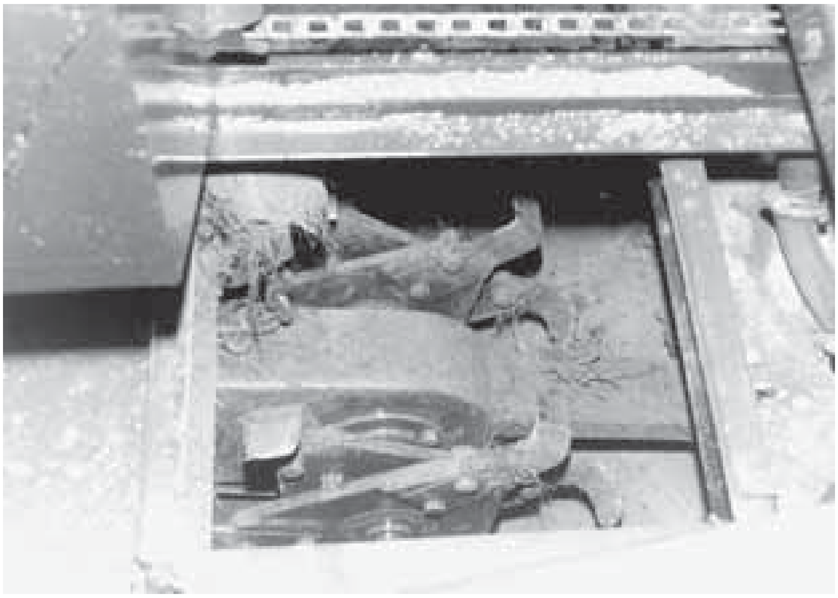

Fig. 4.18. Power till no-tillage openers arranged in pairs (from Baker, 1981a, b).

Later designs attempted to mount each rotating set of blades independently so that they were capable of following the soil surface. This proved to be inordinately expensive, because, while each set of blades required its own flexible drive train, it also had to offer some protection from stone damage. Belt drives allowed slippage in these circumstances.

Some designs compromised by mounting blade sets in pairs. Figure 4.18 shows the head of a twin rotor model in which the rotors are able to articulate up and down. Other designs attempted to power each rotor individually through a chain driven by a wavy-edged ground-engaging disc ahead of the rotor in the hope that the disc would slip in the soil when a stone was encountered by the rotor. Figure 4.19 shows such a device.

Although power till openers have been an obvious design route for many engineers, with a number of models released for commercial production around the world, very few have been commercially successful due to the disadvantages mentioned above. Perhaps their greatest use is where other openers cannot function. An example of such a condition is the revegetation of high-altitude pastures where ambient temperatures remain sufficiently low to discourage complete decomposition of organic matter. The result is a build-up, over centuries, of a mat of undecomposed vegetation, which can be several centimetres thick (Fig. 4.20) and which simply resists the operation of any other no-tillage opener except designs that physically chop it up and mix it with soil. In these conditions, the objective is to drill improved pasture species by no-tillage to increase animal carrying capacity on otherwise low-producing fragile farmland.

Power till openers in general create more short-term mechanical aeration within the slot than any other type of opener, although the benefits of this are usually temporary in comparison with openers that encourage natural aeration by earthworms (see Chapter 7). They have a tendency to compact the base of the slot, but, unlike double disc openers, this does not seem to cause difficulties for seedling roots.

Furrowers

One opener, designed in England especially for pasture renovation, consisted of two vertical discs, spaced laterally several centimetres apart, which cut two vertical slits. The discs were followed by a miniature mouldboard-plough, which scooped out the soil between the slits at the same time as it created a small track in the base of the broad U-shaped slot, where seed was deposited (Haggar, 1977; Choudhary *et al.*, 1985). The function of scooping was to eliminate weed competition in the seed zone without spraying and to allow early seedling development to take place in a sunken zone physically protected from

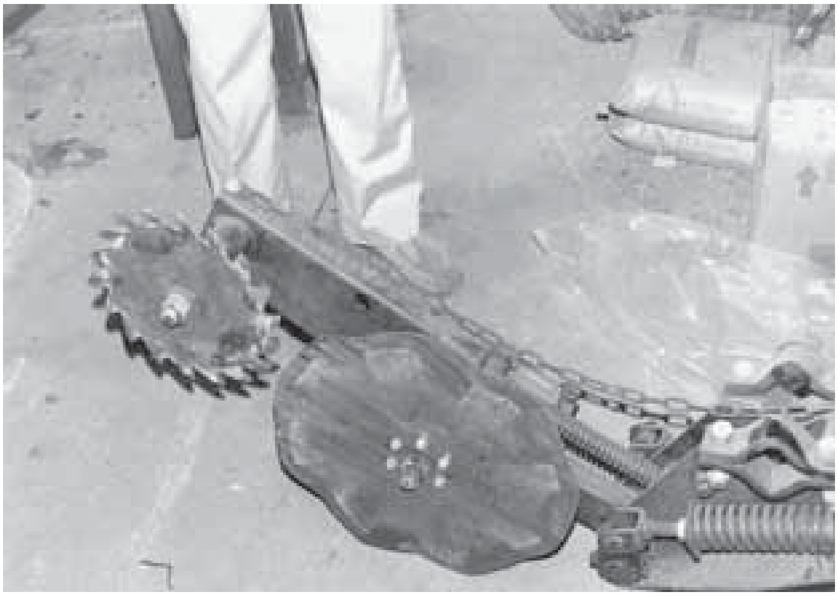

Fig. 4.19. A power till no-tillage opener driven by a ground-engaging wavy disc (from Baker *et al.*, 1996).

Fig. 4.20. Undecomposed sod in the Scottish Highlands (from Baker, 1981a, b).

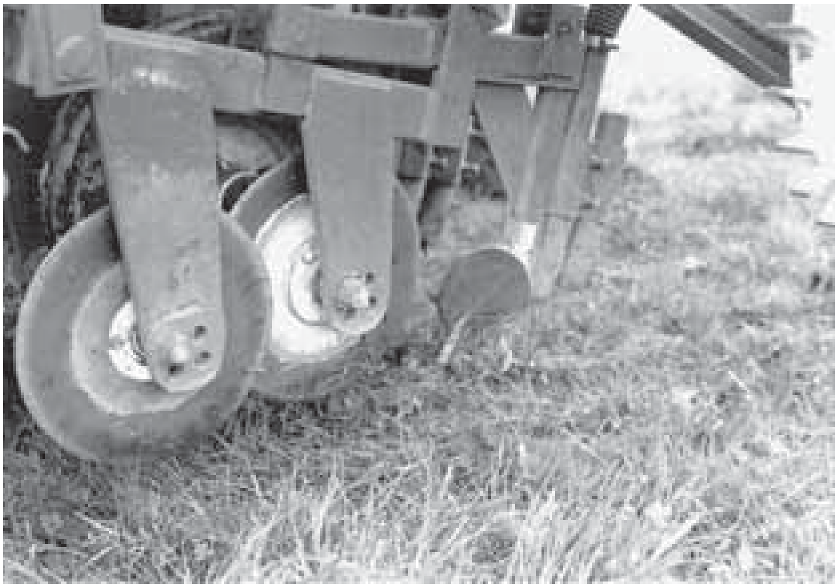

Fig. 4.21. A furrowing no-tillage opener (from Choudhary *et al.*, 1985).

treading by cattle (Fig. 4.21). Seed cover in the damp English climate is not a high priority, but such openers are regarded as specialist tools designed solely for one intended purpose.

Vibrating openers

Several designers have attempted to reduce the downforces required to push the discs and other components of no-tillage openers into the ground by causing the openers to vibrate. Such a task has been particularly demanding when applied to a disc since the vibration mechanism needs to operate on the disc hub as it rotates, as well as moving up and down in response to natural undulations in the ground surface. Individual vibrating hydraulic motors have been used on individual openers, which increase the cost, complexity and power requirement considerably. Very slow operating speeds and difficulty in keeping all bolts and nuts tight because of the general vibrations generated throughout the machine have also been disadvantages.

In the end, it is the shape and action of the soil-engaging components that determine the biological success or otherwise of no-tillage openers more than the forces required for penetration of draught. Vibrating openers do nothing to improve biological reliability. Most designers have found it cheaper to add weight and/or use a larger tractor to overcome penetration and draught forces than to engage relatively complex vibrating devices.

Horizontal Slots

Inverted-T-shaped slots

All of the openers discussed so far have been adaptations of openers designed originally for tilled soils (with the exception of the specialized furrow and vibrating openers). The modifications to such openers, when employed for no-tillage, have mostly consisted of increased robustness, with only minor changes in function.

The inverted-T-shaped slot is the only known horizontal no-tillage slot shape and is one of very few slot shapes that have been developed specifically for no-tillage purposes, with few functions applicable to tilled soils.

The inverted-T principle was developed when researchers explored geometrical alternatives to the more common V and U slot shapes to overcome several of their inherent disadvantages (Baker, 1976a). The researchers reasoned that the most radically different shape would be to invert the wide-top narrow-base V shape and to create instead a narrow-top, wide-base slot. Practicality dictated that the simplest way to achieve this was to construct an opener consisting of a vertical shank with sub-surface wings that were horizontal in the lateral plane but inclined downwards towards the front in the longitudinal plane.

The other reasoning behind the winged concept was that the designers wanted to be able to fold the residue-covered soil back over the slot for moisture conservation and seedling protection. Since wings tended to undercut the surface layer of soil with a horizontal slicing action, this would allow the formation of horizontal shelves on either side of a vertical slit. In most conditions the wing action also created horizontal flaps of residue-covered soil with which to cover the shelves. It was a major objective of the inverted-T concept to create horizontal slots with a high degree of control and predictability.

Two winged opener concepts were developed, both of which created essentially the same inverted-T-shaped slots.

Simple winged opener

The first simple winged opener design consisted of a vertical shank attached to the bottom of a hollow tine (Baker, 1976a, b). Figure 4.22 shows the original winged opener design. The opener was hollow, to allow passage of seed, and open at the back. The shank curved out at its base on both sides to form a pair of symmetrical wings, which were downwardly inclined towards their fronts by 10° and projected laterally approximately 20 mm either side.

A leading vertical flat disc was used ahead of the shank to provide a neat vertical cut through pasture. The leading disc was not expected to give the opener an ability to clear lying surface residue (see Chapter 10), but to ensure passage of the opener through standing pasture (sod) with minimal tearing and disruption to the soil surface.

A commercial company in New Zealand successfully adapted the winged opener concept for pasture renovation purposes. This market opportunity was based on

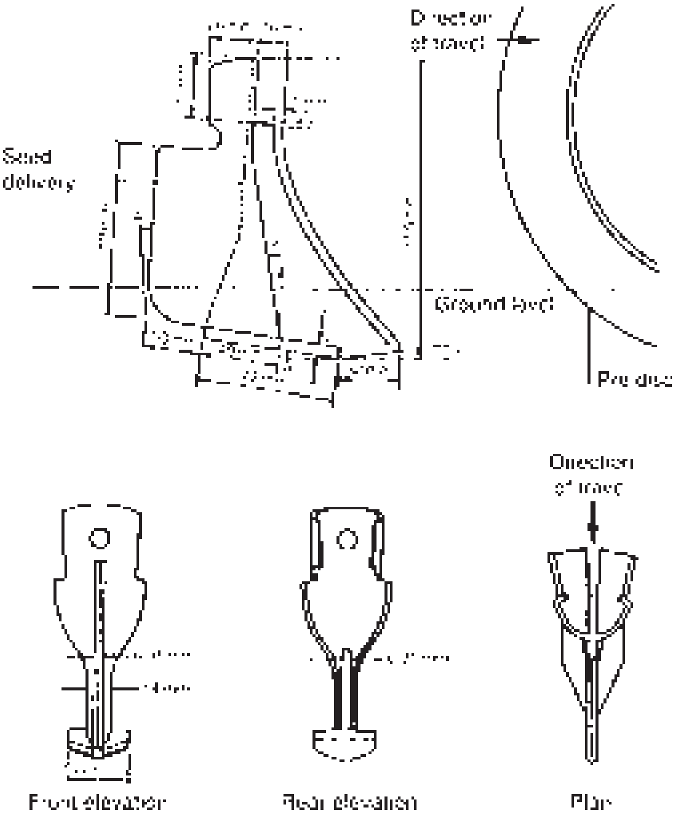

Fig. 4.22. The original inverted-T-shaped no-tillage opener (from Baker, 1976b).

knowledge that there is six times as much area of the world's surface under grazing land as there is under arable crop production (Kim, 1971; Brougham and Hodgson, 1992), although, of course, not all of the world's grasslands are accessible to tractors.

The design was simplified by fashioning the shank from plate steel and welding a vertical flat plate to its rear edge so as to entrap a wedge of soil ahead of this zone. Seed delivery was altered from the hollowed opener itself to a permanent tube positioned behind the vertical flat plate. The reasoning had been that, as the opener became worn and was eventually discarded, the modified design would allow the seed tube component to remain and only the minimum possible amount of replacement component would be discarded, thus reducing the cost. It was also reasoned that the soil wedge trapped ahead of the flat plate would reduce wear of the opener in that zone. Later, other designs also provided reversible and replaceable leading edges and tungsten overlays on the opener in an attempt to further reduce the effects of wear. Figure 4.23 illustrates a number of versions of the same modified opener, which eventually became known generically as the 'Baker boot', after the originator of the inverted-T principle.

Unfortunately, some of these benefits in the modified designs were achieved at the cost of retaining control over the exact shape of the slot. The thickness of the soil wedge that is retained by the vertical flat plate is a function of soil type, stickiness and moisture content. As a result, in sticky soils it is common for this soil wedge to become wider than the wings beneath it, with the result that the intended function for the wings to undercut the surface layer of soil is lost and the opener at times functions more as a wedge, creating a U-shaped slot.

Fig. 4.23. Several versions of the 'Baker boot' inverted-T-shaped no-tillage opener (from Baker *et al.*, 1996).

Although several manufacturers produced almost identical versions of the modified opener, not all of them provided a leading disc as originally envisaged, with the result that the slot edges were often torn and inconsistent, making controlled closure of the slot difficult, if not impossible. Since low cost was a primary objective with this simple opener, most designs attached the opener to very simple drills that had limited depth control (Fig. 4.24). One design provided a vertical pivot ahead of each opener to assist with cornering (Fig. 4.25).

Despite these shortcomings, the modified version of the simple inverted-T-shaped opener succeeded in its intended purpose of pasture renovation. Its principal advantage has been that the inverted-T-shaped slot, however poorly made, is demonstrably more tolerant of dry and wet soil conditions (see Chapters 6 and 7) than nearly all other opener designs, with the result that the success of the pasture renovation process improved noticeably.

The largest disadvantages of this opener have been that, by being a rigid shank, it has poor residue-handling qualities and speed of operation is limited. Where it is incorporated on simple drills, surface-following ability is limited.

Other designers have utilized the winged opener concept to separate the discharge of seed and fertilizer into two or more horizontal bands (double or triple shoot). Figure 4.26 shows a double-shoot winged opener.

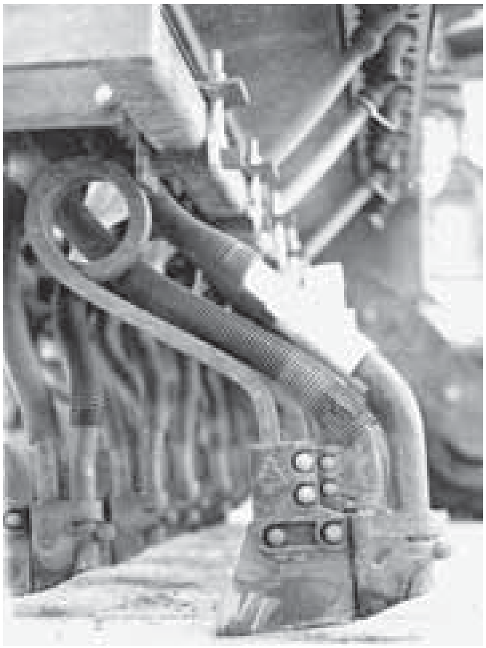

Fig. 4.24. A simple drill featuring 'Baker boot' inverted-T-shaped no-tillage openers (from Baker *et al.*, 1996).

Winged opener based on a central disc

Given the superior biological results obtained with the inverted-T-shaped slot concept from numerous experiments conducted in

Fig. 4.25. A simple drill featuring a self-steering version of the ‘Baker boot’ inverted-T-shaped no-tillage opener.

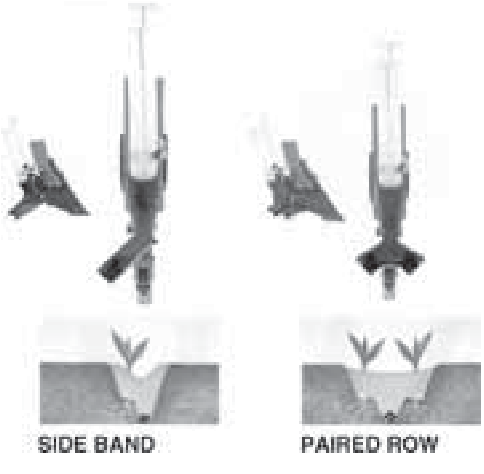

Fig. 4.26. Two versions of double-shoot winged openers.

New Zealand, Canada, Australia, Peru and the USA, it became imperative that the shortcomings of the simple opener should be overcome by designing a version that would suit arable agriculture as well as pasture-land. After all, it is the repeated tillage of arable land that has damaged the world’s most productive soils. The potential of no-tillage to reverse this process is fundamental to the long-term sustainability of world food production.

A number of functional principles were considered essential if such an opener were to become fully capable of such an assignment:

1. The most important aspect was to maintain the inverted-T shape of the slot itself, even at high forward speeds and shallow seeding depths.
2. Ability to reposition loose residue on top of loose soil to cover the horizontal slot, as well as to fold back more structured, previously untilled material such as flaps of turf.
3. Effective separation of seed and fertilizer in the slot with a single opener, and to perform this function reliably over a wide range of soil type, moisture contents and forward speeds.
4. Handling without blockage of surface residue, even when configured in narrow (150 mm, 6 inch) rows, in difficult conditions ranging from dry or wet crop stubble to tangled, well-rooted sod, on soils ranging from soft and wet to hard and dry.

5. Self-closure of the slot without undue soil compaction for seedling emergence.
6. Capability to maintain a constant seeding depth by consistently following the ground surface.
7. Replacement parts to be inexpensive and easily removed and replaced in the field.

The resulting design, shown in Fig. 4.27, has working principles quite unlike other openers designed for either tilled or untilled soils (Baker *et al.*, 1979c). Essentially, the disc version of the winged opener arose from splitting the simpler winged opener both vertically and longitudinally and rubbing the insides of the leading edges of the two sides against a central disc. It is centred on a single flat vertical disc (smooth or notched) running straight ahead to cut the residue and the vertical portion of the soil slot. Two winged side blades are positioned so that the interior of their leading edges rubs on either side of the central disc. This patented principle effectively sheds residue from the side blades without blockage.

Fig. 4.27. A disc version of the winged opener for creating inverted-T slots.

The winged side blades cut horizontal slots on either side of the disc at seeding depth by partially lifting the soil. Seed and fertilizer flow down special channels between the side blades and the disc on either side, respectively, and are placed on the horizontal soil shelf. To achieve this, the side blades are held sufficiently clear of the disc at their rear edges to form a passageway for seed or fertilizer. Such a gap is narrow in comparison with other opener designs but movement of even large seeds is facilitated by the fact that one side of the passageway comprises the moving face of the revolving disc.

The fertilizer blade can be made slightly longer than the seed blade so that the fertilizer can be separated vertically from the seed as well as horizontally, i.e. diagonally, although in most circumstances horizontal separation has proved to be sufficient, if not preferable (Fick, 2000).

Two angled semi-pneumatic wheels follow the blades to reset the raised soil and residue, thereby positively closing the slot. They also regulate the depth of each opener independently for excellent soil surface tracking and thus precise seed depth control. Each opener is mounted on parallel arms necessary to maintain the shallow wing angle at seeding depth for tracking the soil surface.

Figure 4.28 is a diagrammatic representation of the horizontal seed and fertilizer separation (double shoot) with the disc version of a winged opener. Separating seed and fertilizer and sowing both with the same opener greatly simplify the design of no-tillage drills and reduce power demand. Fertilizer banding has become an essential function of successful no-tillage seeding for most crops (see Chapter 9). Few, if any, other no-tillage openers effectively and simultaneously achieve these important functions in a wide range of soils and at realistic forward speeds.

The opener is designed especially for no-tillage into heavy surface residues and grass sod where simultaneous sowing of seed and fertilizer is a priority. Because the incline on the wings is set at only 5° to the horizontal (compared with 10° for the

Fig. 4.28. Horizontal separation of seed and fertilizer by the disc version of a winged opener.

simple inverted-T version), it is capable of drilling at depths as shallow as 15 mm. It functions equally well, without modification, in heavy crop residues, pastures and sports turf (Ritchie, 1988), and can be used unmodified to sow the full range of field crops and pasture seeds, as well as for precision drilling of vegetables (Ritchie and Cox, 1981), maize and horticultural crops. It commonly retains 70–95%, of surface residues intact. Figure 4.29 shows 95% residue retention after passage of a disc-version inverted-T opener.

The main advantages of the disc version of the inverted-T-shaped opener are that it fulfils all of the design objectives listed above, without compromise. The same opener can be used unmodified for precision seeders, as well as grain drills and pasture renovation machines, in tilled and no-tillage farming.

Its disadvantages are that it has a slightly higher draught requirement, is relatively expensive to construct and requires a heavy drill frame design to ensure proper functioning. The relatively high cost can be weighed against its ability to maximize and even improve crop yields beyond those commonly experienced with other no-tillage openers and even tillage (Saxton and Baker, 1990). An apparent economic disadvantage when put in the fuller context becomes very cost-effective.

Fig. 4.29. Almost complete replacement of residues over the slot created by a disc version of an inverted-T-shaped opener (Class IV cover).

Punch Planting

Punch planters make discrete holes into which one or more seeds are placed before moving on to the next hole. Ancient farmers used pointed sticks to make the holes because there was insufficient energy to make continuous slots and utilize the convenience of continuous flow of seed and fertilizer into them.

Modern engineering has attempted to mechanize punch planting so that it can be performed with less human labour and with greater accuracy and speed. The devices created have mostly consisted of steel wheels with split spikes attached to their rims. The split spikes are hinged at their bases so that they can be forced to open in much the same way as a bird's beak. Figure 4.30 shows an example of a prototype mechanized punch planter.

In operation, the opening and closing functions are actuated by an internal cam and synchronized with a seed dispenser.

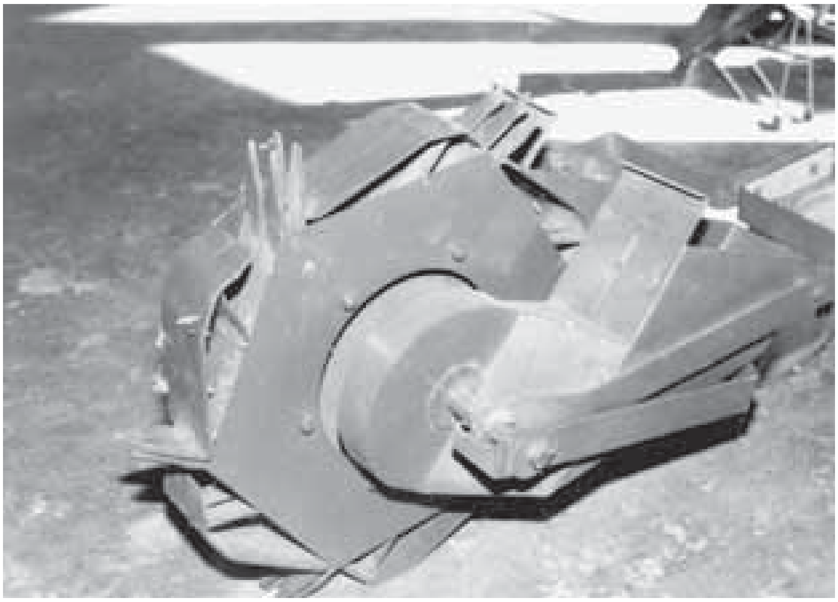

Fig. 4.30. A prototype mechanized punch planter (from Baker, 1981a, b).

After each spike has become fully embedded in the soil, a single seed or small group of seeds is directed from the dispenser tube, located in the centre of the wheel, through a hole in the rim of the wheel into the opened spike and deposited in the soil at a controlled depth and spacing from its neighbours.

Mechanized punch planters were seen as sensible solutions to mechanizing an ancient practice. Their relative mechanical complexity, however, has prevented their widespread adoption to date. The creation of V-shaped holes has all of the biological disadvantages of continuous V-shaped slots. This includes the tucking (hairpinning) of residues into the holes, difficulty in closing the holes and the wedging action of the spikes, which compacts soil under and alongside the seed zone.

Surface Broadcasting

There is little need to elaborate on the practice of surface broadcasting. Again, it is derived from an ancient practice brought about by the absence of energy sources for more mechanized solutions. Certainly, modern machinery is capable of mechanizing the broadcasting process with much increased speed and accuracy, but the absence of positive placement of seed beneath the soil significantly increases the biological risks from desiccation and bird, insect and rodent damage.

Broadcasting is not a recommended practice except in low-energy situations, and only then where local rainfall and humidity are so predictable and reliable that germination and rooting are assured. One thing in favour of no-tillage is that the retention of dead surface residues provides a protective canopy beneath which the humidity is likely to be higher than the surrounding ambient air (see Chapter 6). Research for many years has shown that effective seed and fertilizer placement beneath the soil produces crop yield advantages that surface broadcasting cannot duplicate.

One solution to broadcasting that reduces risk is ‘auto-casting’ in which seed is broadcast mechanically behind the pickup table of a combine harvester. The objective is to allow the straw and chaff to fall on top of the seed at the rear of the machine. This in turn ensures that there is a degree of cover over the seed, but success with this method is still very weather-dependent and there is no opportunity to strategically place fertilizers at the time of seeding. A dry period following harvest increases the risks of failure. Figure 4.31 shows an auto-casting system attached to the rear of a combine harvester table.

Summary of Seeding Openers and Slot Shape

The important functions of seeding openers are their abilities to:

1. Create a suitable seed/seedling micro-environment.
2. Avoid compacting and smearing of the slot walls.
3. Handle surface residues without blockage.
4. Micro-manage the surface residues so that they are positioned where they are of most advantage to the sown seeds/seedlings as well as the field in general.
5. Band seed and fertilizer simultaneously in the slot but separate them so as to avoid 'seed burn'.
6. Either avoid hairpinning altogether or avoid hairpinned residues affecting seed germination.
7. Self-close the slot.
8. Accurately control the depth of seeding.
9. Faithfully follow surface undulations that occur naturally in no-tillage.

The variety of slot shapes made by no-tillage seeding openers can be summarized as:

1. Vertical or horizontal.
2. Vertical slots are either V- or U-shaped.
3. Horizontal slots are usually inverted-T-shaped.
4. V- and U-shaped slots may also be slanted as well as vertical.
5. Compared with continuous slots, seeds can be sown in discrete holes (punch planting) or by surface broadcasting, mostly used where energy is limiting.
6. Most vertical and some slanted V- and U-shaped slots are adaptations of slots originally designed for tilled soils.
7. Most horizontal inverted-T-shaped slots were designed specifically for no-tillage seeding.
8. V-shaped slots are mainly created by double or triple disc openers.
9. U-shaped slots may be created by hoe, angled flat disc, angled dished disc, power till or furrow openers.
10. Inverted-T-shaped slots are created by winged openers.

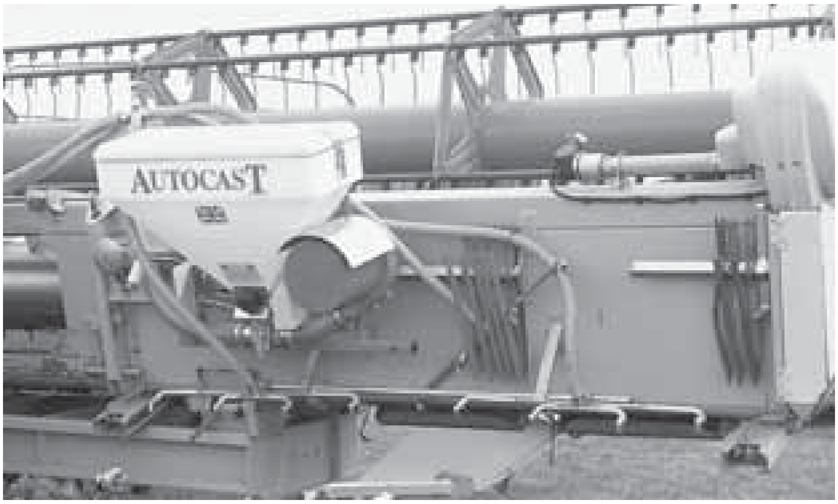

Fig. 4.31. 'Auto-casting' of seed behind the pickup table of a combine harvester.

11. The practices of punch planting and broadcasting have ancient origins but have also been mechanized.
12. There are higher risks of poor plant establishment associated with surface broadcasting than where seed is sown beneath the soil by openers.

The action of openers on the soil varies by the opener design as:

1. Vertical double disc openers in the soil predominantly cut, wedge and compact.
2. Slanted double disc openers cut and heave on the uppermost side and compact on the lowermost side.
3. Punch planters wedge and compact.
4. Hoe openers mostly heave and burst, plus cut if preceded by a disc.
5. Power till openers cut, mix and pulverize.
6. Vertical angled flat disc openers cut, scuff and throw.
7. Angled dished disc openers and slanted angled flat disc openers cut, scuff, fold and/or throw.
8. Winged openers heave and fold, plus cut if associated with a disc.

The advantages and disadvantages of various openers by design are:

1. *Double and triple disc* openers are low-maintenance and have good residue handling. Their disadvantages are V-shaped slots, especially when configured vertically; unreliable seedling establishment; high penetration forces; compaction and smearing of soil; difficulty in covering; no separation of seed and fertilizer (unless doubled up); seed implantation into hairpinned residue.
2. *Punch planter* openers are low-energy and maintenance. Their disadvantages are mechanical complexity, slowness, hole compaction, difficulty in covering and no separation of seed and fertilizer.
3. *Hoe* openers are low-cost, no hairpinning of residue and reasonable penetration forces. Their disadvantages are poor residue handling, high wear rates, smearing in wet soils and no separation of seed and fertilizer unless doubled up.
4. *Power till* openers mix undecomposed organic matter with soil, do not hairpin residue, low penetration forces, burial of seed and dilution of fertilizer with soil. Their disadvantages are poor residue handling, residue destruction, tillage, slot-base compaction, difficulty in handling stones and sticky soils, cost, mechanical complexity, weed seed stimulation, high maintenance and no ability to separate seed and fertilizer.
5. *Vertical angled flat disc* openers have reasonable penetration forces, scuffing action, residue handling and no smearing or compaction. Their disadvantages are seeding into hairpinned residue, no separation of seed and fertilizer (unless doubled up) and affected by forward speed.
6. *Angled dished disc* openers and slanted angled flat disc openers have scuffing action, residue handling and no smearing or compaction. Their disadvantages are high penetration forces, seed implantation in hairpinned residue, no separation of seed and fertilizer (unless doubled up) and affected by forward speed.
7. *Simple winged* openers provide horizontal inverted-T-shaped slots that are easily closed, reliable seedling emergence, no compaction, reasonable penetration forces and do not hairpin residues. Their disadvantages are poor residue handling, high wear rates and no separation of seed and fertilizer.
8. *Disc versions of winged* openers (centred on a vertical disc) provide horizontal inverted-T-shaped slots, self-cover slots, reliable seedling emergence, horizontal or diagonal separation of seed and fertilizer, good residue handling and micromanagement, no seed implantation in hairpinned residue, capable of high forward speeds, low compaction, low weed seed stimulation, good depth control and low maintenance. Their disadvantages are high initial costs, high penetration forces, and high draught.