17 Reduced Environmental Emissions and Carbon Sequestration

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While tillage agriculture contributes
significant greenhouse gases detrimental
to the atmosphere, no-tillage agriculture will
reduce them by both storing new SOM and
reducing the oxidation of existing SOM.

Introduction

Agriculture affects the condition of the environment in many ways, including impacts on global warming through the production of 'greenhouse gases', such as CO_2 (Robertson *et al.*, 2000). In 2004, the US Environmental Protection Agency (EPA) estimated that agriculture contributed approximately 7% of the US greenhouse gas emissions (in carbon equivalents, CE), primarily as methane (CH_4) and nitrous oxide (N_2O). While agriculture represents a small but relevant source of greenhouse gas emissions, it has the potential, with new practices, to also act as a sink by storing and sequestering CO_2 from the atmosphere in the form of soil carbon (Lal, 1999). Estimates of the potential for agricultural conservation practices to enhance soil carbon storage range from 154 to 368 million metric tons (MMTCE), which compare to the 345 MMTCE of reduction proposed for the USA under the Kyoto Protocol (Lal *et al.*, 1998). Thus, agricultural systems can be manipulated for the dual benefits of reducing greenhouse gas emissions and enhancing carbon sequestration. The influence of agricultural production systems on greenhouse gas generation and emission is of interest as it may affect potential global climate change. Agricultural ecosystems can play a significant role in production and consumption of greenhouse gases, specifically, CO_2.

Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the mouldboard plough, reduces the air-filled macropores and slows the rate of carbon oxidation. Any effort to decrease tillage intensity and maximize residue return should result in carbon sequestration for enhanced environmental quality.

Tillage-induced Carbon Dioxide Emissions

Tillage or soil preparation has been an integral part of traditional agricultural production. Tillage is also a principal agent resulting in soil perturbation and subsequent modification of the soil structure with soil degradation. Intensive tillage can adversely affect soil structure and cause excessive breakdown of aggregates, leading

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to potential soil movement via erosion. Intensive tillage causes soil degradation through carbon loss and tillage-induced greenhouse gas emissions, mainly CO_2, which have an impact on productive capacity and environmental quality.

Intensive tillage decreases soil carbon. The large gaseous losses of soil carbon following mouldboard ploughing compared with relatively small losses with no-tillage have shown why crop production systems using mouldboard ploughing have resulted in decreased SOM and why no-tillage or direct-seeding crop production systems are stopping or reversing that trend (Reicosky and Lindstrom, 1993). Reversing the trend of decreased soil carbon with less tillage intensity will be beneficial to agriculture as well as the global population through better control of the global carbon balance (Reicosky, 1998).

Emission measurements

The tillage studies reported in this chapter were conducted in west central Minnesota, USA, on rich soils high in soil organic carbon (Reicosky and Lindstrom, 1993, 1995; Reicosky, 1997, 1998). The CO_2 flux from the tilled surfaces in these studies was measured using a large, portable chamber, described by Reicosky (1990) and Reicosky *et al.* (1990), in the same manner as described by Reicosky and Lindstrom (1993) and Reicosky (1997, 1998). Measurements of CO_2 flux were generally initiated within 1 minute after the tillage pass and continued for various times. The CO_2 flux from the soil surface was measured using the large, portable chamber described by Reicosky and Lindstrom (1993).

Briefly, the chamber, with mixing fans running, was placed over the tilled surface or the no-tilled surface, the chamber lowered and data collected for 1 s intervals for a total of 60 s to determine the rate of CO_2 and water vapour increases inside the chamber. The chamber was then raised, calculations completed and the results stored on computer floppy disk.

The data included the time, plot identification, solar radiation, photosynthetically active radiation, air temperature, wet bulb temperature, output of the infrared gas analyser measuring CO_2 and water vapour concentrations in the same airstream. After the appropriate lag and mixing times, data for a 30 s calculation window were selected to convert the volume concentrations of water vapour and CO_2 to a mass basis and then regressed as a function of time using linear and quadratic equations to estimate the gas fluxes. These fluxes represent the rate of CO_2 and water vapour increase within the chamber from a unit horizontal land area as differentiated from a soil surface basis caused by differences in soil roughness. Only treatment differences in respect of tillage methods, tillage type or experimental objectives are described, with the results.

Tillage and residue effects

Recent studies, involving the dynamic chamber described above, various tillage methods and associated incorporation of residues in the field, indicated major carbon losses immediately following intensive tillage (Reicosky and Lindstrom, 1993, 1995). The mouldboard plough had the roughest soil surface, the highest initial CO_2 flux and maintained the highest flux throughout the 19-day study. High initial CO_2 fluxes were more closely related to the depth of soil disturbance that resulted in a rougher surface and larger voids than to residue incorporation. Lower CO_2 fluxes were caused by tillage associated with low soil disturbance and small voids, with no-tillage having the least amount of CO_2 loss during 19 days.

The large gaseous losses of soil carbon following mouldboard ploughing (MP) compared with relatively small losses with no-tillage (NT) or direct seeding have shown why crop production systems using mouldboard ploughing have decreased SOM and why no-tillage or direct-seeding crop production systems are stopping or reversing that trend. The short-term cumulative CO_2 loss was related to the soil volume disturbed by the tillage tools. Lower CO_2 fluxes were caused by tillage associated with low soil disturbance and small voids, with no-tillage having the least amount of CO_2 loss during 19 days. Similarly, Ellert and Janzen (1999) used a single pass with a heavy-duty cultivator that was relatively shallow and a small dynamic chamber to show that fluxes from 0.6 hours after tillage were two- to fourfold above the pre-tillage values and rapidly declined within 24 hours of cultivation. They concluded that short-term influences on tillage and soil carbon loss were small under semi-arid conditions, in agreement with Franzluebbers *et al.* (1995a, b).

On the other hand, Reicosky and Lindstrom (1993) concluded that intensive tillage methods, especially mouldboard ploughing to 0.25 m deep, affected this initial soil flux differently and suggested that improved soil management techniques can minimize the agricultural impact on global CO_2 increase. Reicosky (2001b) further demonstrated the effects of secondary tillage methods and post-tillage compaction in decreasing the tillage-induced flux. Apparently, severe soil compaction decreased porosity and limited the CO_2 flux after plough tillage to that of the no-tillage treatment.

This concept was further explored when Reicosky (1998) determined the impact of strip tillage methods on CO_2 loss after five different strip tillage tools were used in row-crop production and no-tillage. The highest CO_2 fluxes were from mouldboard plough and subsoil shank tillage. Fluxes from both slowly declined as the soil dried. The least CO_2 flux was measured from the no-tillage treatment. The other forms of strip tillage were intermediate, with only a small amount of CO_2 detected immediately after the tillage operation. These results suggested that the CO_2 fluxes appeared to be directly and linearly related to the volume of soil disturbed. Intensive tillage fractured a larger depth and volume of soil and increased aggregate surface area available for gas exchange, which contributed to the vertical gas flux. Narrower and shallower soil disturbance caused less CO_2 loss, suggesting that the volume of soil disturbed must be minimized to reduce carbon loss and the impact on soil and air quality. The results also suggest that the environmental benefits and carbon storage of strip tillage compared with broad-area tillage need to be considered in soil management decisions.

Reicosky (1997) reported that average short-term CO_2 losses 5 hours after the use of four conservation tillage tools were only 31% of that of the mouldboard plough. The mouldboard plough lost 13.8 times as much CO_2 as the soil area not tilled, while different conservation tillage tools lost an average of only 4.3 times. The benefits of residues on the soil surface to minimize erosion and smaller CO_2 loss following conservation tillage tools are significant and suggest progress in developing conservation tillage tools that can enhance soil carbon management. Conservation tillage reduces the extent, frequency and magnitude of mechanical disturbance caused by the mouldboard plough and reduces the large air-filled soil pores to slow the rate of gas exchange and carbon oxidation.

Reicosky *et al.* (2002) have shown that removal of maize stover as silage for 30 years of continuous maize, compared with returning the residue and removing only the grain, resulted in no difference in the soil carbon content after 30 years of mouldboard ploughing. Fertility level had no observable effect on CO_2 losses. The tillage-induced CO_2 flux data represented the cumulative gas exchange for 24 h for all treatments.

The pre-tillage CO_2 flux from the same area not tilled averaged 0.29 g $CO_2/m^2/h$ for the high-fertility plots at the start of measurements. This contrasts with the largest cumulative flux after tillage of 45 g $CO_2/m^2/h$ on a low-fertility grain plot. The CO_2 flux showed a relatively large initial flux immediately after tillage and then rapidly decreased 4 to 5 hours after tillage. The CO_2 flux decrease continued as the soil lost CO_2 and dried out to 24 hours, when values were lower but still substantially higher than those from the no-tillage treatment. The flux 24 h after tillage on the same plots above was approximately 3 g $CO_2/m^2/h$, considerably higher than the pre-tillage value.

The temporal trend was similar for all treatments, suggesting that the physical release controlled the flux rather than the imposed experimental treatments. The consistency of the C : N ratio across all four treatments suggests little effect of residue removal or addition and that mouldboard ploughing masked the effects of residue removal as silage or grain removal and above-ground stover returned. Intensive tillage with the mouldboard plough overshadowed any residue management aspects and resulted in essentially the same lower carbon content at the end of 30 years. The results suggest that intensive tillage with a mouldboard plough may overshadow any beneficial effect of residue management (return or removal) that might be considered in a cropping system.

Strip tillage and no-tillage effects on CO_2 loss

The impact of broad-area tillage on soil carbon and CO_2 loss suggests possible improvements with mulch between the rows and less intensive strip tillage to prepare a narrow seedbed, as well as no-tillage. Reicosky (1998) quantified short-term tillage-induced CO_2 loss after the use of strip tillage tools and no-tillage. Various strip tillage tools, spaced at 76 cm, were used and gas exchange measured with a large portable chamber. Gas exchange was measured regularly for 6 hours and then at 24 and 48 hours. No-tillage had the lowest CO_2 flux during the study and mouldboard ploughing had the highest immediately after tillage, which declined as the soil dried. Other forms of strip tillage had an initial flush related to tillage intensity, which was intermediate between these extremes, with both the 5 and 24 hour cumulative losses related to the soil volume disturbed by the tillage tool.

Reducing the volume of soil disturbed by tillage should enhance soil and air quality by increasing soil carbon content. These results suggest that soil and environmental benefits of strip tillage should be considered in soil management decisions. Limited tillage can be beneficial and do much to improve soil and air quality, minimize runoff to enhance water quality and minimize the greenhouse effect. The energy savings represent an additional economic benefit associated with less disturbance of the soil. The results suggest environmental benefits of strip tillage over broad-area tillage, which need to be considered when making soil management decisions.

The CO_2 flux as a function of time for each tillage method for the first 5 hours showed that mouldboard ploughing had the highest flux, which was as large as 35 g $CO_2/m^2/h$ and then rapidly declined to 6 g $CO_2/m^2/h$ 5 hours after tillage. The second largest CO_2 flux was 16 g $CO_2/m^2/h$ following subsoil shanks, which also slowly declined. The least CO_2 flux was measured from the no-tillage treatment, with an average flux of 0.2 g $CO_2/m^2/h$ for the 5 hour period. Other forms of strip tillage were intermediate and only a small amount of CO_2 was detected immediately after some tillage operations, which ranged from 3 to 8 g $CO_2/m^2/h$ and gradually declined to approach no-tillage values within 5 hours. These results suggest a direct relationship between the magnitude of the CO_2 flux that appears to be related to the volume of soil disturbed.

The cumulative CO_2 losses calculated by integrating the flux as a function of time for both 5 and 24 h periods showed similar trends. The values for 24 hours may be subject to error due to the long time between the last two measurements and tillage-induced drying, which may have caused the tilled treatments to dry out faster than the no-tillage treatments. The cumulative flux for the first 5 hours after tillage for mouldboard ploughing was 59.8 g CO_2/m^2, decreasing to 31.7 g CO_2/m^2 for the subsoil shank to a low of 1.4 g CO_2/m^2 for the no-tillage treatment. The strip tillage methods had slightly more CO_2 loss than no-tillage. Similarly, the cumulative data for the 24 h period reflect the same trend, the maximum release by mouldboard ploughing, 159.7 g CO_2/m^2, decreasing to 7.2 g CO_2/m^2 for no-tillage. The other forms of strip tillage were intermediate between these, which paralleled the 5 hour data. The results suggest that cumulative CO_2 loss was directly related to the soil volume disturbed by the tillage tool. The narrower and shallower soil disturbance caused less CO_2 loss.

The cross-sectional areas of the soil disturbed by the tillage were estimated from field measurements drawn to scale, using graphical techniques. The drawings were then cut out and run through an area meter. The cumulative CO_2 fluxes for 24 hours were then plotted as a function of these soil areas disturbed and showed a nearly linear relationship between the 24 hour cumulative CO_2 flux and the soil volume disturbed by tillage. These results suggest that intensive tillage fractured a larger depth and volume of soil and increased aggregate surface area available for gas exchange. This increased soil porosity and area for gas exchange contributed to the vertical flux, which was largest following mouldboard ploughing.

The results of short-term CO_2 loss from the strip tillage study for row crops suggest that, to minimize the impact of tillage on soil and air quality, the volume of soil disturbed must be minimized. Tilling the soil volume necessary to get an effective seedbed and leaving the remainder of the soil protected and undisturbed to conserve water and carbon to minimize soil erosion and CO_2 loss should be the preferred strategy. Limited tillage can be beneficial and do much to improve soil and air quality, minimize runoff to enhance water quality and minimize the greenhouse effect. The energy savings represent an additional economic benefit associated with less disturbance of the soil (West and Marland, 2002; Lal, 2004). The results suggest that the environmental benefits of strip tillage over broad-area tillage need to be considered when making soil and residue management decisions.

The concept that each soil has a finite carbon storage capacity is being revisited. This has important implications for soil productivity and the potential of using soil to enhance soil carbon storage and reduce greenhouse gases in the atmosphere. Most agricultural and degraded soils can provide significant potential sinks for atmospheric CO_2. However, soil carbon accumulation does not continue to increase with time with increasing carbon inputs but reaches an upper limit or carbon saturation level, which governs the ultimate limit of the soil carbon sink (Goh, 2004). The relation between no-tillage and conservation tillage in the way they affect soil carbon stocks is open to further debate and definition of carbon pools.

The relationship between tillage-induced changes in soil structure and subsequent effect on carbon loss was reviewed by Six *et al.* (2002) within the framework of a newly proposed soil C-saturation concept. They differentiated SOM that is protected against decomposition by various mechanisms from that which is not protected and discussed implications of changes in land management for processes that affected carbon release. This new model defined a soil C-saturation capacity, or a maximum soil carbon storage potential, determined by the physicochemical properties of the soil, and was differentiated from models that suggested soil carbon stocks increased linearly with carbon inputs. Presumably, this carbon saturation capacity will be soil-, climate- and management-specific. This causes a change in the thinking about carbon sequestration and that a soil-dependent natural limit may exist in both natural and managed systems.

Superimposed on this analysis is the role of glomalin, a sticky substance produced by fungal hyphae that helps glue soil aggregates together (Nichols and Wright, 2004). No-tillage is one management practice that has been successful in increasing the hyphal fungi that produce glomalin. The next researchable challenge will be to determine if the carbon saturation and glomalin over the entire profile in no-tillage and conservation tillage systems are substantially different. Presumably with less tillage-induced breakdown of soil aggregates, no-tillage may have an advantage over other forms of conservation tillage. The final answer awaits further research.

Carbon Sequestration Using No-tillage

Conservation agriculture is receiving much global focus as an alternative to the use of conventional tillage systems and as a means to sequester soil organic carbon (SOC) (Follett, 2001; Garcia-Torres *et al.*, 2001). Conservation agriculture can work under many situations and is cost-effective from a labour standpoint. More importantly, the practices that sequester soil organic carbon contribute to environmental quality and the development of a sustainable agricultural system. Tillage or other practices that destroy SOM or cause loss and result in a net decrease in soil organic carbon do not result in a sustainable agriculture. Sustainable agricultural systems involve those cultural practices that increase productivity while enhancing carbon sequestration. Crop residue management, conservation tillage (especially no-tillage), efficient management of nutrients, precision farming, efficient management of water and restoration of degraded soils all contribute to a sustainable agriculture.

Kern and Johnson (1993) calculated that conversion of 76% of the cropland planted in the USA to conservation tillage could sequester as much as 286 to 468 MMTCE over 30 years and concluded that US agriculture could become a net sink for carbon. Lal (1997) provided a global estimate for carbon sequestration from conversion of conventional to conservation tillage that was as high as 4900 MMTCE by 2020. Combining economics of fuel cost reductions and environmental benefits derived by converting to conservation tillage are positive first steps for agriculture towards decreasing carbon emissions into the atmosphere.

Soil tillage practices are of particular significance for the carbon status of soils because they affect carbon dynamics directly and indirectly. Tillage practices that invert or considerably disturb the surface soil reduce soil organic carbon by increasing decomposition and mineralization of biomass due to increased aeration and mixing plant residues into the soil, exposing previously protected soil organic carbon in soil aggregates to soil fauna, and by increasing losses due to soil erosion (Lal, 1984, 1989; Dick *et al.*, 1986a, b; Blevens and Frye, 1993; Tisdall, 1996). Conversely, long-term no-tillage or reduced tillage systems increase soil organic carbon content of the soil surface layer as a result of various interacting factors, such as increased residue return, less mixing and soil disturbance, higher soil moisture content, reduced surface soil temperature, proliferation of root growth and biological activity and decreased risks of soil erosion (Lal, 1989; Havlin *et al.*, 1990; Logan *et al.*, 1991; Blevens and Frye, 1993; Lal *et al.*, 1994a, b).

Cambardella and Elliott (1992) observed for a loam soil that the soil organic carbon content in the 0 to 20 cm depth was 3.1, 3.5, 3.7 and 4.2 kg/m^2 for bare fallow, stubble mulch, no-tillage and native sod, respectively. They observed that tillage practices can lead to losses of 40% or more of the total soil organic carbon during a period of 60 years. Edwards *et al.* (1992) observed that conversion from mouldboard plough tillage to no-tillage increased soil organic carbon content in the 0 to 10 cm layer from 10 g/kg to 15.5 g/kg in 10 years, an increase of 56%. Lal *et al.* (1998) stated:

> A summary of the available literature indicates that the soil organic carbon sequestration potential of conversion to conservation tillage ranges from 0.1 to 0.5 metric tons ha^{-1} yr^{-1} for humid temperate regions and from 0.05 to 0.2 metric tons ha^{-1} yr^{-1} for semi arid and tropical regions.

They further estimated that the soil organic carbon increase may continue over a period of 25 to 50 years, depending on soil properties, climate conditions and management.

Carbon sequestration in the soil has benefits beyond removal of CO$_2$ from the atmosphere. No-tillage cropping reduces fossil fuel use, reduces soil erosion and enhances soil fertility and water-holding capacity. Beneficial effects of conservation tillage on soil organic carbon content, however, may be short-lived if the soil is ploughed, even after a long time under conservation tillage (Gilley and Doran, 1997;

Stockfisch *et al.*, 1999). Stockfisch *et al.* (1999) concluded that organic matter stratification and accumulation as a result of long-term minimum tillage were completely lost by a single application of inversion tillage in the course of a relatively mild winter. Tillage accentuates carbon oxidation by increasing soil aeration and soil residue contact, and accelerates soil erosion by increasing exposure to wind and rain (Grant, 1997). Several experiments in North America have shown more soil organic carbon content in soils under conservation tillage compared with plough-tillage seed beds (Doran, 1980; Doran *et al.*, 1987; Rasmussen and Rohde, 1988; Havlin *et al.*, 1990; Tracy *et al.*, 1990; Kern and Johnson, 1993; Lafond *et al.*, 1994; Reicosky *et al.*, 1995).

Similar to the merits of no-tillage reported in North America, Brazil and Argentina (Lal, 2000; Sa *et al.*, 2001), several studies have reported a high potential for soil organic carbon sequestration in European soils. In an analysis of 17 European tillage experiments, Smith *et al.* (1998) found that the average increase of soil organic carbon, with a change from conventional tillage to no-tillage, was 0.73 ± 0.39% per year and that soil organic carbon may reach a new equilibrium in approximately 50 to 100 years. Analysis of some long-term experiments in Canada (Dumanski *et al.*, 1998) indicated that soil organic carbon can be sequestered for 25 to 30 years at a rate of 50 to 75 g carbon/m^2/year, depending on the soil type in well-fertilized Cherozem and Luvisol soils cropped continuously to cereals and hay. Analysis of these Canadian experiments focused on crop rotations, as opposed to tillage, and is unique in that it considered rates of carbon sequestration with regard to soil type.

On a global basis, West and Post (2002) suggested that soil carbon sequestration rates with a change to no-tillage practices can be expected to have a delayed response, reach a peak sequestration rate in 5 to 10 years, and then decline to nearly 0 in 15 to 20 years, based on regression analysis. This agrees with a review by Lal *et al.* (1998), based on results from Franzluebbers and Arshad (1996) showing that there may be little or no increase in soil organic carbon in the first 2 to 5 years after a change in management practice, followed by a large increase in the next 5 to 10 years. Campbell *et al.* (2001) concluded that wheat rotation systems in Canada will reach an equilibrium, following a change to no-tillage, after 15 to 20 years, provided average weather conditions remained constant. Lal *et al.* (1998) estimated that rates of carbon sequestration may continue over a period of 25 to 50 years. The different estimates of carbon sequestration may be expected partly based on different rotations and rotation diversity.

Nitrogen Emissions

Cropping systems and nitrogen fertilization affect plant biomass production, partially controlling input of organic carbon to the SOM stocks. Agriculture alters the terrestrial nitrogen cycle as well. Through nitrogen fertilization, annual cropping, monocropping and improper water management, nitrogen is more prone to being lost to both ground- or surface water and the atmosphere. N_2O, a common emission from agricultural soils, is a potent greenhouse gas (310 times more potent than CO_2), which has increased its atmospheric concentration by 15% during the past two centuries (Mosier *et al.*, 1998). Reductions can be achieved through improved nitrogen management, as well as with irrigation water management, because N_2O is generated under both aerobic conditions (where nitrification occurs) and anaerobic conditions (where denitrification occurs) in the soil.

Due to the tightly coupled cycles of carbon and nitrogen, changes in rates of carbon sequestration and terrestrial ecosystems will directly affect nitrogen turnover processes in the soils and biosphere–atmosphere exchange of gaseous nitrogenous compounds. Some data suggest that increasing N_2O emissions may be closely linked to increasing soil carbon sequestration (Mosier *et al.*, 1991; Vinther, 1992; McKenzie *et al.*, 1998;

Robertson *et al.*, 2000). If no-tillage is a truly viable management practice, it must mitigate the overall impact of no-tillage adoption by reducing the net global warming potential determined by the fluxes of all the greenhouse gases, including N_2O and CH_4.

Six *et al.* (2004) assessed potential global warming mitigation with the adoption of no-tillage in temperate regions, by compiling all available data reporting differences in fluxes of soil-derived C, N_2O and CH_4 between conventional tillage and no-tillage systems. Their analysis indicated that, at least for the first decade, switching from conventional tillage to no-tillage would generate enhanced N_2O emissions for humid environments and somewhat lower emissions for dry environments, which would offset some of the potential carbon sequestration gains; and that, after 20 years, N_2O emissions would return to or drop below conventional tillage fluxes. They found that N_2O emissions, with a high global warming potential, drive much of the trend in net global warming potential, suggesting that improved nitrogen management is essential to realize the full benefits from carbon storage in the soil for the purposes of global warming mitigation. They suggested caution in the promotion of no-tillage agriculture to reduce greenhouse gas emissions and that the total radiative forcing needs additional consideration beyond just the benefit of carbon sequestration. They suggested that it is critical to investigate the long-term as well as short-term effects of various nitrogen management strategies for long-term reduction of N_2O fluxes under no-tillage conditions. These results suggest the need for more basic research on N_2O emissions during the transition from conventional tillage to no-tillage and after equilibrium conditions have been achieved to adequately quantify the carbon-offsetting effects in global warming potential.

In Brazil, most, but not all, studies indicate that the introduction of zone tillage increases SOM (Bayer *et al.*, 2000a, b; Sa *et al.*, 2001). Sisti *et al.* (2004) evaluated changes in soil carbon in a 13-year study comparing three different cropping rotations under zone tillage and conservation tillage in a clayey Oxisol soil sampled to 100 cm. They found that, under a continuous sequence of winter wheat and summer soybean, the stock of soil carbon to 100 cm under zone tillage was not significantly different from that under conservation tillage. However, in rotations with a vetch crop, soil carbon stocks were significantly higher under zone tillage than under conservation tillage. They concluded that the contribution of nitrogen fixation by the legume crop was the principal factor responsible for the observed carbon accumulation in the soil under zone tillage. The results demonstrate the role of diverse crop rotations, especially including legumes supplying organic nitrogen under zone tillage, in the accumulation of soil carbon. The dynamic nature of the carbon : nitrogen ratio may require additional organic nitrogen to increase carbon sequestration at depth. Sisti *et al.* (2004) found that much of the nitrogen gain was at depths below the plough layer, suggesting that most of the accumulated soil carbon was derived from crop root residues.

Further work in Brazil reflects the importance of soil and plant management effects on soil carbon and nitrogen losses to 1 m depth (Diekow *et al.*, 2004). They evaluated carbon and nitrogen losses during a period of conventional cultivation that followed on native grassland and 17-year no-tillage cereal- and legume-based cropping systems with different nitrogen fertilization levels to increase carbon and nitrogen stocks. With nitrogen fertilization, the carbon and nitrogen stocks of the oat/maize rotation were steady with time. However, they found increased carbon and nitrogen stocks due to higher residue input in the legume-based cropping systems. The long-term no-tillage legume-based cropping systems and nitrogen fertilization improved soil carbon and nitrogen stocks of the previously cultivated land to the original values of the native grassland. Nitrogen and legume residues in a rotation were more effective for building soil carbon stocks than inorganic nitrogen from fertilizer applied to the grass crop in the rotation. In addition, legume nitrogen does not require the cost of using fossil fuel to manufacture nitrogen fertilizer. The dominant soil change took place in the surface layer; however, deeper layers were important for carbon and nitrogen storage, which leads to improved soil and environmental quality.

The literature holds considerable evidence that intensive tillage decreases soil carbon and supports the increased adoption of new and improved forms of conservation tillage or direct seeding to preserve or increase SOM (Reicosky *et al.*, 1995; Paul *et al.*, 1997; Lal *et al.*, 1998). Based on the soil carbon losses with intensive agriculture, reversing the decreasing soil carbon trend with less tillage intensity should be beneficial to agriculture and the global population by gaining better control of the global carbon balance (Houghton *et al.*, 1983; Schlesinger, 1985). The environmental and economic benefits of conservation tillage and direct seeding demand their consideration in the development of improved management practices for sustainable production. However, the benefits of no-tillage for soil organic carbon sequestration may be soil- or site-specific, and the improvement of soil organic carbon may be inconsistent on fine-textured and poorly drained soils (Wander *et al.*, 1998). Six *et al.* (2004) indicated a strong time dependency in the greenhouse gas (GHG) mitigation potential of no-tillage agriculture, demonstrating that greenhouse gas mitigation by adoption of no-tillage is much more variable and complex than previously considered.

Policy of Carbon Credits

The increase in greenhouse gas concentrations in the atmosphere is a global problem that requires a global solution (Kimble *et al.*, 2002; Lal, 2002). Concern about negative effects of climate warming resulting from increased levels of greenhouse gases in the atmosphere has led nations to establish international goals and policies for reductions of these emissions. Initial targets for reductions are stated in the Kyoto Protocol of the United Nations Framework Convention on Climate Change, which allows trading credits that represent verified emission reductions and removal of greenhouse gases from the atmospheres (United Nations Framework Convention on Climate Change Secretariat, 1997).

Emissions trading may make it possible to achieve reductions in net greenhouse gas emissions for far less cost than without trading (Dudek *et al.*, 1997). Storing carbon in soils using conservation agriculture techniques can help offset greenhouse gas emissions while providing numerous environmental benefits, such as increasing site productivity, increasing water infiltration and maintaining soil flora and fauna diversity (Lal *et al.*, 1998; Lal, 2002). Storing carbon in forests may also provide environmental benefits resulting from increased numbers of mature trees contributing to carbon sequestration (Row *et al.*, 1996). While carbon is a key player for agriculture in solving the problem of global warming, a critical caveat is that other greenhouse gases change with changes in land use, including CH_4 and N_2O. We must look at the net global warming potential, not only for carbon in future trades but global warming potential credits, rather than carbon credits alone.

As interest in soil carbon sequestration grows and international carbon trading markets are developed, it is important that appropriate policies be developed that will prevent the exploitation of soil organic carbon and at the same time replace the lost carbon and establish its value (Walsh, 2002). Policies are needed that will encourage the sequestration of carbon for all environmental benefits that will evolve (Kimble *et al.*, 2002). Making carbon a commodity necessitates determining its market value and doing so with rational criteria.

Both farmers and society will benefit from sequestering carbon. Enhanced soil quality benefits farmers, but farmers and society in general benefit from erosion control, reduced siltation of reservoirs and waterways, improved air and water quality and biodegradation of pollutants and chemicals. Farmers need to be compensated for the societal benefits of carbon sequestration and the mechanisms that develop will allow for carbon trading and maintaining property rights. One important criterion in developing the system is the measurement and verification of the carbon options for sequestration that must be developed and the importance of making policymakers aware of these procedures and the technical difficulties. The use of international carbon credit market mechanisms is intended to help meet the challenge of climate change and future carbon constraints, which enable sustainable development and at the lowest social cost.

Carbon credit accounting systems must be transparent, consistent, comparable, complete, accurate and verifiable (IPCC, 2000). Other attributes for a successful system include global participation and market liquidity, linking of different trading schemes, low transaction costs and rewards for early actions to voluntarily reduce emissions before regulatory mandates are put in place. Characterizing the relationships between soil carbon and water quality, air quality and all the other environmental benefits should be an easy sell to get social acceptance of this type of agriculture. The largest impediment is the educational processes directed at the policymakers and food-consuming public, which require further enhancement.

A growing number of organizations around the world are implementing voluntary projects that are climate-beneficial as a means to improve efficiency and reduce operating costs and risk. Businesses and institutions throughout the world are realizing that the benefits of good environmental management far outweigh the cost, both now and in the future, of good corporate management, which includes strategies to reduce greenhouse gas emissions, risk exposure and costs and to enhance overall competitive operations. Multinational organizations are participating in carbon energy credit trading markets in order to avoid future compliance costs and to protect their global franchise in the face of increasing concern over global warming (Walsh, 2002). In the evolution towards a global economy and as concerns over global environmental impacts increase, CO_2 emission management will become a factor in the planning and operations of industrial and government entities all over the world, creating challenges and opportunities for those who are able to recognize and capitalize on them.

The global ecosystem services provided by farmers and other landowners could provide a source of carbon-emission credits to be sold to carbon emitters and hence provide an additional source of income for farmers, particularly no-tillage farmers. Trade in carbon credits has the potential to make conservation agriculture more profitable and enhance the environment at the same time. The potential for carbon credits has attracted considerable attention of farmers and likely buyers of the carbon credits. However, it is difficult to stay fully informed about developing carbon credits because of their technical complexity and the pace of development on this subject. Rules for trading in carbon credits are not yet agreed upon, but international dialogue is under way to develop a workable system and rules for trading. The number of organizations working on developing a carbon trading system suggests that some type of international mechanism will evolve and that carbon credit trading will become a reality.

Information is rapidly becoming available on publicly traded carbon credits; however, little information is available on privately traded contracts. A great deal of uncertainty exists at this time as to which companies will emerge as reliable sources of high-quality information and entities that can handle trading in a fair and reliable manner. Potential suppliers and buyers of carbon credits are urged to proceed with caution because many of the issues central to carbon credit markets and trade are yet to be clarified. We must convince policymakers, environmentalists and industrialists that soil carbon sequestration is an additional important benefit of adopting improved and recommended conservation agricultural production systems. This option stands on its own, regardless of the threat of global climate change from fossil fuels.

Conservation agricultural practices (especially no-tillage) can help to mitigate global warming by reducing carbon emissions from agricultural land and by sequestering carbon in the soil through regulatory, market incentive and voluntary or educational means (Lal, 2002). Public policy can encourage adoption of these practices. For the present, there is a degree of uncertainty for investors and potential investors in forest-related carbon sinks over the specific rules that will apply to implementation of the sinks provisions of the Kyoto Protocol. Investors and potential investors in carbon sinks need to be aware that there is uncertainty at the international level. Administration and transaction costs could play a key role in determining the success of any carbon credit trading system. Costs in these areas are expected to be minimized through improved techniques and services for measuring and reporting sequestered carbon, private-sector consultants, economies of scale and the emergence of market mechanisms and strategies such as carbon pooling or aggregating. There are risks involved in selling carbon credits in advance of any formalized international trading system and those participating in early trading need to clarify responsibilities and obligations. However, care should be taken in the design of these policies to ensure their success, to avoid unintended adverse economic and environmental consequences and to provide maximum social benefit.

Summary of Reduced Environmental Emissions and Carbon Sequestration

While we learn more about soil carbon emissions, soil carbon storage and their central roles in environmental benefits, we must understand the secondary environmental benefits of no-tillage and what they mean to sustainable production agriculture. Understanding these environmental benefits directly related to soil carbon and getting the conservation practices implemented on the land will hasten the development of harmony between humans and nature while increasing production of food, fibre and biofuels.

Reducing soil carbon emissions and increasing soil carbon storage can increase infiltration, increase fertility, decrease wind and water erosion, minimize compaction, enhance water quality, impede pesticide movement and enhance environmental quality. Increased levels of greenhouse gases in the atmosphere require all nations to establish international and national goals and policies for reductions. Accepting the challenges of maintaining food security by incorporating carbon storage in conservation planning demonstrates concern for our global resources and our willingness to work in harmony with nature. This concern presents a positive role for no-tillage, which will have a major impact on global sustainability and our future quality of life.

18 Some Economic Comparisons

C. John Baker

The long-term economics of no-tillage will be determined more by maximizing crop performance and net cash returns than by minimizing the inputs costs.

In this chapter we look at some economic comparisons of tillage versus no-tillage. But, no matter how the comparisons are analysed, in the end, crop yield will affect the results at least as much as input costs.

Comparisons between different levels of no-tillage are also important. For example, a relatively inexpensive no-tillage drill costing half as much as a more advanced alternative will only need to cause a 4–5% reduction in crop yield to become a bad investment.

But the most common comparison is between no-tillage and tillage. Opinions abound about whether it is cheaper to use no-tillage or tillage. Comparisons are often misleading for the following reasons:

1. Farmers who consider changing from tillage to no-tillage often compare the cost of engaging a no-tillage contractor (custom driller) with the cost of undertaking their own tillage. Many only include direct costs (such as fuel) as the cost of undertaking tillage since they already own the equipment, which they consider has already been paid for. The real issue is not apparent until these farmers have to replace their worn-out tillage equipment. None the less, we attempt to analyse this situation by comparing the cost of used tillage equipment with used no-tillage equipment.

2. Understandably, even if farmers are determined to make a switch to no-tillage, they will often keep their tillage equipment for a few years as a form of insurance – 'in case no-tillage does not work out' – while also paying for a no-tillage contractor. Thus, for a period, they are paying twice, but not by as much as they might imagine, as shown later by the analyses.

3. Many comparisons penalize no-tillage by imposing expected reductions in crop yields and/or increases in seeding and/or fertilizer rates for the first few years. This no longer applies when using modern no-tillage equipment and methodologies. Recent experience has repeatedly shown that using advanced no-tillage machinery and systems will produce crop yields at least comparable to tillage in year 1, and probably significantly better with time. Seeding rates of some crops and pastures have actually been reduced, not increased – some by up to 50%. On the other hand, if lower technology no-tillage systems and equipment are used, temporary yield reductions may well be applicable.

4. Economic comparisons should, but seldom do, factor in no-tillage reductions in labour, tractor numbers, tractor hours, fuel

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use and depreciation. One US farmer, for example, using modern no-tillage methods, recently reported that he now uses more fuel to harvest his crops than to grow them – an unheard-of scenario using conventional tillage (D. Wolf, 2005, personal communication).

5. Tractors often clock only one-quarter of the annual hours using no-tillage compared with tillage and thus last considerably longer. Therefore, the annual depreciation, interest and insurance costs can be reduced and machinery replacement intervals lengthened.

6. Some farmers already have a permanent labour force and no alternative function for that labour when the demand at seeding is reduced; thus there is seemingly little to be gained by adopting no-tillage. On the other hand, enterprising farmers have used the freed-up time to increase the area cropped each year. The economics of this are hard to factor into any analysis.

7. The amount of capital recovered from the sale of second-hand tillage equipment will diminish as no-tillage increases in popularity. The market for second-hand tillage equipment will shrink and this has certainly been a factor for some farmers when making the change.

So how do the figures stack up on both sides of tillage versus no-tillage? We provide answers to this question from two perspectives. The first was to examine four possible scenarios of ownership (C.J. Baker, 2000, unpublished data). We use the costs of equipment in New Zealand because that country has some of the more expensive and capable no-tillage options available, as well as cheaper alternatives. The second analysis was to review the results of charges made by a contractor in England to a client over two seasons. The first season (2002/03) was for tillage and minimum tillage. The second season (2003/04) was for no-tillage (J. Alexander, 2004, personal communication).

In both analyses we assume that crop yields are the same for both tillage and no-tillage. Such an assumption is only realistic if advanced (and usually more expensive) no-tillage equipment is used. If less advanced (cheaper) no-tillage equipment is used, it is likely that crop yields will be depressed below tillage, which will add an effective additional cost to the no-tillage. The comparisons quoted below may therefore require adjustment for less advanced equipment.

Obviously the actual figures will require adjustment for other countries and years. But readers are encouraged to change the input data to those applying locally and recalculate the figures. In most cases the relative values will remain approximately the same, regardless of how the actual figures change over time and location.

New Zealand Comparisons

- Scenario A: Economics of using a tillage contractor or a no-tillage contractor.
- Scenario B: Economics of purchasing new tillage or new no-tillage equipment.
- Scenario C: Economics of retaining used tillage equipment or purchasing either new or used no-tillage equipment.
- Scenario D: Economics of retaining used tillage equipment or engaging a no-tillage contractor.

Assumptions

1. Farmed area 300 hectares – 150 hectares cropped twice annually. (The cropped area could increase substantially with no-tillage but this is not included.)

2. With no-tillage, glyphosate, slug bait and chlorpyrifos are used in spring for weed and pest control.

3. For tillage, glyphosate is applied prior to spring ploughing (at a lighter rate than for no-tillage) but is omitted for autumn sowing.

4. All values are shown in 2004 New Zealand dollars.

Scenario A: Economics of using a tillage contractor or a no-tillage contractor

Establishing 150 hectares of spring wheat (Table 18.1), followed by 150 hectares of autumn forage crop (Table 18.2). Table 18.3 summarizes the pre-tax costs.

Table 18.1. Spring cropping using contractors.

Item	Tillage	No-tillage
Glyphosate (including application)	\$55/ha[a]	\$65/ha
Chlorpyrifos (applied with glyphosate)		\$40/ha[b]
Slug bait (applied with drill)		\$40/ha
Contractor	\$250/ha	\$100/ha
Seed and fertilizer	Same	Same
Total	\$305/ha	\$245/ha
Crop yield	Same	Same
× 150 hectares	\$45,750	\$36,750

[a] Glyphosate is applied at a lower rate for tillage.
[b] The chlorpyrifos cost would reduce to \$8/ha when there was lighter pest pressure.

Table 18.2. Autumn cropping using contractors.

Item	Tillage	No-tillage
Glyphosate		
Chlorpyrifos		
Slug bait		
Contractor	\$150/ha	\$100/ha
Seed and fertilizer	Same	Same
Total	\$150/ha	\$100/ha
Crop yield	Same	Same
× 150 hectares	\$22,500	\$15,000

Table 18.3. Summary of total annual pre-tax costs.

	Tillage	No-tillage
Costs	\$68,250	\$51,750
Costs/ha	\$227/ha	\$172/ha
Difference (in favour of no-tillage)		\$16,500 (\$55/ha)

CONCLUSIONS

1. On a contractor basis, costs (and therefore gross margins) for the year favour no-tillage by \$16,500 or \$55/ha.

2. Even if glyphosate is omitted from tillage in the spring (at \$55/ha), the comparison still favours no-tillage by \$8250 per year or \$27.50/ha for the whole year.

3. No allowance has been made in this analysis for the benefits of establishing autumn crops or pasture using advanced no-tillage methods immediately after harvest, nor for the additional spring utilization of land that comes from no-tillage. These factors alone can be valued at an additional \$440/ha in favour of no-tillage (W.R. Ritchie, 2003, unpublished data).

NOTES

1. When sowing brassicas, peas or other broadleaved crops in spring, the chlorpyrifos cost for no-tillage can be reduced to \$8/ha, which reduces the per-hectare cost of no-tillage in spring to \$213/ha (overall cost \$140/ha), increasing the overall difference between the two to \$87/ha in favour of advanced no-tillage.

2. Contract tillage varies by district from \$250/ha to \$500/ha. The conservative lower figure was used.

3. Contract no-tillage with advanced equipment varies from \$100/ha to \$150/ha, depending on contour, size of field, etc. The conservative lower figure was used.

4. If using cheaper no-tillage equipment, drilling costs will be reduced, but crop yields are likely to be reduced by more than the saving in costs.

5. Herbicides and pesticides are often unnecessary in autumn with no-tillage. Some or all may be necessary in other situations, in which case their cost at reduced application rates should be added to no-tillage.

6. Autumn tillage in New Zealand (NZ) usually involves minimum tillage.

Scenario B: Economics of purchasing new tillage or new no-tillage equipment

Establishing 150 hectares of spring wheat followed by 150 hectares of autumn forage crop. The capital costs associated with purchasing all new equipment are shown in Table 18.4. The annual pre-tax operating costs of the two systems are shown in Table 18.5.

Table 18.4. Pre-tax capital costs of purchased new equipment.

Item	Tillage	No-tillage
1 × 170 hp tractor		$170,000
1 × 120 hp tractor	$120,000	
1 × 80 hp tractor	$80,000	
Sprayer	$6,000	$6,000
Plough (5 furrow)	$28,000	
Power harrow (3 m)	$23,000	
Roller	$6,000	
Leveller	$3,000	
Drill	$34,000	$120,000
Total capital cost	$300,000	$296,000
Difference		Negligible

Table 18.5. Annual pre-tax operating costs of new equipment.

Item	Tillage	No-tillage
Depreciation[1]		
(tractors)	$10,000	$4,250
(other equipment)	$2,500	$3,150
Interest[2] (9%) on average investment	$20,250	$19,980
Maintenance[3] (tractors @ 5%/year)	$10,000	$8,500
Maintenance[3] (soil-engaging equipment @ 7%/year)	$6,580	$8,400
Maintenance[3] (non-soil-engaging equipment @ 3%/year)	$180	$180
Fuel		
(50 l/ha spring tillage) @ 65c/l	$4,875	
(25 l/ha autumn tillage) @ 65c/l	$2,438	
(15 l/ha spring and autumn no-tillage) @ 65c/l		$2,925
Labour		
(4 h/ha spring tillage) @ $15/h	$9,000	
(2 h/ha autumn tillage) @ $15/h	$4,500	
(1 h/ha spring and autumn no-tillage) @ $15/h		$4,500
Total annual operating cost	$70,323	$51,885
Cost per hectare	$234	$172
Difference (in favour of no-tillage)		$18,438 (or $61/ha)

[1,2,3] See 'Notes' on pp. 271–272.

CONCLUSIONS

1. The capital cost of advanced no-tillage equipment was very similar to new tillage equipment.

2. With new equipment, annual savings in operating costs of approximately $18,000 per year ($61/ha) will be achieved by purchasing advanced no-tillage equipment rather than tillage equipment.

NOTES

1. Depreciation was calculated on a straight-line basis as:

Tillage tractors: Annual depreciation = new price minus trade-in price (50% of new price) divided by service life (10 years).

No-tillage tractor: Annual depreciation = new price minus trade-in price (50%

of new price) divided by service life (20 years).

All other equipment: Annual depreciation = new price minus trade-in price (50% of new price) divided by service life (20 years).

2. Interest was calculated on the average investment (new price plus trade-in price divided by 2) × 0.09.

3. Maintenance was from published data (Bainer *et al.*, 1955).

4. Actual total cost of labour will probably be closer to $20/hour if allowance is made for downtime, travel, maintenance, etc.

Scenario C: Economics of retaining used tillage equipment or purchasing either new or used no-tillage equipment

Establishing 150 hectares of spring wheat followed by 150 hectares of autumn forage crop. The capital costs associated with purchasing new or used no-tillage equipment, compared with retaining ownership of used tillage equipment, are shown in Table 18.6. The annual pre-tax operating costs of new or used no-tillage equipment versus used tillage equipment are shown in Table 18.7.

CONCLUSION. Capital costs are virtually halved by owning second-hand equipment (tillage or no-tillage) compared with new equipment. Some $95,000–$97,500 in capital cost is saved by purchasing second-hand tillage or no-tillage equipment.

NOTE

1. The value of used equipment was assumed to be two-thirds of its new value and the equipment is halfway through its service life. The trade in value remains at 50% of the new value at the end of its service life.

Table 18.6. Pre-tax capital costs of new no-tillage and used tillage and no-tillage equipment.

Item	Tillage (used)[1]	No-tillage (new)	No-tillage (used)[1]
1 × 170 hp tractor		$170,000	$114,000
1 × 120 hp tractor (3300 h)	$80,000		
1 × 80 hp tractor (3300 h)	$54,000		
Sprayer	$4,500	$6,000	$4,500
Plough (5 furrow, used)	$19,000		
Power harrow (3 m, used)	$15,500		
Roller (used)	$4,500		
Leveller (used)	$4,500		
Conventional drill (used)	$23,000		
No-tillage drill		$120,000	$80,000
Total capital cost	$205,000	$296,000	$198,500
Difference (in favour of used equipment – see Scenario B above)	$95,000		$97,500

Table 18.7. Annual pre-tax operating costs of new and used no-tillage and used tillage equipment.

Item	Tillage (used)	No-tillage (new)	No-tillage (used)
Depreciation[1] (tractors)	$6,800	$4,250	$2,900
Depreciation[1] (other equipment)	$2,100	$3,150	$2,150
Interest[2] @ 9% (tractors and equipment)	$15,975	$19,980	$15,592
Maintenance[3] (tractors @ 5% new price/year)	$10,000	$8,500	$8,500
Maintenance[3] (soil-engaging equipment @ 7% new price/year)	$3,360	$8,400	$8,400
Maintenance[3] (non-soil-engaging equipment @ 3% new price/year)	$180	$180	$180
Fuel			
(50 l/ha spring tillage) @ 65c/l	$4,875		
(25 l/ha autumn tillage) @ 65c/l	$2,438		
(15 l/ha spring and autumn no-tillage) @ 65c/l		$2,925	$2,925
Labour			
(4 h/ha spring tillage) @ $15/h	$9,000		
(2 h/ha autumn tillage) @ $15/h	$4,500		
(1 h/ha spring and autumn no-tillage) @ $15/h		$4,500	$4,500
Total annual operating cost	$59,228	$51,885	$45,147
Cost per hectare	$197	$173	$150
Difference (in favour of no-tillage)		$7,343 (or $24/ha)	$14,081 (or $46/ha)

[1,2,3] See 'Notes' on p. 273.

CONCLUSIONS

1. Annual costs of owning and operating used tillage equipment ($59,228/year) were approximately $11,000 lower than for new tillage equipment ($70,323/year – Scenario B).

2. The annual costs of owning and operating used tillage equipment ($59,228/year) were approximately $7000 (or $24/ha) greater than owning and operating new advanced no-tillage equipment ($51,885/year) and approximately $14,000 (or $46/ha) greater than used advanced no-tillage equipment.

NOTES

1. Depreciation was calculated on a straight-line basis as follows:

Tillage tractors: Annual depreciation = used price minus trade-in price (50% of new price) divided by remaining service life (5 years).

No-tillage tractor: Annual depreciation = new or used price minus trade-in price (50% of new price) divided by remaining service life (20 years for new or 10 years for used).

All other equipment: Annual depreciation = new or used price minus trade-in price (50% of new price) divided by remaining service life (20 years for new or 10 years for used).

2. Interest was calculated on the average investment (used or new price plus trade-in price divided by 2) × 0.09.

3. Maintenance was from published data (Bainer *et al.*, 1955).

4. The maintenance costs shown for used equipment are conservative because maintenance could be expected to increase with age of machines.

Scenario D: Economics of retaining used tillage equipment or engaging a no-tillage contractor

Establishing 150 hectares of spring wheat followed by 150 hectares of autumn forage crop. The annual pre-tax costs of operating used tillage equipment versus hiring a no-tillage contractor are shown in Table 18.8.

Table 18.8. Costs of used tillage equipment versus hiring a no-tillage contractor.

Item	Tillage	No-tillage
Annual operating costs of used tillage equipment (from Scenario C)	$59,228	
Glyphosate in spring (from Scenario A)	$8,250	
Annual cost of contractor including glyphosate and pesticides (from Scenario A)		$51,750
Totals	$67,478	$51,750
Cost per hectare	$225	$172
Difference (in favour of no-tillage)		$15,728 ($52/ha)

CONCLUSION

1. Ownership of used tillage equipment was more expensive (by approximately $15,000 per year or $52/ha) than engaging a contractor with advanced no-tillage equipment.

Summary and conclusions

The A–D scenarios outlined above are summarized in Table 18.9.

General conclusions

1. It made little difference whether such comparisons were made between new or used equipment, hiring contractors, or combinations of these options. No-tillage was less expensive than tillage for all situations.

2. For 150 hectares cropped twice per year, it was cheaper to use advanced no-tillage equipment in any form than to use any form of tillage ($7000–$18,000/year, or $24–$61/hectare).

3. The smallest difference was ownership of used tillage versus ownership of new no-tillage equipment ($24/ha).

4. The largest difference was ownership of new tillage versus ownership of new no-tillage equipment ($61/ha).

5. All other comparisons result in an approximate $50/ha saving using no-tillage.

6. Hiring a no-tillage contractor with advanced equipment is most often accompanied by a high level of specialist expertise.

7. The only valid economic argument for not adopting advanced no-tillage is if a farmer does not have access to an advanced no-tillage drill. Substandard crop yields will be likely, if not a regular occurrence, with less advanced no-tillage equipment. Tillage is more forgiving of substandard equipment.

8. If a farmer chooses to continue ownership of the used tillage equipment while hiring a no-tillage contractor with advanced equipment on a trial basis (a sensible practice), the costs of depreciation and interest on the tillage equipment will remain although it is not being used ($80/hectare, Scenario C). Since the use of

Table 18.9. Summary of Scenarios A–D.

Scenario	Tillage ($/year)	Tillage ($/ha)	No-tillage ($/year)	No-tillage ($/ha)	Differences $/year	Differences $/ha
Scenario A (contractors)	68,250	227	51,750	172	16,500	55
Scenario B (own new equipment)	70,323	234	51,885	173	18,438	61
Scenario C (own used equipment)	59,228	197	45,145–51,885	150–173	7,343–14,081	24–47
Scenario D (own used equipment versus contractor)	67,478	225	51,750	172	15,728	53

a no-tillage contractor is less than a tillage option ($53/ha, Scenario D), the net cost of trying out advanced no-tillage for a year will be about $27/ha ($80–$53), which is a modest price to pay with the prospect of saving $24–61/ha/year for every year thereafter with the adoption of no-tillage.

European Comparisons

In these comparisons, an English tillage contractor provided the following figures for a client who cropped 404 hectares (1000 acres) per year. The tillage and minimum-tillage figures were actual charges made to the farmer in previous years. The advanced no-tillage figures were quotations for 2004.

Two scenarios are compared: plough-based tillage versus no-tillage, and minimum tillage versus no-tillage. The tillage and minimum-tillage programmes are outlined in Tables 18.10 and 18.11 and are considered typical for many English properties.

The no-tillage quote was for an advanced and more expensive no-tillage drill (which would assure crop production with at least equal yield to the tillage systems), as reflected in the higher per-hectare charge rate. As with the New Zealand comparison, substituting a less advanced no-tillage drill for the advanced no-tillage drill might have had the potential to reduce the costs of no-tillage but it also had the potential to reduce the no-tillage crop yield.

Scenario (A) Comparison of no-tillage with full plough-based tillage

Establishing cereal grain on a 404 hectare (1000 acre) farm using a plough-based tillage system, compared with advanced no-tillage (contractor charges). Comparative costs are shown in Table 18.10.

Table 18.10. Comparison of tillage and no-tillage costs in England.

	Cost/ha	Area	Total
Tillage machines			
Subsoiler, with packer roller	£31.75	404	£12,827.00
Ploughing	£36.00	404	£14,544.00
‘Cultipress’	£14.20	404	£5,736.80
Rolling	£10.75	404	£4,343.00
Power harrow	£25.60	200	£5,120.00
Fertilizing	£7.50	404	£3,030.00
Combination conventional drill	£29.75	304	£9,044.00
Cultivator-drill	£30.00	100	£3,000.00
Spraying	£7.00	404	£2,828.00
Total			£60,472.80
No-tillage machines			
Advanced no-tillage drill	£55.00	404	£22,220.00
Spraying	£7.00	404	£2,828.00
Total			£25,048.00
Difference			£35,424.80
Difference per hectare			£87.68/ha

Scenario (B) Comparison of no-tillage with minimum tillage

Establishing cereal grain on a 404 hectare (1000 acre) farm using a minimum-tillage system, compared with advanced no-tillage (contractor charges). Comparative costs are shown in Table 18.11.

Table 18.11. Comparison of minimum tillage and no-tillage costs in England.

	Cost/ha	Area	Total
Minimum-till machines			
Subsoiler, with packer roller	£31.75	202	£6,413.50
Tillage train	£35.00	404	£14,140.00
‘Cultipress’	£14.20	404	£5,736.80
Rolling	£10.75	404	£4,343.00
Fertilizing	£7.50	404	£3,030.00
Cultivator-drill	£30.00	404	£12,120.00
Spraying	£7.00	404	£2,828.00
Total			£48,611.30
No-tillage machines			
Advanced no-tillage drill	£55.00	404	£22,220.00
Spraying	£7.00	404	£2,828.00
Total			£25,048.00
Difference			£23,563.30
Difference per hectare			£58.32/ha

Conclusions

1. On a contractor basis, minimum tillage was cheaper than tillage by £29/ha.
2. On a contractor basis, advanced no-tillage was cheaper than plough-based tillage by £87/ha.
3. On a contractor basis, advanced no-tillage was cheaper than minimum tillage by £58/ha.
4. These comparisons may not have been valid if less advanced no-tillage machines had been used.
5. Comparisons between tillage, minimum tillage and no-tillage are machine-dependent, since no-tillage drill designs have the potential to influence crop yields markedly.

Summary of Some Economic Comparisons

1. The most common economic comparison is between no-tillage and tillage but such comparisons are often misleading for any one of a number of reasons and assumptions.
2. Several possible scenarios provide economic examples of tillage versus no-tillage, but the items and figures will require changing for other countries and years.
3. Machine costs involved with changing from a tillage to a no-tillage system are a major consideration.
4. Maintaining ownership of tillage machines for a period after beginning no-tillage adds some costs to the transition but may be a comforting and affordable choice for many farmers.
5. Economics of using a tillage contractor or a no-tillage contractor favours using a no-tillage contractor.
6. Economics of purchasing new tillage or new advanced no-tillage equipment showed similar capital costs in either case but significantly lower operating costs for no-tillage.
7. Economics of retaining used tillage equipment or purchasing either new or used no-tillage equipment showed that capital costs are virtually halved by owning second-hand equipment (tillage or no-tillage), compared with new equipment, but again operating costs are in favour of no-tillage.
8. Economics of retaining used tillage equipment or engaging a no-tillage contractor showed that ownership of used tillage equipment was more expensive than hiring a contractor with advanced no-tillage equipment.
9. It made little difference whether comparisons were made between new or used equipment, hiring contractors, or combinations of these options. No-tillage was less expensive than tillage for all situations.
10. Hiring a no-tillage contractor with advanced equipment is most often accompanied with a high level of specialist expertise.
11. A US farmer who recently converted from tillage to no-tillage reports a ‘win–win’ situation with advanced no-tillage equipment. He has not only recorded his best crop yields ever with no-tillage, but he now also uses less fuel to grow his crops than to harvest them.

19 Procedures for Development and Technology Transfer

C. John Baker

Measuring the mechanical performance of no-tillage machines is far less important than measuring their biological performance.

One of the distinguishing aspects of experiments conducted with agricultural tillage machines is that there are very few common experimental techniques and standardized instruments that can be universally applied. The designs and functions of most agricultural machines are quite diverse; thus the techniques used to evaluate them are tailor-made for specific purposes and to answer specific questions.

This situation contrasts with experiments with plants, for example, in which the most common procedure is to grow plants in pots or plots of soil, each with a designated treatment. Since all plants perform essentially the same functions of utilizing the sun's energy to convert nutrients from the soil, atmosphere and water into biomass, there is a high degree of commonality of plant experiments.

In the study of no-tillage drills, planters and openers, design scientists have sought knowledge not only about resulting plant growth, using well-established experimental procedures, but also about their mechanical performance and, perhaps most importantly, about the interactions between infinite design variations of the machine components, the soil, surface residues, pests and the plants.

Described here are some of the experimental procedures and techniques used by the authors and their colleagues to gain knowledge about the functions and performance of no-tillage components and subsequently to develop new no-tillage technologies, designs and practices. Many of the techniques developed are specific to no-tillage but should be useful to others pursuing similar investigations. Some were unique experiments, while others followed well-established common procedures.

This is not an attempt to provide a comprehensive review of all techniques used by scientists in this field, although the results of much relevant work by a wide range of scientists are reported elsewhere in this book. The technique descriptions and instrumentation given here are restricted to those used or devised by the authors. We explain how many of the experiments were conducted in some detail because they were designed to address a variety of questions about how plants and soil interact with no-tillage machines, and because there were no known methodologies for those purposes available at the time.

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The techniques and procedures described examined the following subjects:

1. Plant responses to no-tillage openers in controlled conditions.
2. The micro-environment within and surrounding no-tillage seed slots.
3. Soil compaction and disturbance by no-tillage openers.
4. Locating seeds in the soil.
5. Seed travel within no-tillage openers.
6. Drag on a disc opener.
7. Accelerated wear tests of no-tillage openers.
8. The effects of fertilizer banding.
9. Prototype drills and management strategies.

Plant Responses to No-tillage Openers in Controlled Conditions

It is often assumed that most seeds will germinate and grow satisfactorily if sown into moist soil followed by favourable climatic conditions. Unfortunately, under no-tillage this assumption is not always correct. Early experience with no-tillage had suggested that, as the soil and climatic conditions became less favourable, seed, seedling and plant performance often suffered more than where seeds were sown into tilled seedbeds.

Thus, it became important to develop a fundamental procedure to evaluate the biological performance of different no-tillage openers under controlled conditions. The aim was to create a facility where scientists could put stress on the no-tillage system by superimposing unfavourable soil moisture conditions followed by unfavourable climatic conditions without the risk of intervention by unpredictable weather.

Sowing seeds in the field was considered too impractical and imprecise to control the soil moisture and climate. Conventional ‘rainout’ shelters, which involve large movable transparent canopies covering several plots of soil, were expensive and would have limited the experiments to one site. This contrasted with tillage experiments, where the soil beneath a ‘rainout’ shelter can be re-tilled several times to repeat several experiments on the same site.

The scientists also did not have the convenience of being able to place seeds in disturbed soils that had been prepared in pots or trays so that they could later be transported into glasshouses or other artificially controlled climate laboratories. For no-tillage experiments, the soils had to have been truly undisturbed for at least 12 months, and preferably longer, and to remain this way throughout the experiments.

A new technique was developed to transport untilled soil in bins to an indoor climatically controlled facility. This involved removing large 2.0 m × 0.7 m × 0.2 m blocks of soil weighing approximately 0.5 t from the field in an undisturbed state, controlling pre-drilling soil moisture content, drilling with openers arranged to duplicate their performance on a field drill or planter and then controlling the post-drilling climate and soil moisture content for the duration of the experiment (Baker, 1969a, 1976a, b).

Rectangular steel bins were constructed with both ends open. The front end of each bin was able to be attached to the rear of a stirrup-shaped soil cutter, which was itself attached to and pulled through the soil by a tractor (Fig. 19.1). The horizontal blade of the cutter was hollow, with exit ports drilled along its rearmost edge. Water was pumped into the hollow blade during extraction of the 0.5 t soil blocks to create a thin slurry on the underside of each soil block and thus temporarily lubricate it as it slid along each of the 2 metre bins. The base of each bin was lined with a veneer of stainless steel to assist this process.

In practice, it was found that 2 m was about the maximum slice length that a 200 mm deep undisturbed soil slab could be expected to slide without becoming compressed and perhaps buckled. Increasing the depth beyond 200 mm may have permitted longer blocks to be extracted, but such bins would have been difficult to handle because of their added weight and length.

Although a 200 mm soil depth could not be expected to sustain plant growth for long periods before roots reached the stainless steel bases, all of the studies that utilized

Fig. 19.1. A stirrup-shaped soil cutter with bin attached for extracting undisturbed soil blocks (from Baker, 1969a).

these bins concentrated on the germination and seedling emergence phases of crop production, since these were considered to be the most critical phases obstructing reliable no-tillage. It was also considered that machine influences on plant growth were likely to be greatest at the germination and emergence phases and thereafter would be of less influence than other factors, such as weather, soil and management effects.

The soil remained in its bin throughout each experiment. Bins were transported from the field to the laboratory using heavy lifting equipment on a tractor (Fig. 19.2). The moisture content of the soil in each bin was manipulated either by covering each bin with clear plastic and leaving it to air-dry or by irrigating it from above by sprinkler or from below by placing the perforated bins in shallow troughs containing a predetermined quantity of water.

Two processes were used to drill these undisturbed blocks of soil with a variety of no-tillage openers. Where measurements of the drilling process itself were to be made or multiple openers were to be tested in each bin, five bins were placed end to end on the raised bed of a ‘tillage bin’ arrangement, which also had a tool carrier on a moving gantry that straddled the line of bins and could be moved forwards or backwards at infinitely variable speeds from 0 to 8 km/h (0 to 5 mph) (Fig. 19.3).

Where drilling took place indoors, the openers on test were usually arranged at 150 mm row spacing with three rows to a bin. This resulted in 200 mm of clearance between the outside rows and the edges of the bins. The slightly larger distance in this zone was to avoid soil disturbance at the bin edges. All openers were mounted on parallel drag arms attached to a subframe. The vertical angle was variable to alter the opener pitch for any geometrical arrangement. Downforce was applied by adding weights to individual openers and draught forces were measured by a load cell mounted within the drag arm attachment subframe.

Mounting openers on parallel arms and applying downforce by application of weights were not a true duplication of common field practice. Weights ensured that the downforce applied to any one opener remained constant regardless of its position in the vertical plane. This seldom happens in practice. But the objective was to remove most ancillary functional differences between openers and their modes of operation to

Fig. 19.2. A filled soil bin being transported.

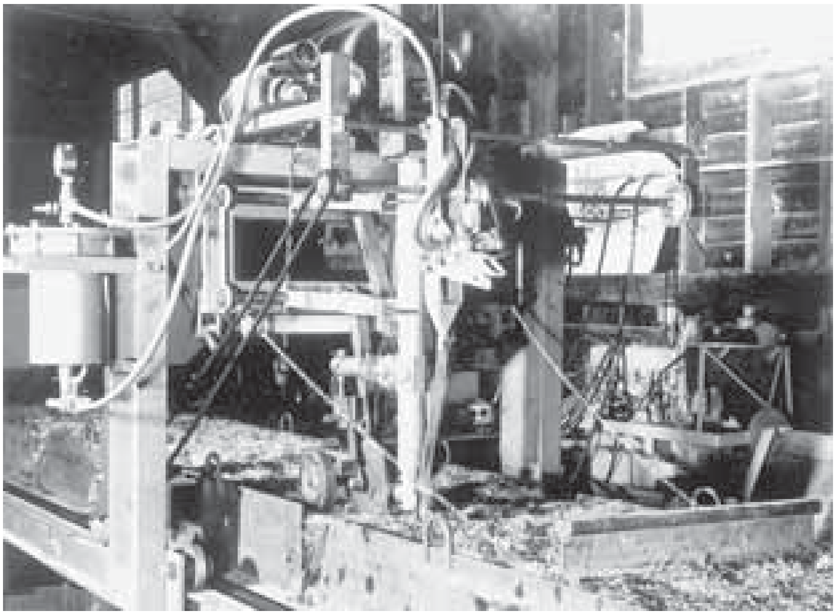


Fig. 19.3. The 'tillage bin' with soil bins arranged end to end ready for drilling (from Baker, 1969a).

evaluate differences associated with their actions in the soil and the shape of the slots they created.

Individual seeds were metered by a modified vacuum seeder designed by Copp (1961). As drilling was usually conducted at slow speeds, a visual count was made of the seeds entering the soil by observing them as they passed down a clear plastic delivery tube at bench height. In this manner, the exact number of seeds sown was known to make accurate counts of germination percentages. With the 'tillage bin' elevated to bench height, this allowed instrumentation to be inserted from beneath or beside the soil to monitor variables such as vertical and/or lateral soil forces resulting from the passage of individual openers.

It was occasionally necessary to test openers operating on actual field drills. In this case, the open-ended steel bins were left embedded in the soil after pulling them in with a tractor and the stirrup-shaped cutter. A field drill was then operated over them while they were *in situ*, taking care to avoid contact with the steel side walls of the bins. The soil bins could then be removed to controlled climate facilities.

The 'tillage bin' facility successfully allowed an accurate measure of how different shapes of no-tillage openers and slots respond to different soil conditions in terms of their abilities to promote satisfactory seed germination and seedling emergence. Almost all previous no-tillage experiments had used field conditions reporting successful establishment, but the results may have been as much a function of favourable conditions as of mechanical performance. While field experiments served to demonstrate that no-tillage seeding could work, there was a need to identify and eliminate the causes of failures. This required precise control to be exercised over the seeding conditions.

The tillage bin facility, because of its moving gantry, was also used for a variety of other related experiments. Among these were a study of spray droplet dissipation in pasture (Collins, 1970; see Chapter 12), monitoring of seed spacing from precision spacing planters (Ritchie and Cox, 1981; Ritchie, 1982; Carter, 1986; see Chapter 8) and the transplanting of cabbage seedlings into untilled soil (Pellow, 1992).

The micro-environment within and surrounding no-tillage seed slots

To learn the environmental requirements of seeds and seedlings within the seed slot, the following variables were tested to define the effects of opener designs: (i) soil moisture regime within the slot; (ii) soil-air humidity within the slot; (iii) soil oxygen within and around the slot; and (iv) soil temperature within the slot.

No attempt was made in these experiments to monitor the presence of allelopathic substances from decaying residue or other root material in the slot, since this was being well researched by Lynch and others at the time (Lynch, 1977, 1978; Lynch *et al.*, 1980). However, later experiments on wet soils by the authors and their colleagues added knowledge about these effects and how they might be avoided through opener design (see Chapter 7).

Soil moisture regime within the slot

Most non-destructive devices for measuring the liquid water content of soil sample a reasonably large soil volume. This is necessary to average the variations inherent in small soil volumes. The slot zone left by a no-tillage opener represents a relatively small volume of soil, which has made monitoring of liquid-phase moisture particularly difficult.

Gypsum blocks and most other physical absorption-based devices work best at the wet, low-tension, end of the moisture range, which made them unsuitable for experiments with dry soils. Early designs of dew-point psychrometers were tried, but the steep temperature gradients at or near the soil surface made them unreliable. Eventually, recourse was had to destructive gravimetric sampling, in which miniature cores of soil (20 mm diameter × 10 mm deep) were removed from the slot zone and oven-dried to provide a measurement of the liquid-phase soil moisture content on a differential weight basis. More sophisticated instruments have become available since these experiments were conducted.

The research showed that the liquid-phase water content of the soil in and around contrasting slot shapes did not greatly differ, at least in the short term, even when there were marked differences in seedling emergence between openers in otherwise relatively dry soils. While this at first seemed anomalous, it was decided that exhaustive testing of further alternative devices for measuring liquid-phase soil water was not justified. Rather, attention shifted to the measurement of slot humidity, or vapour-phase soil water.

Soil-air humidity within the slot

Soil physics shows that the atmosphere (air) in soil macropores and voids forms an equilibrium water vapour pressure with the liquid water contained in the surrounding soil pores. At a given temperature, the vapour-phase water in these soil spaces represents soil-air humidity. Since soil temperature at seeding depth does not change rapidly and is easily measured, soil humidity became a reasonably reliable way to measure the water-vapour pressure of the soil atmosphere.

Choudhary (1979) first monitored soil-air humidity within no-tillage slots using an aspirator to slowly draw quantities of air from the slot and pass these through a dew-point hygrometer for a direct reading of the relative humidity of the air sample. While this method produced interesting figures, the scientists were conscious that the removal of air from the slot inevitably resulted in its being replaced with air drawn predominantly from the atmosphere above the soil surface. Thus, the slot air samples only partly reflected the humidity within the slot.

The accuracy of the method relied on the removal rate of the slot air and the diffusion resistance of the slot cover, which controlled the rate that atmospheric air replaced that being removed. A high diffusion resistance of the slot cover, for example, might result in the removed slot air sample being replaced by additional slot air from further down the slot, while a low diffusion resistance might contain a larger proportion of atmospheric air. As it turned out, this diffusion resistance was later identified as an important variable in seed/seedling survival, but in the meantime a method was found that sampled the relative humidity *in situ* without removing air from the slot.

A modified direct-reading humidity probe was inserted into the slot and allowed to equilibrate with the undisturbed slot atmosphere for at least 2 minutes. The probe selected was originally designed to monitor relative humidity between sheets of newsprint. As such it was flat and thin in shape. The point was removed and a small piece of fibreglass filter material was wrapped over the end to prevent soil from falling into the sensitive probe. The filter was left behind in the soil when the probe was withdrawn and was not reused. Figure 19.4 shows a humidity probe being inserted into a dry no-tilled soil that is contained within a climate-controlled room.

This method yielded a direct reading of relative humidity, approximating what the seeds experienced in the slot. The information gathered with this technique had far-reaching consequences. The experiments showed that no-tilled seeds could germinate in a high-humidity slot atmosphere, i.e. without access to substantial amounts of liquid-phase water, a fact that was later confirmed by Martin and Thrailkill (1993) and Wuest (2002).

More importantly, subsurface seedlings could survive beneath the soil for several weeks if the slot atmosphere was maintained at or near 100% relative humidity. The latter observation was shown to be a function of the diffusion resistance of the slot cover and the humidity gradient between the slot air and the ambient air outside the slot. Slot cover was itself a function of slot shape, the presence of surface residues over the slot and the design of the opener.

Being able to monitor slot atmosphere humidity was one thing, but being able to control and vary that humidity for the purposes of experimentation was quite another matter. Even rain-protection covers were not satisfactory since they were unable to alter the ambient humidity of the day. Utilizing a multi-room controlled-climate facility, the 0.5 t blocks of soil in their steel bins were moved after drilling into climate-control rooms in groups of three. Each room had an artificial climate in which the temperature, humidity, light intensity, light spectrum, day length, nutrients and, if necessary, wind speed and direction could be controlled. In this way, the effects of high and low ambient humidity levels and/or

Fig. 19.4. Sampling soil humidity in the field.

temperatures were varied and the effects on the establishing seedlings measured (see Chapter 6).

Soil oxygen within and around the slot

The main consequence of a no-tilled soil becoming very wet after drilling is restriction of oxygen supply to the germinating seeds and embryonic roots. In a tilled soil, there is much artificial loosening, which exaggerates the oxygen regime around the seeds for a time. In an untilled soil, seeds rely almost entirely on the ability of the soil to remain adequately oxygenated in its natural state. To test a range of opener designs to provide varying oxygen conditions with wet soil conditions, variables of oxygen diffusion rates, earthworms, infiltration and soil temperatures were considered.

Several scientists have described an oxygen-diffusion measurement technique involving pushing a small platinum electrode into the soil and measuring the current passing between this electrode and a reference electrode. The current has the effect of reducing electro-reducible material, in this case oxygen, at the platinum surface. The size of the current is governed by the rate of oxygen diffusion from within the soil to the surface of the electrode and thus gives an indication of the oxygen diffusion rate (ODR) within the soil.

Most scientists agree that the ODR values obtained with platinum electrodes are only an approximation of what a root might experience, but the technique provides a relative measure of the difference between a range of soil conditions. The advantages are that it is cheap, non-destructive, quick, easy and capable of sampling very small zones of soil in the vicinity of the slot.

Chaudhry (1985) sampled ODR in a grid pattern around the basal area of a range of slots in a wet soil and used a computer program to draw iso-ODR lines reflecting the contrasting oxygen regimes generated by the passage of no-tillage openers and the presence or absence of surface residues and earthworms (see Chapter 7).

Earthworm activity was a likely contributor to the soil slot oxygen status. Mai (1978), Chaudhry (1985) and Giles (1994) monitored the numbers of earthworms present in the general plot soil and those around a seed slot. Cylindrical cores of soil centred on the slot were extracted and earthworms counted and weighed. Chaudhry also monitored earthworm activity on the soil surface by estimating the percentage of a given area of soil that was covered with earthworm casts. He termed this the ‘casting index’.

Water infiltration into the slot zone was another potential factor in providing oxygen exchange. Relative infiltration rates were monitored by rectangular metal boxes (infiltrometers) inserted into the soil surface centred on the slot (Chaudhry, 1985; Baker *et al.*, 1987).

Exhaustive temperature comparisons were made by Baker (1976a) within a range of slot configurations. Temperature is relatively easy to measure in small discrete zones using miniature thermometers or electronic thermocouples. Short-term readings were by simple mercury thermometers, while thermocouples were used for continuous readings, such as diurnal ambient fluctuations.

Soil Compaction and Disturbance by No-tillage Openers

It had long been thought that a logical result of no-tillage openers operating in untilled soils would be progressive compaction and restricted root growth in the slot zone. Therefore, several studies centred on monitoring these aspects. The parameters measured were: (i) soil strength; (ii) instantaneous soil pressure (stress); (iii) instantaneous and permanent soil displacement; (iv) soil bulk density; and (v) smearing.

Soil strength

Soil strength is traditionally assessed by measuring the force required to push a probe (penetrometer) into the soil. To more closely resemble the actions of a root, the probe ends are usually conical in shape so that the force dissipation is radial as well as longitudinal. Such probes, however, are usually designed to sample reasonably large volumes of soil and, because of the natural heterogeneity of soil, repetitive sampling with a single probe is common.

To get the benefits of multiple soil probing within the confines of the slot zone, a miniature multi-point penetrometer was designed (Dixon, 1972; Baker, 1976a; Baker and Mai, 1982b). This device consisted of 20 1 mm diameter stainless steel probes mounted in a common horizontal press bar in such a way that the vertical position of each probe with respect to the bar could be adjusted and clamped individually. The press bar could be angled at any desired position from horizontal to vertical and was attached to a threaded shaft that acted as the thrust mechanism, together with a sensitive ring-shaped force-measuring device (known as a ‘proving ring’). Two different displacement-measuring devices have been used to monitor the changes in diameter of the ring. Initially, a micrometer sufficed, but in later tests a displacement transducer was substituted to facilitate recorded results. The multi-point penetrometer is shown in Fig. 19.5.

Because soil tends to flow as a plastic body to a limited extent for several seconds after a rigid probe is inserted, it was necessary to insert the probes at a predetermined and constant speed and to read the force applied at a standard time interval after the probe penetration had been stopped at the desired depth (when plastic flow had ceased). The probes were inserted at a constant speed of penetration by rotating the threaded shaft at a constant speed, using a slow-speed electric motor drive, which was immediately disconnected upon reaching the desired depth, and then waiting 10 seconds before reading the gauge.

To accommodate the irregularities of the soil surfaces, the press bar was positioned parallel to the chosen surface and each probe was slipped through the bar until it lightly contacted the soil surface, then clamped in that position. Care was taken to ensure that an equal number of probes on each side of the central threaded shaft contacted the soil to ensure, as nearly as possible, symmetry of forces about the central point when all of the probes were pushed into the soil. Even then, a single probe would occasionally contact a stone, greatly distorting the symmetry, and the readings were discarded.

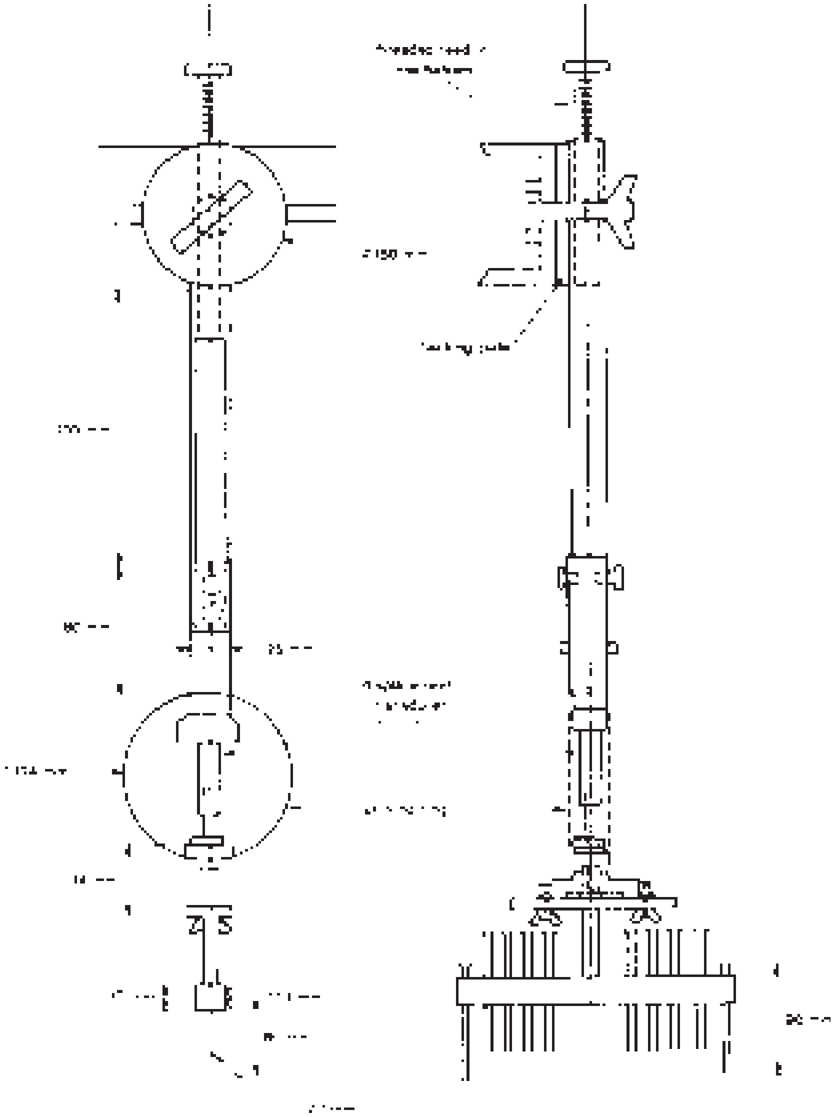


Fig. 19.5. A multi-point penetrometer attached to a ‘proving ring’ force-measuring device (from Baker and Mai, 1982a).

Using the tillage bin facility previously described, the multi-point penetrometer was inserted from a number of directions: (i) from above the ground to test soil strength vertically downwards at the base of slots (Baker and Mai, 1982b); (ii) from the side perpendicular to the side walls of slots (Mai, 1978; Baker and Mai, 1982b); (iii) from beneath the bins pushing upwards to measure the resistance of slot cover to shoot emergence (Choudhary, 1979); and (iv) perpendicular to the cross-sectional end faces of soil blocks in their bins to test the soil strength in a grid pattern surrounding a cross-section of the slots (Mitchell, 1983).

The penetrometer was not usable in the field as its high sensitivity required a very stable base from which to derive the penetration force. This could only realistically be provided by the tillage bin supported on a concrete floor. Even then, a person pressing on one of the bins could cause the penetrometer reading to deflect.

Instantaneous soil pressure (stress)

As the opener passes through the soil, pressures are created to move the soil aside, with multiple potential consequences from compaction to smearing. These pressures were measured using a specially designed diaphragm pressure pad (Mai, 1978). A small length of 9.5 mm diameter brass tube had a rubber diaphragm attached to one end. The other end had a sensitive electronic miniature pressure transducer attached. The tube was filled with water to act as a non-compressible liquid and a small bleed screw was used to expel all air. These tubes were inserted through holes in the side walls and base of the steel bins into close-fitting pre-bored holes in the soil so as to position the rubber diaphragm in intimate contact with soil a set distance (as close as 10 mm) from the expected pathway of a no-tillage opener to be tested.

Since each opener travelled a well-controlled pathway on the tillage bin tramway, it was possible to very accurately predetermine the side position of the soil-stress devices. The depth of penetration of each opener was somewhat less predictable, despite common ground-gauging wheels being used with each opener, because the ground surface of each bin did not finish exactly the same distance from the base of its steel bin during the field extraction process. Thus, somewhat more latitude was allowed for vertical positioning.

Even so, the water-filled tubes were used to protect the expensive miniature pressure transducers in the event of mechanical contact with a passing opener. The brass tubes and their rubber diaphragms were considered expendable in the event of an accident. The expensive pressure transducers were not. Figure 19.6 shows one such tube. In this manner, the contrasting instantaneous soil stresses created by a range of passing openers in an untilled soil were monitored and reported (Baker and Mai, 1982a).

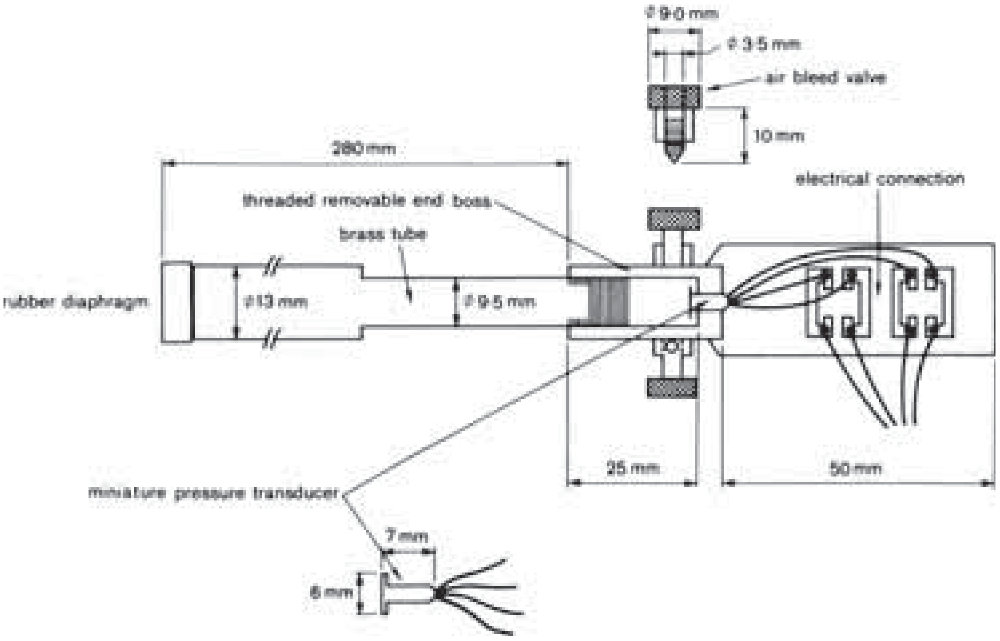


Fig. 19.6. A soil pressure measuring tube (from Baker, 1969a).

Instantaneous and permanent soil displacement

This was measured by placing small vertical probes in the soil at predetermined distances from the anticipated pathway of an opener to be tested in the soil bins on the tillage bin (Mai, 1978). A light non-stretchable thread was attached at one end to each probe and at the other end to a small electronic displacement transducer, which recorded both the instantaneous horizontal displacement of the soil as the opener passed and the permanent displacement after it had passed. The displacement data gave a measure of the direction in which an opener displaced the soil, as well as the plasticity of the soil and how it had responded to the mechanical action of that particular opener.

Soil bulk density

This was measured by extracting small soil cores (10 mm × 10 mm) from the slot zones in a location and pattern required by the specific experiment (Mai, 1978; Chaudhry, 1985). The cores were weighed and a standard procedure was used to calculate soil bulk density as the weight per unit volume of soil.

Smearing and compaction

This was a difficult parameter to accurately quantify, since smearing, in particular, was often confined to a layer less than 1 mm thick. It was determined that smearing in any case only affected root growth when it was allowed to dry and become a crust. Other environmental parameters determine slot drying, as previously described. Thus, no effort was made to develop a direct method to accurately quantify smears. It appeared that the difference between a smear and a compacted layer was only a matter of thickness.

Locating Seeds in the Soil

Three aspects of seed position within the soil were considered important to the design of no-tillage seed drills and planters (Ritchie, 1982): (i) seed spacing along the row; (ii) seed depth; and (iii) lateral position of the seed relative to the centre line of the slot.

Seed spacing

Measuring seed spacing is relatively simple. At least, it is if no account is taken of seed bounce in the slot and other soil factors, such as cloddiness. Accurate measurement can be achieved by simulated drilling, which involves moving a seeder over a sticky plate or paper so that the seeds dropped from the seeder are immediately fixed on the paper as the machine moves forward. The tillage bin and moving gantry described earlier were ideal for this function (Ritchie, 1982; Carter, 1986). Seed spacing can also be determined directly by measuring the distance along the surface of the soil between emerged seedlings. The latter method takes no account of displacement of shoots from the original positions of the seeds (by, for example, weaving around soil clods or stones) or of failure of seeds to germinate or of seedlings to emerge.

Seed depth

Measuring seeding depth is a deceptively difficult problem. For obvious reasons, the position of seeds in the vertical plane in the soil can only be determined after they have been sown, unlike horizontal seed spacing, which can be simulated on sticky paper without the opener having to penetrate the soil.

The problem is that when scientists excavate the soil to find individual seeds, it is almost inevitable that other seeds in the vicinity will be disturbed. In recent years, scientists have used one of four approaches:

Manual excavation (Hadfield, 1993; Thompson, 1993)

Despite the disadvantages, careful excavation of the soil in the field to expose individual seeds is still the most common method. This method has the problem that inherent errors are difficult to quantify and correct. With tilled soils, the seeds are approached from above, but, because of the lack of disturbance and the relative stability of some untilled soils and slots, it is sometimes possible to cut a trench alongside and approach the seeds from the side, which reduces the risk of disturbing other seeds.

Scoop sampling

A semi-cylindrical horizontal core of undisturbed soil, which centres on a drilled row, is removed with a specially shaped scoop, and then carefully split open on a bench in a laboratory to expose the seeds (Baker, 1976a). This technique can only be used with untilled soils because tilled soils are too friable and the cores collapse. It is somewhat more accurate than manual excavation from above because the seeds are approached from the side. It is also more convenient than field sampling from the side because the operator works mostly at bench height and the soil samples can be laid on their sides on the bench. The technique removes relatively short lengths of row at a time, and transports these to a laboratory. It is more time-consuming than other methods. It is more useful for locating and counting seeds and seedlings in a given length of row than for accurately recording their positions relative to the soil surface.

Tracing down seedlings

After emergence of seedlings, careful tracing down from the emerged shoots to the seed position will establish the original position of sown seeds within the soil (Stibbe *et al.*, 1980; Pidgeon, 1981; Allam and Weins, 1982; Choudhary *et al.*, 1985). This procedure has been mechanized for automatic recording to provide measurements for relatively large numbers of seedlings. But, because it only measures the emerged seedlings, it fails to record any position for non-emerged seeds. Since identifying disadvantaged seeds was one of the more obvious aims of locating them in the soil for no-tillage studies, the technique has had limited application.

X-ray imagery of seeds

By coating seeds with red lead oxide (a common bird repellent) prior to sowing, images of the seeds can be recorded by X-raying samples of soil removed from the field in metal boxes using a veterinary X-ray facility (Campbell, 1985; Choudhary *et al.*, 1985; Praat, 1988; Campbell and Baker, 1989; D. de Kantzow, 1985, 1993, personal communication). Both aluminium and steel are suitable for the boxes, as X-rays readily pass through these metals without an image. The technique is non-injurious to the seeds (they will germinate after X-raying) and it positively identifies seeds beneath the soil without disturbing them. It is also largely unaffected by soil type, moisture content or organic matter levels, but it is best suited to large seeds and relatively small numbers of samples because it is time-consuming and relatively expensive.

X-rays are derived from a point source on the X-ray machine; thus, as the X-rays scan a sample, a parallax error is created at all positions except those directly beneath the point source. This parallax error increases towards the extremities of the sample and affects the accuracy of quantifying the distances between individual seeds or between seeds and the surface of the soil. Campbell (1985) derived a mathematical correction for this error. He also used a strip of lead soldering wire to indicate the position of the soil surface in the X-rays. Figure 19.7 shows pea seeds coated with lead oxide X-rayed beneath the soil after seeding.

Lateral position of seeds relative to the centre line of the slot

As with seed depth, manually locating the lateral position of seeds after they have been drilled presents problems arising from the possibility of inadvertently displacing them before their positions can be recorded. Both scoop sampling and X-ray imagery were used on the few occasions this parameter was studied.

To date, no totally satisfactory method has been devised to positively, cheaply

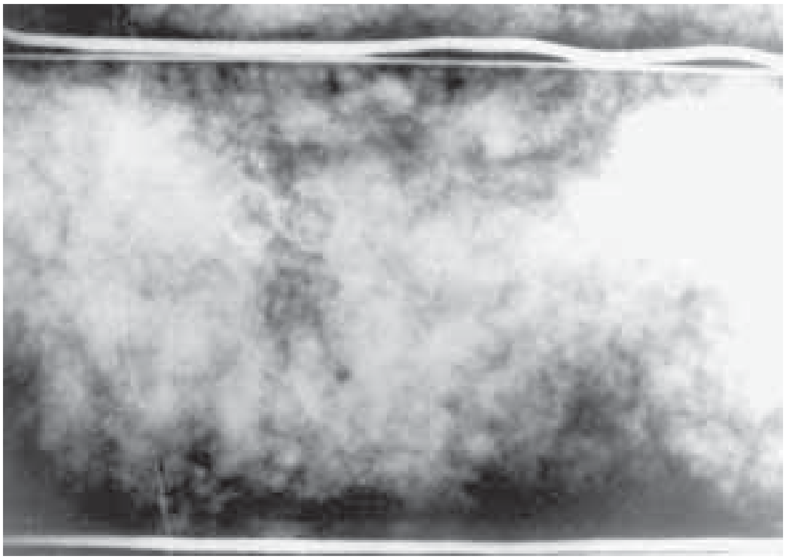


Fig. 19.7. Pea seeds coated with lead oxide X-rayed beneath the soil after seeding (from Campbell and Baker, 1989).

and repeatably identify the final three-dimensional position of seeds in the soil. Perhaps this accounts for why most designers of furrow openers and seed drills seem to satisfy themselves with defining how well their openers follow the ground surface, with the implied assumption that final seed placement is solely related to this capability.

Seed Travel within No-tillage Openers

The pathway seeds are required to travel through and from no-tillage openers is often more tortuous and less predictable than with simpler openers for tilled soils. Thus, it has been important to monitor seed travel and to analyse the causes of blockage or disruption to the flow.

All of the techniques adopted by the authors have involved use of video camera and slow replay facilities. Ritchie (1982) studied discharge of seeds from precision singulation seeders, together with a range of delivery tubes, by videotaping the seeds as they fell. He calculated the delay times between passage of successive seeds past a grid and the resulting potential variations in horizontal spacing along the row. The video was then replayed on a frame-by-frame basis against a background grid calibrated on both a time and distance basis. Figure 19.8 shows seed ejection being monitored in this manner using the tillage bin moving gantry as the source of seeder movement.

One study of seeds within the disc version of a winged opener involved substituting a clear Plexiglas disc for the normal steel disc on the opener and videotaping the seed pathway through the transparent disc. This opener is somewhat unique in that much of the internal pathway for the seeds involves a three-sided tube in close proximity to a revolving disc. The rotation of the disc forms one wall of this delivery tube and moves continuously. Scientists wanted to study the influence of this moving wall and the geometric shape of the stationary walls on seed drop and ejection from the opener. Figure 19.9 shows the seed flowing through such an opener.

To date, no satisfactory technique has been found for viewing seeds as they emerge from an opener beneath the soil, although knowledge of such action would assist greatly in designing openers with improved

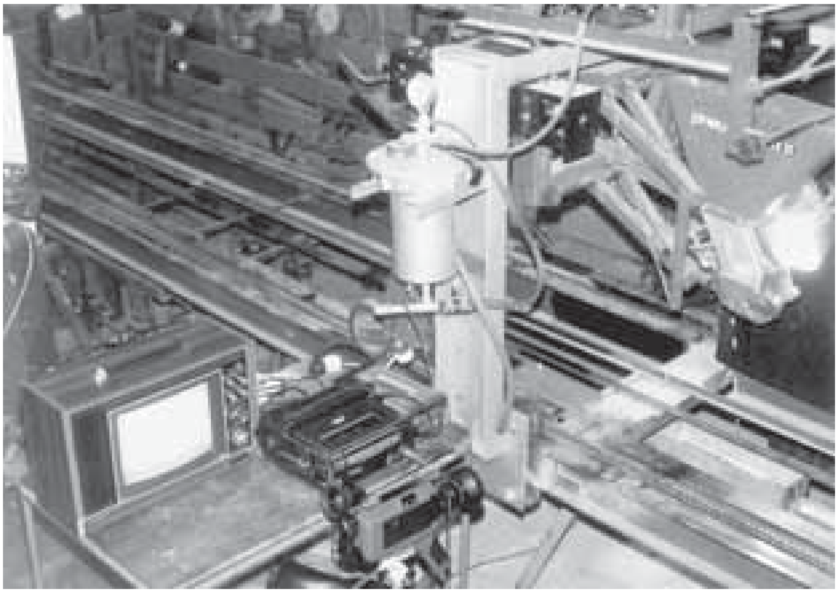


Fig. 19.8. The ejection of seeds from a no-tillage opener being filmed on video. Four individual maize seeds can be seen dropping from the precision seeder at the centre right of the photograph.

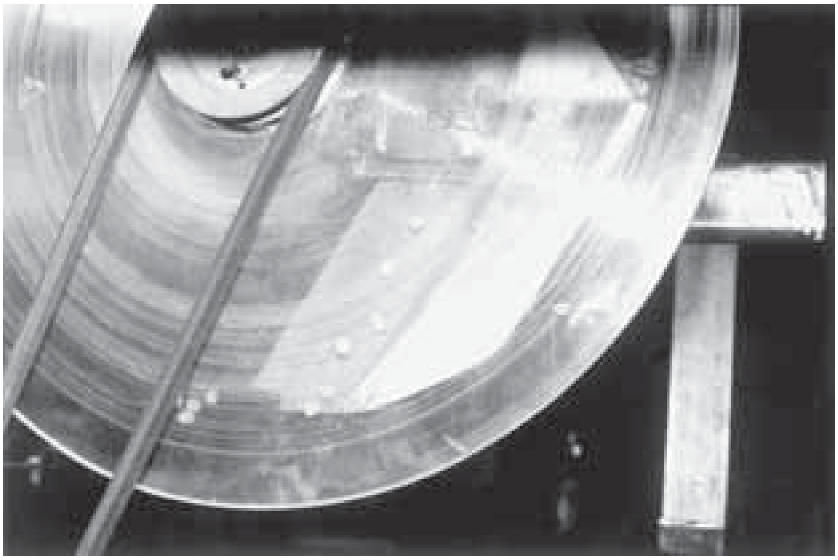


Fig. 19.9. Seed flow being monitored through a clear Plexiglas disc.

seed ejection and depth control qualities. The advent of endoscopes and laparoscopes appeals as a possibility, but dust collection on the lens while operating beneath the soil would seem to be inevitable, and continuous dust removal, by, for example, a small jet of air, might interfere with the seed ejection process itself. None the less, there is potential for innovative design in the pursuit of this objective.

Drag on a Disc Opener

The disc version of winged openers, in particular, operates on the principle of a central vertical disc with a number of other components rubbing on it, creating a drag on the disc, resisting turning. Contact between the disc and some of these components, e.g. the left- and right-hand side blades and scrapers, is essential to the residue-handling and seed-placement functions of the opener. So, too, is continued and uninterrupted rotation of the disc. Thus, it became important to be able to quantify the magnitude of the various torsional drag forces opposing continuous rotation of the disc so that those that are unnecessary might be eliminated and those that are useful could be minimized.

The method adopted consisted of designing a special test stand in which a single opener was mounted in such a way as to allow each of the components contributing to torsional drag to be individually attached and removed without otherwise affecting the function of the opener (Javed, 1992). The test stand with opener attached was pulled through a range of test soils at a constant and known ground speed. The disc had a modified motorcycle disc brake assembly attached to it, which was capable of stopping the disc, resulting in 100% disc slip in the soil. The force required to achieve any intermediate and predetermined degree of braking of the disc was recorded by an electronic force transducer mounted between the disc brake assembly and the frame of the test stand. The speed of the disc, in revolutions per minute, was indicated by a tachometer and was directly proportional to disc slip in the soil at any given forward speed. Figure 19.10 shows the disc drag test stand and opener.

The free disc, i.e. without any torsionally dragging components attached, was first braked down to a predetermined speed, representing a set amount of disc slip in the soil. Then each of the components thought to cause torsional drag was added to the opener individually and measurements were taken of the residual braking found necessary to achieve the same set amount of disc slip. The difference between this and the original reading represented the torsional drag on the disc attributable to the added component. Variability of the soil that provided the tractive forces driving the disc required that a large number of recordings

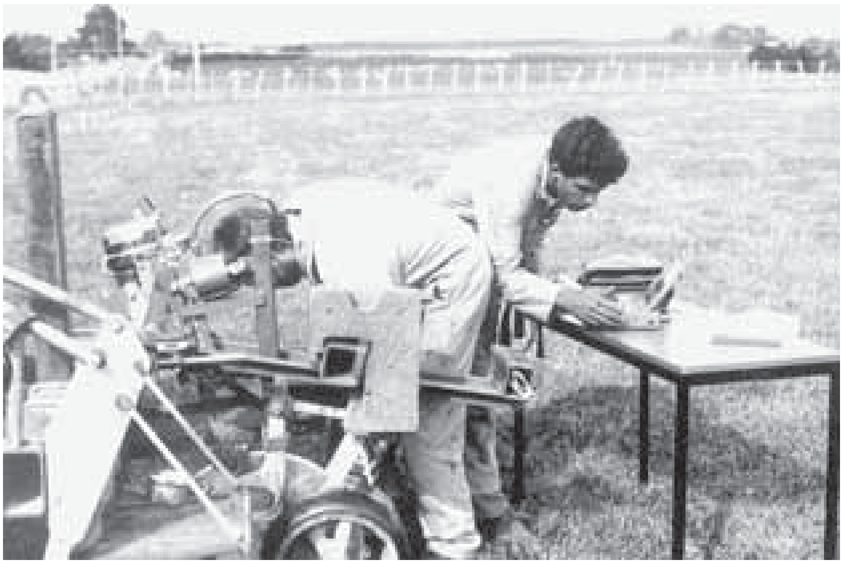


Fig. 19.10. A test stand for monitoring disc drag of a no-tillage opener.

be made to develop accuracy. These were made using a high-speed electronic data logger, which recorded some 10,000 individual readings per test.

Accelerated Wear Tests of No-tillage Openers

The disc version of the winged opener was quite different from other seed drill openers for either tilled or untilled seedbeds. Thus, little was known about the relative wear rates of its essential components, although Baker and Badger (1979) had studied aspects of wear on earlier simple winged openers. The two most important areas of wear on this opener were considered to be the soil-to-metal wear on the outside of the side blades and their wings and the metal-to-metal wear between these side blades and the rotating disc.

Indeed, it had not yet been determined whether the side blades actually rubbed on the disc (metal-to-metal contact) or were held fractionally clear of the disc by a fine film of soil passing between the two components, in which case the contact would result in metal-to-soil-to-metal wear. The question of possible contact between the side blades and the disc was important because, if there was no direct contact, it would allow the side blades to be manufactured from material of considerably greater wear resistance. If there was direct contact, hard side blades might have eroded the discs themselves, which would have been unacceptable.

A technique was developed to examine both questions (Brown, 1982; Brown and Baker, 1985). A single opener was assembled in such a manner as to electrically isolate the side blades from the disc. It was then operated in the soil with leads connected to both the disc and side blades through a 12-volt battery to complete a circuit if the two made electrical contact and monitored by a meter or resistance light bulb. In the soils tested, a thin film of soil continually isolated the blades from the disc. Subsequent field experience confirmed that the hardness of blades had no effect on the life and integrity of the face of the disc, and that the abrasion patterns on both the disc and insides of the blades are consistent with metal-to-soil-to-metal wear.

None the less, the thin film of soil wears both components at this interface. A further technique was developed to accelerate wear testing of alternative strategies for prolonging the life of the side blades. The opener was modified so that the axle of the disc could be powered, causing it to rotate when the opener was stationary. The modified opener was arranged so that the base of the disc and blades were immersed in an open box of crushed (and, in one case, slurried) soil at normal sowing depth. The side blades were held against the disc with springs to simulate the forces experienced in the field if the opener was proceeding forwards. The test stand was left to run continuously in this manner for extended periods so as to monitor the pattern of wear at the interface between the blades and the disc. Figure 19.11 shows the accelerated wear box and test opener.

Where normal field wear patterns on the outside of the blades and wings were being studied (soil-to-metal wear), there was no substitute for continuous field drilling. By definition, the openers were required to experience continuously undisturbed soil; thus, re-drilling the same area repeatedly was not an option. In one test, a single-row drill was constructed and 16 hectares of undisturbed land were drilled in single rows. The opener covered some 500 km, which was equivalent to 225 hectares of continuous drilling with a 4.5 metre (15 foot) wide drill. Wear of the various blade treatments was measured both dimensionally and as weight loss (Brown, 1982; Brown and Baker, 1985).

Effects of Fertilizer Banding in the Slot

A number of experiments were conducted to determine the most appropriate position to place fertilizer separately from seed. Apart from the more common field experimentation techniques (which are not described in detail here), a number of

Fig. 19.11. An accelerated wear box for testing a no-tillage opener.

specialized experimental facilities were developed.

Horizontal, vertical or diagonal separation directions were compared using modified disc-version winged openers with side-blade combinations as follows:

1. The side blades were on opposite sides of the disc and of equal length (horizontal separation).
2. The side blades were on opposite sides of the disc but the fertilizer blade was 20 mm longer (diagonal separation).
3. One side blade was extended below the disc to create a deep band beneath and to one side of the seed (deep banding).
4. A short and a long side blade were both positioned on the same side of the disc (vertical separation).

Crop performance and seed damage were compared with field trials of these combinations. The horizontal option performed better than the diagonal or vertical options in all respects (see Chapter 9). This was fortunate, because the vertical option would have been difficult to implement on a field scale because the placement of two blades on one side of the disc would have been a difficult engineering task for other than experimental purposes. Figure 9.4 (Chapter 9) shows the experimental vertical placement opener.

Surprisingly, the extended diagonal option did not seem to interfere with the ability of the opener to handle surface residues, but it did cause undesirable wear patterns on the inside edges of the blades because each blade contacted the disc in the gullet zone for approximately half of the time, whereas contact was continuous if above the gullets. Longer blades also resulted in an increase in torsional drag on the disc because of the extended contact zone between the two. Since there was no benefit for the longer, more complicated, fertilizer blades, the option was not pursued.

Afzal (1981) studied vertical versus horizontal placement of fertilizer relative to seed without using an opener by extracting small blocks of undisturbed soil from the field and placing these in pots and boxes. For vertical placement, he bored small holes vertically into the soil, placed a preweighed amount of fertilizer in the base of the hole and replaced a known quantity of loose, tamped soil on top.

For horizontal separation he repeated the process described above but bored the vertical hole only to the seeding depth and covered the seeds with the plug of undisturbed soil. He then bored a horizontal hole from the side of the pot or box to position the fertilizer a predetermined distance from but at the same height as the seed. This hole was also closed using a plug of undisturbed soil, but in this case without surface residues.

Prototype Drills and Management Strategies

As part of the logical development of a new field technology, laboratory developments eventually need to be tested on a field scale. With seed drills and planters, this can only be partially achieved using small experimental machines. For example, one of the most important functions of no-tillage drills is the ability to handle surface residues. A single-row experimental machine might suggest how well an opener would perform this task, but only a machine with multiple openers would experience interactions of adjacent openers over a field with variable residue amounts and configurations. Thus, it is important to observe opener and drill performance on a field scale along with monitoring component wear and durability.

It is also necessary to compare different opener design performances on a field basis, but only after testing their biological performance in controlled laboratory conditions. When laboratory details are complete, appropriate field comparisons are possible using a test machine with several openers.

Operation in the field offers opportunities to monitor farmer reaction to the new technologies and to learn from farmers the constraints imposed by their management systems. It also allows the scientists, working with innovative farmers, to evolve new management strategies based on the increased capabilities of no-tillage and related emerging new technologies.

The development sequence involves testing: (i) single-row test drills; (ii) universal toolbars for field-testing several different designs of openers at the same time; (iii) plot-sized field drills and planters; and (iv) field-scale prototype drills and a drilling service for farmers.

Single-row test drills

A range of single-row drill designs were constructed for three objectives. First, they were a facility to test the mechanical performance of prototype openers in a field soil. Usually, the scope of such tests was focused on quantifying the mechanical functioning in different soil or residue conditions. Occasionally, as previously described, they may be used to drill an extended area for accelerated wear tests.

Generally, these single-row test drills consist of an opener rigidly mounted in a subframe attached to a tractor three-point linkage, with the downforce provided by removable ballast. In this manner, the tractor three-point linkage acted as the articulating drag arms for the opener, although the geometries of such linkages were seldom adjustable to form a perfect parallelogram. Within the limited range of vertical movement required of the test machines when the opener was in the ground, the tractor linkages were considered acceptable.

Secondly, single-row units were used for seeding purposes, at which time simple seed and fertilizer distribution systems were added to the basic machines. These simple drilling units offered field experience for verifying the laboratory biological performance of seed and fertilizer placement.

Thirdly, they became a convenient, although limited, machine to demonstrate the new opener capabilities to farmer groups without the need to transport heavy multi-row machines to the field. But developers learned that, even with the aid of being able to see how each opener operated on the single-row demonstration drills, few observers were able to visualize the capabilities of a full-sized multi-row drill operating in the same circumstances. Consequently, the single-row demonstration concept played only a minor role in the wider technology transfer process, but was important in the engineering development process.

The single-row no-tillage drill concept was extended to become a commercially available machine as a plot drill for experimental stations; as a commercial drill for establishing edible shrubs by no-tillage on steep and erodible land; and as a commercial drill for small farmers in developing nations. The adaptability was further enhanced with the provision of a wheeled front steering frame to ensure that the wing angle on the opener remained correct and to facilitate turning corners when draught animals were used. A platform was added to the rear to allow an operator to step on or off to act as the downforce ballast. Figures 19.12, 19.13 and 19.14 illustrate several single-row test machines used to test and/or demonstrate the disc version of winger openers.

Simultaneous field testing of several opener designs

It is difficult to conduct a valid test of contrasting openers on a field scale without the ability to control the soil and climatic conditions. Almost invariably, such tests reveal the dominance of one opener over others being compared in that particular set of conditions, only to have the order altered in different conditions. The field conditions must be carefully identified under which any one opener is dominant, to learn the strengths and weaknesses of contrasting designs.

Often several parameters may vary, making it very difficult to isolate the reasons for one or more openers being superior for that particular set of conditions, without results from laboratory experiments that provide the biological capabilities of various no-tillage openers. And, unless the openers require very similar toolbar controls or are self-controlled, a single setting of height, down-pressure or speed may not be appropriate to all openers, biasing the results towards those openers that benefit most from the test settings.

It is interesting that, when people are asked to comment on the pros and cons of various no-tillage machines, many believe that such judgements cannot be made until several machines are lined up beside each other and tested in the same field. This seemingly obvious answer, however, is flawed because such field tests do not usually identify, let alone isolate, the individual causal processes of any differences that do arise. It

Fig. 19.12. A commercially available single-row no-tillage drill.

Fig. 19.13. An early single-row demonstration unit.

Fig. 19.14. A single-row machine for testing the residue-handling capability of a no-tillage opener.

is doubtful if any scientifically useful purpose has ever been served by field comparisons of multiple no-tillage machines.

Field toolbars are useful as an intermediate stage in the engineering field testing and development of prototype openers before any are considered sufficiently promising to incorporate into either a multi-row drill or planter, or even a self-contained single-row drill.

Figure 19.15 shows a universal field toolbar for evaluating a variety of openers,

Fig. 19.15. An example of a universal plot seed drill.

as designed by the University of New England, NSW, Australia (J. Scott, 1992, personal communication).

Plot-sized field drills and planters

Once the capabilities of an opener, e.g. the disc version of winged openers, are published or made public, it is common that other research organizations will design and construct plot-sized drills and planters equipped solely with these openers to sow test plots and fields for evaluation. In general, most designs of the plot machines have been an attempt to duplicate the mechanical arrangements of commercial field machines as faithfully as possible while at the same time incorporating facilities to more accurately monitor seed and fertilizer application rates, clean the product boxes between plots and adjust various mechanical options. These machines are made convenient to be easily transported to remote plots or farm field demonstrations. Such plot-sized drills have been an important intermediate stage of development before full-sized field prototype machines are contemplated. Figure 19.16 shows a selection of typical plot drills based on the disc version of winged openers.

Several designs of plot drills were used for plant-breeding purposes where plot sizes were small and the quantity of seed available was limited. Innovative mechanisms were introduced to delay release of the seed from the front gang of openers so that both the front and rear gangs began and ended seeding on the plot edges.

Field-scale prototype drills and a drilling service for farmers

The ultimate objective of any seed drill development programme is to produce a field-capable machine that can prove itself in normal commercial operation. One of the problems in developing effective no-tillage drills was that the drilling requirements were largely unknown and highly variable in this new style of farming, and few users could identify the causes of success or failure. Thus, field demonstration and proving took on a new dimension.

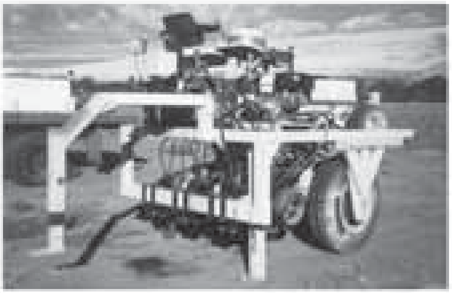
At first, a prototype drill was transported to a series of farmers' properties who were willing to try it on their farms, but this

RESEARCH–SCALE CROSS SLOT DRILLS

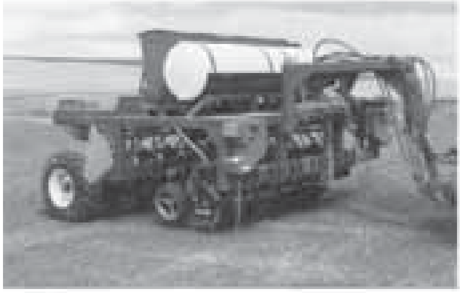
USDA-1, Pullman, WA

USDA-2, Pullman, WA

WSU Variety Testing – Pullman, WA



WSU Extension – Dayton, WA



WSU Research – Lind, WA

NDSU Research – Williston, ND

Fig. 19.16. Several plot drills based on the disc version of the winged opener.

often required modifying the hitches and hydraulic fittings each time a new farmer and tractor was involved. The problem of the incompatibility of hydraulic couplings was at first solved by equipping the test drill with a self-contained hydraulic system operated by a stationary petrol engine mounted on the drill itself, but this did not solve the other problems outlined above. It was also difficult to find a serious commitment from farmers to manage the no-tilled crops in a manner to provide reliable data on production and economics useful for field analyses.

A successful example of prototype testing and evaluation was a fully self-contained tractor, drill and truck developed and transported around New Zealand (Ritchie and Baker, 1987). That country offered a wide variety of agricultural enterprises, microclimates, farming systems and soil types representative of many of the agricultures of the world within a convenient travelling distance.

A charge was made to the farmers to both fund the operation and involve the participating farmers in a more committed and meaningful way. Thus, what was still primarily a field testing operation for the scientists also became a contract drilling service for the farmers ('custom drilling') and a highly effective technology transfer process for both parties. Over a 10-year period, during which three generations of prototype drills were utilized, this field drilling operation was used on approximately 200 separate fields on over 100 different properties, many of which were drilled for a number of successive years. Figure 19.17 shows the self-contained field operational machine.

While the primary purpose of this prototype drilling operation was to provide vital field performance information for the originating scientists and function as a technology transfer medium, the operation became the cornerstone for development and evaluation of new and innovative farm management techniques and strategies. And cooperating scientists and consultants used the opportunity as the means to introduce drought-tolerant pasture species into existing dryland grasslands by other scientists (Barr, 1986; Ritchie, 1986a, b; Milne and Fraser, 1990; Milne *et al.*, 1993).

Summary of Drill Development and Technology Transfer

1. There are few known or standardized experimental procedures for objectively evaluating no-tillage technologies.

2. The study of no-tillage drills, planters and openers requires developing knowledge about experimental procedures, mechanical performance and resulting plant growth.

3. Removing large soil blocks from the field in an undisturbed state to a climatically controlled environment is a useful method to control soil moisture, drill with openers to simulate field performance and control post-drilling climate.

4. Environmental requirements of seeds and seedlings within the seed slot involves studying such variables as: (i) soil moisture regime within the slot; (ii) soil-air humidity within the slot; (iii) soil oxygen within and around the slot; and (iv) soil temperature within the slot.

5. Soil disturbance by drill openers requires monitoring the parameters of: (i) soil strength; (ii) instantaneous soil pressure (stress); (iii) instantaneous and permanent soil displacement; (iv) soil bulk density; and (v) smearing.

6. Important aspects of seed position within the soil after drilling are: (i) seed

Fig. 19.17. A fully self-contained drilling machine for field testing and on-farm demonstrations.

spacing along the row; (ii) seed depth; and (iii) lateral position of the seed relative to the centre line of the slot.

7. The pathway seeds travel from metering to and through successful no-tillage openers is often more tortuous and less predictable than with simpler openers for tilled soils.

8. It is important to quantify the drag forces opposing rotation of disc openers to eliminate those that are unnecessary and minimize those that are useful.

9. Normal field wear of all drill components (blades, wings, discs, bearings, etc.) must be studied with continuous field drilling in undisturbed soil.

10. Adding components to openers for fertilizer placement may cause undesirable wear patterns or interfere with the ability of the opener to handle surface residues.

11. Field toolbars with multiple openers are useful to field-test prototype openers.

12. The ultimate objective of any seed drill development programme is to produce a field-capable machine that can prove itself in the normal commercial operation for which it is intended.

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