Soil Compaction and Farm Sustainability Indicators

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Soil Compaction and Farm Sustainability Indicators

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0. Introduction

New Zealand, and many other countries, are working to develop environmental quality indicators. The objective of these national efforts is to derive better sustainable development indicators (Williams and Mulcock 1996). Land, is one of three major media identified in New Zealand for national indicator development. Land quality indicators can potentially be developed at national, regional or local level. This paper examines the issues surrounding one aspect of land quality to determine the possibility of developing farm level indicators of sustainability.

Considerable research effort has focussed on the idea of weak sustainability which allows depletion of one capital stock to be offset by increases in the stocks of other forms of capital. At the farm level this idea might be useful if manufactured or human capital can be substituted for natural capital. If decline in soils' natural productivity can be offset by increases in manufactured capital, then farming systems may pass a test of weak sustainability.

Soil compaction is the particular focus of attention in this research and data on soil compaction and its effects are drawn from longitudinal research into maize cropping in the Manawatu region of New Zealand. The term soil compaction is used in this report to describe the loss of soil structure generally, rather than specifically under wheel traffic.

Worldwide, soil compaction has been recognised as a serious threat to the productivity of current agricultural practices (Ouwerkerk and Soane, 1994). At the farm level, soil compaction results in reduced yields and lower quality output, particularly in wet years. Increased inputs, such as greater tillage inputs and fertiliser applications, are symptomatic of soil compaction. These increases in inputs can partially compensate for the decline in soil structure and in natural soil fertility. The combination of reduced revenues and increased costs, lead to smaller crop Gross Margins. Soil compaction can also result in significant off-site environmental externalities.

This paper outlines the bio-physical processes and consequences of soil compaction, its economic significance for farmers, and the possible reasons for mismanagement of soil. Methodologies for valuing the effects of soil degradation are surveyed. The goal of developing a sustainability index for on-farm monitoring, leads to a review of economic modelling of soil use in cropping. Considerable insight has been gained overseas by modelling of cropping, soil degradation, and farmer choices regarding management of soil. The impacts of soil compaction, and the slow rate of rejuvenation of soils in the Manawatu, are sufficiently well understood to conclude that increased inputs of manufactured capital, energy and fertilizer inputs cannot substitute for lost soil properties.

But a lack of suitable data and an absence of precise knowledge about the relationships between cropping and soil degradation, and the rate at which other inputs can substitute for soil properties, means that farm level indices of sustainability are not feasible at present. The report concludes by proposing targets for future soil compaction research.

1. Soil Compaction Processes

Soil compaction can be either a natural or induced phenomena. Wet soil is particularly prone to compaction and deformation but the occurrence and consequences of compaction vary widely. Factors such as climate, soil type, initial soil condition, farm management practices, crop type and equipment used, all influence the likelihood of damage to soil by compaction (Oskoui and Voorhees, 1991). Pugging of soils by animal footprints particularly occurs on dairy farms, along tracks and other intensively grazed areas. Cultivation practices on cropping farms is a second major cause of soil structural degradation. Soil structure can be lost through sustained cropping, leading to a loss of organic matter, and eventual soil granule breakdown. A third cause is cultivation when soils are wet. Damage to soil occurs when cultivation practices and wheel traffic, leads to compaction, remoulding and consolidation of the cultivated layer Shepherd (1992). A combination of pressure and wet soil are the most likely dual explanations for the loss of soil structure (Haynes 1995). This study focuses on the compaction of agricultural soils through the use of agricultural machinery.

Changes in soil properties

Compaction changes a number of important soil properties. Table 1 shows the changes in soil properties as a result of continuous maize cropping on Kairanaga soils in the Manawatu region (Shepherd, personal communication 1997). This data shows the increases in bulk density, and decreases in total carbon, oxygen diffusion rate, air permeability, hydraulic conductivity and macroporosity to below the levels known to effect root development and plant growth (Shepherd, personal communication 1997). After 11 years of continuous maize cropping all the above indicators had reached or exceeded the critical limits beyond which productivity is severely affected.

The slow rate of recovery after damage is also shown in these results: after ten years in pasture three of the six soil indicators remain at or beyond the critical levels. For at least one of the soil quality indicators - total carbon - the period required under pasture to return to pre cropping levels can be as long as 90 years (Shepherd, Dando, Parshotam).

The changes in soil properties outlined above adversely affect productivity. Compacted soil is less permeable to air and water and is resistant to root penetration. Even after tillage operations, soil that has lost its structure can resettle and consolidate quickly, particularly if there is heavy rainfall or subsequent wheel traffic.

Crop Growth and Development[1]

Compaction of the soil increases soil strength and mechanical resistance to root penetration. The reduction in air capacity and respiration limits root development (Raghavan et al, 1978). The depletion of available oxygen and build up of carbon dioxide constrains the respiratory processes of plants and micro-organisms within the soil. The poor aeration also induces anaerobic processes, the by-products of which are toxic to plants (Hillel, 1980; Van Cleemput and El Sebaay, 1985).

Anaerobic conditions can also result in an increase in pathogens and a lower resistance to pest attack (Carter and Johnson 1989). For maize, the severity of these effects will depend upon which stage of development the plant is at when root diseases strike (Shepherd 1992).

The lower hydraulic conductivity has numerous deleterious effects. It can exacerbate the anaerobic conditions, lead to nutrient loss through increased run-off and leaching, and if the soils remain waterlogged, result in lower soil temperatures due to increased evaporation (Feddes 1971).

In anaerobic conditions the lack of respiration and build up of toxins substantially reduces the live organic matter in the soil, with subsequent reductions in nutrient supply.

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[1] The effects outlined are well established in the literature. However, as noted later the exact nature of these processes, and in particular the interactions and inter-relationships between them, are not well established. This uncertainty regarding the scientific aspects of soil compaction and the consequences of various remedial actions, is a barrier to rigorous economic modelling.

As existing organic matter is removed through mineralisation, the natural fertility of the soil is reduced. Shepherd (1992) found that organic matter decreased by up to 32,300 kg/ha in some Manawatu soil types after 11 years of continuous maize cropping.

The occurrence of anaerobic conditions increases denitrification, further reducing soil fertility. While losses of nitrogen due to denitrification are generally low, increases of up to 500 percent have been recorded in compacted soils (Soane and Van Ouwerkerk, 1995). The poor drainage properties and increased applications of fertiliser associated with soil compaction are principal causes of the increase in denitrification (Soane and Van Ouwerkerk, 1995).

The incidence of erosion may increase with subsequent reductions in rooting depth, nutrient loss and soil water retention. Shepherd (1992) notes the loss of soil structure due to compaction means that tillage operations are pulverising the soil to dust, making it highly susceptible to wind erosion. Increased water erosion may also occur as the lower hydraulic conductivity leads to increased run-off.

Farm Operations and Management

Soil compaction increases the energy, capital and labour inputs for tillage operations. Greater soil strength increase plough resistance, demanding greater draught requirements (Vorhees and Hendrick 1977; Shepherd 1992). At the same time the clods become both larger and stronger, decreasing the effectiveness of each tillage operation and requiring a greater number of passes to prepare the seedbed (Chancellor 1976). As compaction increases, more powerful and heavier equipment is required. The use of heavier equipment and the greater number of passes compounds the compaction problem. Oskoui and Voorhees (1991) found that wheel slippage increases with compaction, the loss of traction leading to further cost increases.

Lower hydraulic conductivity in compacted soils impairs drainage, decreasing the time available for seedbed preparation and sowing (Shepherd 1992). In areas where the growing season is short, delays in sowing can substantially reduce margins.

Lower natural fertility means substantial increases in fertiliser application rates are required to maintain productivity. Impaired root growth and increased nitrification can reduce the effectiveness of fertiliser applications (Shepherd 1992). In some instances, poor emergence rates necessitate re-sowing. This further reduces the growing season and incurs additional costs.

In summary, the physical, chemical and biological effects of soil compaction substantially reduce the gross margins of cropping. Lower germination and emergence rates, poor root growth and development, increased susceptibility to disease and pest attack, all contribute to lower yield quality and quantity. At the same time costs rise due to increases in tillage requirements, fertiliser applications, possible re-sowing and extra drying costs due to uneven ripening.

Research on the effects of continuous maize cropping on soil quality has been conducted in the Manawatu region for almost two decades Shepherd (1992). Data from that research has been used to construct the table of cultivation costs below, for one site in the Manawatu region. The data in Table 2 starkly illustrates the cultivation cost increases directly associated with continuous cropping. Number of cultivation operations, engine size, energy and labour required, all more than double in magnitude over the eleven year period reported. The overall effect is a trebling in cultivation costs from $101 to $324 per hectare.

These tillage cost increases are likely to be accompanied by fertiliser cost increases of a similar magnitude as farmer attempt to maintain the soil's productivity level Shepherd (1992). Haynes (1995 p.16) provides indicative figures on costs increases, revenue and gross margin decreases, for maize grown on compacted soils in the Manawatu district. Shepherd (1992 Figure 1), provides a useful graphical illustration of these simultaneous, revenue and cost effects, on maize gross margins. In some instances the cost increases can be sufficient to reduce gross margins to zero, or even to negative values.

The messages are clear from the research on soil compaction at one site in New Zealand that has alow resistance and resilience to structural degradation. Continued cultivation, maize growing and harvest lead to dramatic changes in soil quality, cultivation costs, and Gross Margins. Increased inputs of energy, labour, fertilizer and manufactured capital can partially offset decline in soil quality, and help maintain crop yields. Soil rejuvenates under pasture although there is considerable variation amongst the soil characteristics in their rates of recovery.

Off-Site Effects

Soane and van Ouwerkerk (1995) outline a number of off-site effects on the atmosphere, ground and surface water, and the physical soil resources. The off-site effects are generally detrimental but their impact is difficult to assess.

The atmospheric impacts relate principally to increases in Greenhouse gas emissions. For instance, there is a substantial one-off increase in carbon emissions with the loss of organic matter within the soil. Shepherd (1992) found losses of organic carbon of 16,800 kg/ha after 11 years of continuous cropping, which if aerobic conditions exist, will be released into the atmosphere as carbon dioxide. Increases in energy inputs for tillage operations and fertiliser production will result in further carbon dioxide and nitrous oxide emissions (Oskoui and Vorhees 1991).

Methane and nitrous oxide emissions from the soil can also increase, both of which are many times more potent than carbon dioxide as Greenhouse gases. Methane emissions are the result of anaerobic conditions in the soil. The extent of the increase of nitrous oxide is uncertain, with some researchers suggesting soil compaction may even reduce these emissions due to the decline in nitrification (Soane and Van Ouwerkerk, 1995).

The pollution of surface waters can occur through increases in run-off which is carrying slurry, nutrients, pesticide residues and sediment into waterways. Groundwater pollution can also increase as the reduced plant uptake of nitrates (due to poor root development) and the slower downward movement of water, combine to increase the nitrate content of water reaching groundwater aquifers (Soane and Van Ouwerkerk, 1995). Compaction may also reduce the ability of the soil and micro-organisms to filtrate and breakdown pesticides and other chemical substances, further degrading water supplies (Soane and Van Ouwerkerk, 1995).

Where water or wind erosion occurs, the transposition of soil may constitute a benefit to the recipient zones. However, it may also lead to silting of dams and water supplies (Bojö 1996), or the diffusion of soil borne pathogens that have built up due to compaction (personal communication Shepherd, 1997). The net benefits of erosion are therefore uncertain.

Remedial Actions

Rejuvenation is an obvious response to consider to compacted soil and subsoiling is the technique used in New Zealand. Subsoiling is achieved by pulling a rigid tine through the soil, below the normal cultivation depth. This practice loosens the compacted layers by cracking and lifting them and creating airspaces (Haynes 1995). The airspaces create pathways which aid root penetration and the movement of air and water.

Subsoiling has been shown to increase yields on compacted soils. In North Otago, subsoiling of compacted soils can lead to yield increases for wheat, barley and field peas of between 0.7 and 1.5 tonnes per hectare (Haynes 1995).
Rejuvenation is only achieved at a cost - equipment, fuel and labour are required to pull the tine through the soil 30-50 cm below ground surface. Costs per hectare of $150 are typical (Haynes 1995).

2. Economic Analysis of Soil Compaction

Much recent economic literature has focussed on the topic of sustainability (Stiglitz 1974; Solow 1974; Victor 1991). Defining the concept has proved difficult, and numerous variants have been proposed (Pearce et al 1989). A widely debated idea in much of the sustainability literature is the substitutability of inputs such as manufactured capital and labour, for natural resources.

Two concepts have been developed to describe extreme differences in views on sustainability. Strong sustainability regards natural resources as providing some functions which cannot be substituted by manufactured capital or labour. Weak sustainability in contrast accepts that manufactured capital or labour are completely substitutable for natural resources. Acceptance of the idea of substitutability of inputs underlies much of the research into the possibility of continued economic growth in a world of large but ultimately finite resources (Solow 1974; Gutes 1996). Advocates of this view have argued that an economy is sustainable if its savings rate is greater than the combined depreciation rate of manufactured capital and natural resources (Pearce and Atkinson 1993; Gutes 1996).

Much economics literature describes natural resources as natural capital. Under this view soil can be considered an example of natural capital. This paper adopts the view that soil is an essential but degradable input to agriculture. Hence substitution of other inputs - labour, energy, manufactured capital - can substitute, within limits, for some of the services provided by soil. The stock of soil can provide flows of benefits, but the level of these flows can decline over time if the stock is degraded. Economic analysis of soil use and misuse can therefore parallel many other capital stock management analyses.

Economic literature on soil degradation is primarily concerned with the efficient use of the soil resources. From this perspective soil degradation is not necessarily a bad thing as trade-offs need to be made between the net benefits of degradation versus conservation. In other words, the efficient use of the soil resource almost always justifies some level of degradation, as zero degradation generally implies the land is excluded from productive use (Bishop 1992). Conversely, some degree of conservation is also justified to facilitate future production.

Value of capital reflects future earning potential. Where soil degradation has diminished the future earnings potential of land, the capitalised value of the land is likely to be reduced. Soil conservation actions will maintain or even increase earnings potential and hence should increase the capital value of land.

The economic literature on soil degradation is dominated by water erosion studies, rather than soil compaction (Bojö, 1996). However, many of the economic issues surrounding soil compaction are common to all forms of land degradation, hence soil erosion and salination research offers insights into the modelling and valuation of soil compaction. Bishop (1992), Kirby and Blyth (1987) and Stonehouse and Bohl (1990) provide discussion of the general economic issues involved in soil degradation.

Optimal Soil Structural Degradation

Use of soil for crop production implies some degradation of the soil will occur. At the farm level the degradation of the soil might be offset by increased use of fertilisers, greater cultivation hours, and larger machinery. If soil is regarded as one of many inputs into the crop production process, then profit maximising farmers can consider what is the appropriate rate and level at which to degrade soil. Because soil can provide benefits over many years, dynamic efficiency rather than static efficiency is the stance used to judge the appropriate rate of soil degradation.

The returns from agricultural land consist of two components: a stream of net returns during ownership, followed by a capital gain (or loss) at the end of the ownership period Stonehouse and Bohl (1990). The decision to conserve soil will affect both of these components, and is a function of many variables such as the marginal productivity of fertile land, input and output prices, discount rates, information availability and attitudes to risk Bishop (1992).

Culver and Seecaran (1986), Gould et al (1989) and Featherstone and Goodwin (1993) have all studied the factors influencing a farmers decision to invest in soil conservation. The economically optimal level of soil degradation occurs when the discounted stream of future net returns from land ownership and use are maximised ie net present value (NPV) is maximised. In reality farmers are likely to make annual or more frequent judgements about soil use, as they weigh up the expected benefits in the current time period from soil use, to the foregone future benefits because of soil use and degradation (Milham 1994).

Deviations from Optimal Soil Use

Many researchers have suggested that the rate of soil degradation may diverge from the economically optimal rate (Kirby and Blyth 1987). There is a considerable body of economic literature on the reasons for the actual rate of degradation diverging from the optimal rate (Kirby and Blyth 1987; van Kooten and Furtan 1987; Bishop 1992). This literature outlines various sources of market failure and public policy options to remedy these failures. This literature is important to the current research as it highlights the limitations of market prices as a valuation tool for estimating the loss of natural capital, a topic which is discussed further in the section on hedonic pricing. However, the considerable literature that exists regarding the role of Government in rectifying such problems and the cost effectiveness of various policy options is beyond the scope of this paper.

The reasons for non-optimal soil degradation are discussed below.

Information Gaps, Risk and Uncertainty

A lack of knowledge is the most commonly cited reason for excessive soil degradation. The extent and impact of soil degradation may be masked by its slow but insidious nature, changes in technology and farm management practices or climatic variations. Even where soil compaction is recognised as an issue, it may not be acted upon as information on the extent and remedies can be costly to obtain. As information on soil compaction frequently contains public good aspects, individuals are prone to under-invest in information.

The complexity of soil degradation processes means that even when considerable investments are made to obtain information, a high degree of uncertainty can persist (Kirby and Blyth 1987). For instance, soil degradation involves time lags and threshold effects, and cost-benefit predictions are subject to the stochastic vagaries of other complex systems, such as climate, technological change and market expectations[2].

Incentives for Conservation

Farmers may under-invest in soil conservation due to their inability to appropriate its benefits. For example, tenure arrangements such as communal ownership, or short term leases (Kirby and Blyth, 1987) can lead to under-investment in soil conservation. Even where individual property rights are clearly defined and the on-site benefits can be appropriated by the land owner or farmer, capital markets frequently fail to recognise the value of soil conservation measures, as the section below on hedonic pricing indicates. If soil conservation investments are not reflected in land prices, the benefits to land owners of investments in soil conservation can be substantially reduced.

Externalities

The optimal private level of soil conservation may deviate from the socially optimal level due to externalities and public good aspects to soil conservation. The most significant externalities appear to be the off-site environmental impacts, such as water and air pollution (McConnell 1983; Stonehouse and Bohl 1990). The security of food supply is frequently cited as an example of a public good aspect to soil conservation, particularly in the literature of the mid-1980's.

Milham (1994) compares the optimal social rate of soil degradation with the optimal private rate of soil degradation. He suggests that distortions in capital markets and input and output prices are important factors but that the external costs and benefits may be the most significant cause of a differential between the optimal private and social rates of soil degradation.

Price Distortions

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2 Despite the prevalence of uncertainty in the analysis of soil degradation, there appears to be relatively little work regarding the impact of uncertainty on farmers, and farmers levels of risk aversion (Ardilia and Innes, 1993). Setia (1987) used Monte Carlo simulation to illustrate how two risk management strategies may lead to different preferred management systems. Ardilia and Innes (1993) develop two theoretical models to illustrate the impact of risk, wealth and production levels on output and, consequently, soil depletion.

Kirby and Blyth (1987) suggest that distortions in the prices of inputs and substitutes lead to excessive levels of soil compaction. For instance, subsidies on the prices of fertiliser can compensate for the lower levels of natural fertility due to compaction. Similarly, subsidies for land clearance may reduce the value of conservation measures on existing agricultural land.

Subsidies for land rejuvenation following soil degradation, will lower the economic penalty associated with soil degradation, compared with the situation where there are no subsidies. This may have the perverse effect of increasing the amount of soil degradation which occurs (LaFrance 1992). Landowners may continue cultivation and cropping practices which degrade soil, in the knowledge that there are low economic penalties. One possible consequence of lower penalties for soil degrading practices, is that there will be more soil degradation than would otherwise occur (Kirby and Blyth 1987).

Investment Constraints

Soil conservation generally requires investment in some form or other. This can take the form of expenditure on information, changes to capital equipment, or forgoing current productivity and income in exchange for increased productivity in the future. Some farmers will lack the resources to make such investments (Bishop, 1992).

Farmers' opportunity costs can diverge from that of society. Bishop (1992) suggests that the true opportunity costs of many conservation investments are higher than they initially appear as the timing of such investments coincides with the beginning of the growing season, when the demands on farmers time and capital is a its peak.

Discounting

The valuation of land degradation or soil conservation efforts requires a comparison of costs and benefits occurring over many time periods. Discounting is commonly used to facilitate such comparisons and the expected returns of soil investment options will depend on the choice of discount rate (Miranowski 1984; Kirby and Blyth 1987).

The discount rate reflects, among other things, consumers time preferences and the rate of return of capital (opportunity cost). It may also include a premium to reflect risk associated with the investment. Despite a vast amount of literature on discounting there is still no clear consensus on the circumstances in which discounting is appropriate, what rate should be used, or how the rate should be determined (Hanley and Spash 1993). The use of discounting where there are potentially irreversible impacts, and in issues regarding sustainability, is particularly controversial.

There is considerable debate over the possibility of divergence of private and social discount rates. The use of discounting and the selection of an appropriate discount rate involves subjective decisions. The decisions taken by landowners may cause private investments in soil conservation to diverge from what is socially optimal. It is widely argued that social discount rates should be lower than private discount rates (Pearce et al 1989). If this proposition is accepted, one consequence is the socially optimal level of soil degradation will be below the level tolerated by farmers if they use higher discount rates in decision making (Bishop, 1992).

This brief review suggests there can be many reasons why private decisions of landowners and managers can result in faster than socially optimal soil degradation. A second implication of these ideas is that land prices may be imperfect indicators of changes in soil quality, and of the true costs associated with soil degradation.

3. Mathematical modelling of farming and soil quality

A key issue in resource economics is how to maximise social welfare if soil (or other depletable resources) are depleted by economic activity. Mathematical economic techniques have been developed to gain insights into these issues. If adequate data is available two approaches may be used: simulation, and dynamic optimisation methods such as dynamic programming and control theory. The fundamental difference between these two approaches is that simulation addresses 'what if' questions, while programming models address 'what should be' questions (Greiner, 1996).

Some issues can be noted before selectively reviewing this literature. Problems for any modelling methodology include questions of scale, and aggregation and dis-aggregation. Compaction may be studied at the molecular level and up to the global impacts but it is not legitimate to generalise from one to the other. Plant growth models are amongst the most accurate but aggregating from these to farm level or regional level production is prone to major errors (Whisler et al, 1989). The complexity of soil processes and food production systems are further problems. The effects, even at one site, of variations in climate, farming practices, inputs, soil types, are difficult to manage. The information problems that hamper farmers making optimising decisions also affect the researcher.

Walker (1982) employs a two step simulation process. First he estimates via non linear regression a soil-depth-wheat-yield equation. Second a damage function is established to estimate the effect on net present values of various cultivation and cropping regimes. Sensitivity analysis is conducted to test the effects of variation in: soil-loss rates; discount rates, production costs and product prices. The modelling suggests that deferred conservation via minimum tillage is appropriate for deep topsoil areas, but immediate switch to minimum tillage is appropriate for sites with shallower eroded topsoil. Walker notes his work is site-specific, and the outcomes could vary greatly for different soils, crops, precipitation zones and tillage systems.

Miranowski (1984) employs a multiple period linear programming model with a penalty function in the terminal period. The objective function in his model is designed to maximize the present value of crop production over a fifty year period, less the present value of the cumulative productivity losses to the end of the fiftieth year discounted into perpetuity. Soil losses due to cropping are estimated via the Universal Soil Loss Equation (USLE), and these projected soil losses are subsequently translated to yield losses. Miranowski concludes that given the assumptions of his model, if farmers recognize the productivity impacts of soil loss and maximize long run net returns, they will adjust their crop management practices in response to the significant yield losses associated with soil erosion.

Walker and Young (1986) investigate the implications of technological change on the decision to invest in soil conservation. They conclude that the effect depends on the nature of the technological change: where the change is complementary to soil conservation the incentives for conservation are enhanced; where it is a substitute for conservation the incentives decline.

Considerable modelling of farming and its effects on soil quality has been completed in North America. The US Department of Agriculture's Erosion Productivity Impact Calculator (EPIC) model is used in some of these studies to generate output on soil loss. As the title suggests EPIC is directed at projecting productivity losses associated with erosion of topsoil. This soil loss data can be used as input data for economic modelling to search for optimal cropping regimes. Faeth (1993) is an example of research which builds upon EPIC generated data, to calculate via programming models, the present value of various tillage, and crop rotation regimes.

Milham (1994) employs an optimal control framework to determine the rate of soil depletion which maximizes the discounted value of the stream of annual net profits plus the market value of the land at the end of the planning period. Milham notes that researchers such as King and Sinden (1988) have recently recognized that soil has at least three unique components namely depth, fertility and structure. His model explicitly recognizes these three separate components, and he comments that soil fertility and structure are renewable features and hence, are in effect harvested, while soil depth can only be depleted. Despite the distinction, his summary conclusion is quite general, if farmers are well informed as to how soil degradation affects future profits and farm resale values, soil degradation will be incurred until the value of returns from additional degradation equals the marginal costs of degrading the soil.

Milham observes several caveats must be noted. First, decisions by profit maximizing farmers will only be optimal to the extent that they are well informed about the contribution of soil depth, fertility and structure to both current production and the terminal value of the land. Second, choice of commodity to produce and production technique are made under uncertainty regarding product prices and environmental effects. Errors in these judgements could lead to significantly greater, or lower, rates of soil degradation than anticipated. Third, external costs are typically ignored by farmers and hence private decisions will not mimic social decisions. Fourth, capital markets are often imperfect and high private discount rates will lead to faster than optimal soil degradation rates.

Some comments on modelling

Physical and biological science experiements are rarely set up to provide data which is useful for economic research. It is noticeable that almost all of the economic modelling surveyed focuses on soil erosion and not on soil compaction. It is relatively straight forward to measure change in soil depth and to relate that to change in soil productivity. It is more difficult to quantify soil compaction and then to relate that to change in soil productivity.

To establish rigorous economic models for either programming or for simulation, requires knowledge of the relationships between the factors involved. Some authors suggest that current knowledge is inadequate to create mechanistic models, and hence statistical estimation of the required relationships is required. Statistical estimation requires adequate data to ensure that relationships can be calculated with sufficient reliability. Economic modelling of soil stuctural degradation seems unlikely to progress until further knowledge of key relationships, or appropriate data, are available.

Modelling prospects in New Zealand

Data illustrating changes in soil characteristics, cultivation costs and crop yields for soil compaction prone soils have been collected for several years in the Manawatu region (Shepherd 1992). Table 2 above provides calculated cultivation costs associated with continued cropping of one soil type, and for a second soil type in Table 1 Shepherd

(1992). But this data does not allow robust statistical estimation of the impacts of cultivation on soil productivity, as many confounding influences must be controlled for. These include weather during growing seasons, timing of cultivation, and the effects of different farming practices.

To attempt to go further and explain what are the optimal cropping rotations on soil compaction prone soils, will require the following:

- development of an index for soil compaction and its application at various sites
- knowledge of the relationship between soil compaction index values and productivity for various crops at each site
- knowledge about the effects of stochastic elements such as weather, timing of cultivation, effects of various tillage practices on crop yields at these sites
- knowledge about the effects of various remedial actions on soil productivity following varying levels of soil compaction at various sites

Almost no knowledge is available on those items at present. There is no single best indicator, or an index, of soil compaction. Table 1 provides 4 snapshots of soil quality: under permanent pasture; after 4 years cultivation, maize growing and harvesting; after 11 years cultivation, maize growing and harvesting; and after a further 10 years of pasture. This data is valuable in illustrating the major changes which occur in soil quality, and can be used in an inductive fashion to draw general conclusions. But it is clear that a considerable volume of pooled cross section - time series data is required to support statistical estimation and deduction of precise answers on optimal cultivation and cropping regimes.

When there is insufficient data to support statistical analysis, simulation provides an alternative analytical technique. Scrimgeour (1995) provides a New Zealand attempt to model the effects of soil compaction via simulation of profits over a 20 year period. This approach assumes a linear reduction in yields over time and makes no allowance for increases in cultivation costs or fertilizer costs.

This approach could be used as a basis for establishing the Net Present Value (NPV) maximizing cropping rotations on these soils, if more detailed information is available about the expected yields, cultivation costs, fertiliser requirements, terminal land values, etc under a variety of cropping rotations. In the absence of that knowledge, only crude rules about cropping rotations seem possible at present.

4. Estimating the Costs resulting from Loss of Natural Capital

Where they exist, appropriate economic models can provide accurate data on the private and social losses resulting from soil degradation. In the absence of such models, alternative methods are required to estimate these losses. Estimating the costs which follow loss of natural capital is more complex than first appearance would suggest. Bojö (1996) discusses ten cost concepts which may be used in evaluation of the costs of land degradation. As well as these ten measures, a range of methodologies exists which have been used to assess the economic impacts of soil degradation Bishop (1992). The purpose of this section is to outline the strengths and weaknesses of each of the methodologies and to discuss their previous application to soil degradation research. In past empirical studies the choice of method has usually been dependant on practical concerns such as data availability, analytical capacity and time available (Bojö, 1996).

Hedonic Pricing

Hedonic pricing compares sale or rental values with respect to variations in attributes of properties. In theory, sale or rental prices should reflect the future income potential of an area of land. Soil degradation, which decreases land's future income, should be reflected in the unit price of land. This may be expressed as $P = P(X)$ where P is the price per unit of land, and X is a vector of land and soil characteristics. The partial derivatives of this function give the willingness to pay for each characteristic.

There are a number of limitations in using hedonic pricing to value land degradation or soil conservation measures. It is assumed that the agricultural land markets are sufficiently well developed to incorporate the effects of degradation and are not plagued by information barriers, price distortions or other constraints. This is often not realistic (as previously outlined). Even when markets are functioning well, prices will only capture the costs and benefits to the parties involved. The wider costs and benefits to society, such as the off-site impacts, will not be recognised in market prices.

Empirical hedonic pricing studies focussed on the degradation of agricultural land, generally relate to erosion rather than soil compaction. These studies have given mixed results. Miranowski and Hammes (1984) found that agricultural land markets do discount degraded soil but they did not assess whether price changes properly reflect the decline in productivity. Ervin and Mill (1985) concluded that farm prices underestimate erosion effects and suggest that the high costs of information are the principal cause. A similar conclusion is reached by Gardner and Barrows (1985) who found that farm prices do not accurately reflect soil conditions, except where extensive erosion has occurred and the problem is clearly visible. They conclude imperfect information is the most likely cause, particularly as the relationship between erosion and productivity is non-linear - it contains a threshold effect - which complicates productivity assessments.

In contrast to these studies King and Sinden (1988) found that land condition was clearly recognised in land prices in the area under study in Australia. Moreover, the price variations accurately reflect appropriate values for conservation measures. It is noteworthy that King and Sinden (1988) deliberately selected an area where conservation measures had been actively encouraged and assisted by the New South Wales State Government for many years. The land markets in that area may therefore be more aware and better able to estimate the impacts of soil degradation, than is the case in other areas.

In conclusion, it appears that agricultural land markets are generally hampered by information barriers and that the discounting of degraded land is insufficient to accurately value the effects of soil degradation, or conservation. However, when sufficient information is provided the changes in land productivity may be accurately reflected in land prices. The harmful effects of soil compaction are unlikely to be fully recognised in land prices because there are no widely recognised, comprehensive indicators of change in soil quality following continuous cropping.

Productivity Losses

Estimates of productivity loss are commonly used to assess the economic impact of land degradation. There are numerous empirical studies of this type for soil erosion, but relatively few for soil compaction. The basis of this method is to assess the decline in farm productivity due to soil degradation. The productivity loss may be calculated as either a gross or net figure, but in practice gross estimates are more common (Bojö, 1996). Gross measures look only at changes in revenue and ignore farmer responses to soil degradation. They also often ignore soil re-deposition on contiguous land areas.

Bishop (1992) suggests that a common mistake in this technique is to compare productivity losses from virgin soil with the losses from degraded soil. This implies that crops may be grown without any loss of soil fertility, which is generally unrealistic. More realistic measures compare changes in long run farm income, with and without soil conservation practices.

A further difficulty with this method is that the relationship between soil degradation and yield losses is not well defined (Bishop 1992).

Bojö (1996) outlines five methods that can be used to assess productivity losses: expert judgements; inferred soil loss decline functions; directly estimated soil loss yield decline functions; depth loss yield decline models; and/or plant growth models. The method which is employed will depend upon the degree of rigour required, analytical capacity, and the data and time available.

Examples of assessment of soil erosion's impact via each of the five approaches are given in Bojö (1996) and in Bishop (1992). Relatively few examples exist with respect to soil compaction. A New Zealand example is Shepherd (1992) who reports soil losses, yield reductions, cost changes, and declines in Gross Margins. The application of Productivity Loss methodology to assessment of erosion impact has produced a wide range of estimates, but these have generally been lower than expected. Estimates for the tropics are given in Bojö (1996), who concludes the magnitudes of cumulative losses should not invoke images of a rapidly approaching doomsday. Stonehouse and Bohl (1990) suggests the impacts are lower than initially feared in Canada.

Replacement Costs

The basis of this approach is to estimate the additional inputs required to compensate for the loss of soil fertility. In the soil erosion literature these costs usually refer to the cost of commercial fertiliser to replace the nutrients lost, although Bishop (1992) suggests that it could also include increased labour inputs. For soil compaction it would appear that the costs of any of the remedial measures outlined by Shepherd (1992) could be estimated to provide a replacement cost for the lost capabilities of Manawatu cropping soils.

The advantage of this approach is that it can be simple to apply (Bojö, 1996). For example, if data is available on nutrient losses, then the fertiliser equivalent may be readily estimated. However, there are also limitations. For instance, adjustments will need to be made to account for nutrient availability (Bojö 1996; Bishop 1992). As nutrient loss is being used as a proxy for productivity loss, it will only be appropriate if nutrient loss is the binding constraint (Bojö 1996). This will equally apply to other remedial actions.

The replacement approach appears to be less readily applicable to soil compaction as the complexity of the soil degradation process is greater than for soil erosion. Soil compaction changes a number of soil properties and before remedial action can be taken the binding constraint must be identified. Equally there is no certainty that all changes to soil properties can be overcome by the use of substitute inputs. Time, and natural soil forming processes may have few substitutes.

Net benefits of conservation.

Bishop (1992) suggests that the net benefits of soil conservation offers an alternative technique to the estimation of soil degradation losses. This method appears to be the same as the productivity loss approach, except here the emphasis is on valuing the improvements in productivity attributable to soil conservation, rather than valuing land degradation. It would therefore contain the same advantages and disadvantages of that method and could be applied as a gross or net measure.

Treatment of Off-site Costs

None of the above methods take into account off-site costs or benefits. The estimation of off-site costs is constrained by the lack of physical data. Moreover, the absence of markets for many of these off-site effects makes valuation problematic even where data is available. As a consequence valuation of off-site costs has been largely confined to off-site impacts that are readily measured and costed, such as the cost of removing accumulated silt from dams after erosion has occurred.

Estimation of off-site costs and benefits is problematic due to the absence of physical data. In addition, many of the costs are beyond markets and hence non-market estimation procedures are required. These can incur heavy data requirements. A useful insight into off-site cost estimation is provided by Bishop (1992, Box 5) who cites two South East Asian studies which calculate silt removal costs, reduced hydroelectric output and irrigated crop production losses due to soil erosion.

Contingent Valuation Method

One further possibility is to use Contingent Valuation Method (CVM), to assess Willingness to Pay (WTP) for land with compacted soil compared to WTP for non-degraded land. The WTP calculated are expected to provide estimates for the annual losses associated with soil compaction. Some initial work using CVM, has been initiated by Scrimgeour (1995) who used both a postal survey, and personal interviews with farmers to estimate WTP to avoid compacted soils. The results generated provide some support for the usefulness of the approach.

CVM has proved extremely valuable for eliciting WTP for many environmental assets Bishop, Champ and Mullarkey (1995), but it is reliant on some key items including the following. Respondents to the survey questions must have a consistent, unambiguous understanding of the nature of the item they are expressing WTP for. In the soil compaction case, this requires conveying to respondents a clear picture of the nature, impact, and likely duration of the costs associated with soil compaction. An 'index of soil degradation' and its expected change over time, would be very helpful in summarising to respondents the nature of the soil compaction.

Some comments on valuation methodologies
Hedonic pricing has proved a useful valauation technique where there are robust markets for well understood, and measured, products. Housing markets are an obvious example where Hedonic Pricing works well. In the absence of those criteria, the standard errors of valuation estimates can be very large, or the technique may not be able to provide any estimate of the item to be valued. Replacement Cost technique is only applicable in valuation of losses associated with soil degradation, when soil degradation is the binding constraint to production. The replacement costs estimated are at best only a proxy for productivity losses. Contingent Valuation is a very versatile technique, but the veracity of any values estimated is crucially dependent on survey respondents being well informed on the precise nature of the item for which they express Willingness To Pay.

The limitations of Hedonic Pricing, and Replacement Cost, suggests the Productivity Loss approach is among the few viable method to assess the costs associated with soil compaction. CVM also appears worthy of further research effort to assess its usefulness at estimating the losses linked with soil compaction.

5. Linking Losses of Natural Capital to National Accounts

Conventional Systems of National Accounts (SNA) which are used in many countries, provide misleading statements about national income because, among many reasons, they overlook degradation of natural resources, and other changes in natural resource assets. Several countries have explored ways to improve their National Accounting systems to provide more accurate statements of their sustainable income flows (Common, 1995).

Bigsby (1995) has recently explored the linkages between New Zealand forestry sector activities and the New Zealand System of National Accounts (NZSNA). By treating forests as a stock or 'material in process', growing forests add to the nation's assets. The changes in forest value can arise from changes in area, age class, market prices or silvicultural practices. Additions to the value of the forest estate comprise a significant component of New Zealand's recent GDP growth Bigsby (1995).

The economic impact of soil degradation will already effect New Zealand's national income if soil compaction leads to higher tillage costs, lower yields and lower farm profitability. It might also be included in enhanced National Accounts if soil compaction today, foreshadows diminished future farm productivity. If there is a consistent evidence of lower future farm profitability because of soil compaction, this will lead to reductions in farm valuations and ultimately effect New Zealand's GDP growth rate.

The crucial information required for this modification to reported National Income levels, is accurate data on asset values. The preceding section of this report outlines the difficulties faced in accurately measuring the losses associated with soil degradation. It is notable that Bojö (1996) reporting on a survey of 12 Sub-Saharan Africa land degradation studies concludes that ... 'Potential adjustments to the National Accounts appear modest, but are still worth doing from a conceptual point of view' (Bojö 1995, p172). A similar conclusion may be warranted for New Zealand.

6. Future Directions on Sustainability and Soil Quality Research

Much of the economic literature on soil degradation argues that well informed landowners and land markets make rational decisions about rates of degradation of soil. Soil degradation is expected to reduce both current farm incomes, and terminal land values. Crucial to those conclusions are availability of information about both on-farm costs, and external costs associated with soil degradation.

Soil quality is a key input in agriculture, and soil compaction significantly reduces the sustainability and profitability of cropping in the Manawatu region (Scrimgeour and Shepherd, 1997). The data presented in Section 1 above clearly indicates both the physical and the financial impacts of repeated cropping on one soil type. However the data available is too sparse to enable development and calibration of mechanistic models of cropping, cultivation, and soil quality. Equally, it appears that land markets are insufficiently informed about the impact of soil compaction on sustainable income levels, and land prices do not fully reflect changes in land productivity. Finally, is not possible at present to construct an index of sustainability for cropping farms, based on changes in quality and stock of natural and manufactured capital.

To enable progress toward those goals the following actions seem advisable.
1. Establish, validate, and publicise readily measurable indicators of soil quality for soil susceptible to structural degradation.

2. Conduct long term monitoring of soil quality, cultivation costs, yields on several cropping farms to establish a data base which allows statistical analysis to be conducted on the relationship between cultivation practices, weather, cropping rotations, soil characteristics, yields.
3. Complete more work on the rates of rejuvenation of compacted soils, particularly to establish 'ideal' cropping rotations for soil compaction prone soils.
4. Disseminate widely information regarding the effects of cultivation and harvesting on soil quality, cultivation costs, yields, and Gross margins to land owners in soil compaction prone areas.

Where there is widespread knowledge of soil compaction status following continued cropping, farmers can be expected to change cropping patterns, and land markets better reflect sustainable income levels. If those outcomes occur the case for farm level economic sustainability indicators is greatly diminished.

References

Ardilia, S, and Innes, R. 1993. Risk, risk aversion and on-farm depletion. Journal of Environmental Economics and Management. 25: S27 - S 45.

Bigsby, H, 1995. Accounting for Plantations: National accounts and forestry. New Zealand Forestry, 40(1): 15-18.

Bishop, J, 1992. Economic analysis of soil degradation. London Environmental Economics Centre, Gatekeeper Series GK 92-01.

Bishop, R, Champ and Mullarkey, 1995. Contingent valuation. In, Handbook of Environmental Economics, ed, DW Bromley, Basil Blackwell, 629-654.

Bojö, J, 1996. The costs of land degradation in Sub-Saharan Africa. Ecological Economics, 16: 161-173.

Carter, MR and Johnson, HW, 1989. Association of soil macroporosity and relative saturation with root rot severity of spring cereals. Plants and Soil. 120: 149-152.

Chancellor, WJ, 1976. Compaction of soil by agricultural equipment. University of California Division of Agricultural Science, Bulletin, # 1881.

Common, M, 1995. Sustainability and Policy: Limits to economics. Cambridge University Press, Cambridge.

Culver, D and Seecaran, R, 1986. Factors that influence the adoption of soil conservation technologies. Canadian Farm Economics, 20(2) 9-13

Ervin, DE, and Mill, JW, 1985. Agricultural land markets and soil erosion: Policy relevance and conceptual issues. American Journal of Agricultural Economics, 65: 938-942.

Featherstone, AM and Goodwin, BK, 1993. Factors influencing a farmer's decision to invest in long-term conservation improvements. Land Economics 69(3), 67- 81.

Faeth, P, 1993. An economic framework for evaluating agricultural policy and the sustainability of productions systems. Agriculture, Ecosystems and Environment, 46: 161-173.

Feddes, RA, 1971. Water heat and crop growth. Communications Agricultural University, Wageningen, The Netherlands No. 71 -12.

Gardner, K, and Barrows, R, 1985. The impact of soil conservation investments on land prices. American Journal of Agricultural Economics, 65: 943-947.

Gould, BW, Saupe, WE, and RM Klemme, 1989. Conservation tillage: The role of farm and operator characteristics and the perception of soil erosion. Land Economics. 65(2), 167-180.

Greiner, R, 1996. on-farm costs of soil salinisation: A case study for the Liverpool Plains in New South Wales. Review of Marketing and Agricultural Economics. 64(1), pp

Gutes, MC, 1996. The concept of weak sustainability. Ecological Economics, 17: 147-156.

Hanley,N and Spash C, 1993. Cost benefit analysis and the environment. Edward Elgar, Aldershot.
Haynes RJ, 1995. Soil structural breakdown and compaction in New Zealand soils. MAF Policy Technical Paper 95/5, Wellington
Hillel, D, 1980. Soil, air and aeration. Ch 11. Fundamentals of soil physics. Academic Press.
King, DA and Sinden, JA, 1988. Influence of soil conservation on farm land values. Land Economics, 64(3): 242-255.
Kirby, MG, and Blyth, MJ, 1987. Economic aspects of land degradation in Australia. Australian Journal of Agricultural Economics. 31(2): 154-174.
LaFrance,JT, 1992. Do increased commodity prices lead to more or less soil degradation? Australian Journal of Agricultural Economics, 36(1): 57-82.
McConnell 1983. An economic model of soil conservation. American Journal of Agricultural Economics, 65: 83-89
Milham, N, 1994. An analysis of farmer's incentives to conserve or degrade the land. Journal of Environmental Management, 40: 51-64.
Miranaowski, JA, 1984. Impacts of productivity loss on crop production and management in a dynamic economic model. American Journal of Agricultural Economics, 66: 61-71.
Miranowski, JA and Hammes, BD, 1984. Implicit prices of soil characteristics for farmland in Iowa. American Journal of Agricultural Economics, 66: 745-749.
Ouwerkerk, C van and Soane, BD, 1994. Conclusions and recommendations for further research on soil compaction in crop production. In, Soil compaction in crop production, eds, BD, Soane and C van Ouwerkerk, Elsevier , Amstredam.
Oskoui, KE and Voorhees, WB, 1991. Economic consequences of soil compaction. Transactions of the ASAE, 34(6): 2317-2323.
Pearce, DW and Atkinson, GD, 1993. Capital theory and the measurement of sustainable development: An indicator of weak sustainability. Ecological Economics. 8, 103-108.
Pearce, DW, Markandya,A, and EB Barbier, 1989. Sustainable Development, Earthscan, London.
Raghavan, GSV, McKyes, E, Gendron, G, Borglum, B, and Le HH, 1978. Effects of soil compaction on development and yield of corn (maize). Canadian Journal of Plant Science, 58: 435 - 443.
Scrimgeour F. 1995. The economics of soil compaction: A case study from the Manawatu. AERU Discussion Paper # 142: 324-333.
Scrimgeour,FG and Shepherd, TG, 1997. The economics of soil structural degradation under cropping: Some empirical measurements from New Zealand. Australian Journal of Soil Research. (In press).

Setia, PP, 1987. Evaluating soil conservation management systems under uncertainty. A simulation modelling approach. Proceedings of the National Symposium on Conservation systems. ASAE, St Joseph, Michigan.
Shepherd, TG, 1992. Sustainable crop management and its economic implications for grain growers. In, Sustainable Land Management: The Proceedings of the International Conference on Sustainable Land Management, ed, PR Henriques, Hawkes Bay Regional Council, 141-152.
Shepherd,TG and Dando,JL, 1997. Physical indicators of soil quality for environmental monitoring. In, Proceedings of Soil and land Indicators Workshop, Hawkes Bay Regional Council Technical Report EMT 96/3 , pp 33-42.
Shepherd,TG, Dando,JL, and Parshotam A, (in preparation). Morphological, physical and biochemical properties of a poorly drained soil under pasture, cropping and under reversion back to pasture. Soil Science American Journal.
Soane, BD and Ouwerkerk, C van, 1995. Implications of soil compaction in crop production for the quality of the environment. Soil and Tillage Research, 35: 5-22.
Solow, R, 1974. Intergenerational equity and exhaustible resources. Review of Economic Studies, Symposium: 29-45.
Stiglitz. J, 1974. Growth with exhaustible natural resources: efficient and optimal growth paths. Review of Economics Studies. Symposium: 123-137. Stonehouse, PD and Bohl, M, 1990. Land degradation issues in Canadian Agriculture. Canadian Public Policy. 16(4): 418-431.
Stonehouse,DP, and Bohl, M, 1990. Land degradation issues in Canadian Agriculture. Canadian Public Policy, 16 (4): 418-431.
Van Cleemput, O and El Sebaay, AS, 1985. Gaseous hydrocarbons in soil. Advances in Agronomy. 38: 159-181.
Van Kooten, GC and Furtan, WH, 1987. A review of issues pertaining to soil deterioration in Canada. Canadian Journal of Agricultural Economics, 35; 33-54.
Victor, PA, 1991. Indicators of sustainable development: Some lessons from capital theory. Ecological Economics, 4: 191-213.
Vorhees, WB, and Hendrick, JG, 1977. Compaction: Good and bad effects on energy needs. Crop Soils Magazine, 29: 11-13.
Walker, DJ, 1982. A damage function to evaluate erosion control economics. American Journal of Agricultural Economics 64(nov): 690-698.
Walker, DJ, and Young, DL, 1986. The effect of technical progress on erosion damage and economic incentives for soil conservation. Land Economics, 62 (1): 83-93.
Whisler,FD, Acock,B, Baker, DN, Fye, RE, Hodges, HF, Lmbert, JR, Lemmon,HE, McKion,JM, and VR Reddy, 1989. Crop simulation models in agronomic systems. Advances in agronomy, 40: 141-208.

Williams, MJ and Mulcock, CM, 1996. National environmental indicators: Building a framework for a core set. Agriculture New Zealand, Christchurch.

Biophysical indicators of ***soil quality*** of the Kairanga soil under various land uses

Land use	Oxygen diffusion rate (at -10 kPa ψ_s) (10^{-8} g O_2 cm^{-2} min^{-1})	Air permeability (at -10 kPa ψ_s) (10^{-13} m^2)	Hydraulic conductivity ($mm\ hr^{-1}$)		Air-filled porosity (at -5kPa ψ_s) (%)	Bulk density (Mg/m^3)	Total carbon (%)
			K -10	K- 40			
Permanent pasture	83 (11)	97 (17)	23 (3)	13 (2)	5.4 (0.4)	1.03	5.56
4 yrs maize	25 (3)	8.2 (1.2)	3.8 (0.9)	1.7 (0.3)	5.0 (0.3)	1.26	3.24
11 yrs maize	7 (1)	<0.5 (0.1)	0.2 (0.06)	0.1 (0.05)	0.1 (0.03)	1.39	2.53
11 yrs maize + 10 yrs pasture	17 (4)	36 (4)	9.7 (2.8)	2.9 (0.8)	3.2 (1.0)	1.21	3.01
Critical limit	20	4	1	0.4	5	1.28	2.50

Standard errors are given in parentheses

Figure 1
Costs of Seed Bed Preparation ($1996)

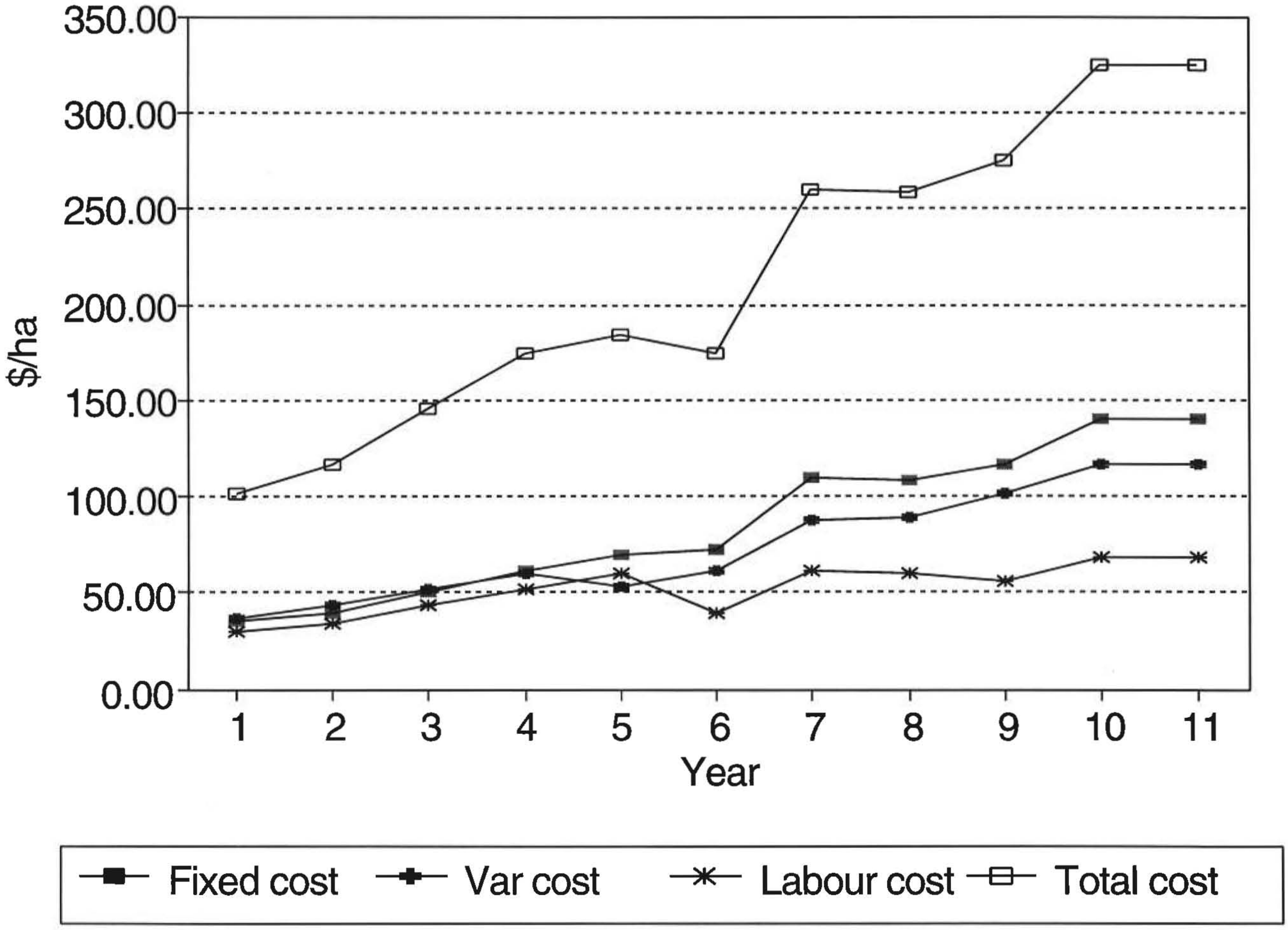

Table 2
Costs of Preparation - Maize Seed Bed ($1996/97)

Year	Fixed costs	Variable Costs (excl labour)	Variable Costs (incl labour)	Total Costs (excl labour)	Total costs (incl labour)
1	$34.85	$37.21	$66.86	$72.06	$101.70
2	$39.51	$43.24	$76.85	$82.74	$116.36
3	$50.68	$51.77	$94.88	$102.45	$145.56
4	$61.64	$60.21	$112.65	$121.85	$174.29
5	$70.41	$53.54	$113.44	$123.95	$183.86
6	$72.80	$61.29	$101.69	$134.09	$174.50
7	$110.61	$88.29	$149.68	$198.90	$260.30
8	$108.61	$89.04	$149.32	$197.64	$257.93
9	$115.99	$102.09	$158.63	$218.08	$274.62
10	$139.65	$116.33	$184.85	$255.97	$324.50
11	$139.65	$116.33	$184.85	$255.97	$324.50

Notes:

The upwards trend is interrupted in some places because:

- in Year 5 variable costs (excluding labour) decline when the number of passes declines from 7 to 4, thus reducing total fuel despite the use of the rotary hoe
- in year 6 total costs decline reflecting the lower labour requirement associated with the use of the larger (85 hp) tractor
- in Year 8 there is a slight decline in labour and therefore total costs when a disc and roller pass is substituted for the slower rotary cultivator. There is also a small reduction in fixed costs which are calculated on a per hour basis.

Cultivation Costs for Maize Seed Bed

Tractors:

Hp	Purchase Price	Resale Price	Fixed cost per hour	Variable cost per hectare
55 Ford	$40,000	$20,000	$10.40	4
85 John Deere	$67,000	$38,860	$15.94	6.7
100 John Deere	$81,000	$46,980	$19.04	8.1

Assumptions: Interest rate used in opp. cost and sinking fund calculations = 7% (real)
Tractors sold after 6 years and 3,500 hours

Fuel Cost per hectare:

Operation	Fuel (l/ha)	$/ha
Heavy cultivation	13	$5.98
Plough	21	$9.66
Light cultivation	8	$3.68
Rotary cultivation	13	$5.98
Drill	4	$1.84

Labour:

Wage rate/hour $8.85

Cost Calculations:

Year	Hours per ha	Fixed costs	Variable costs (excl labour)	Labour costs	Total varia Costs	Total costs
1	3.35	$34.85	$37.21	$29.65	$66.86	$101.70
2	3.80	$39.51	$43.24	$33.61	$76.85	$116.36
3	4.87	$50.68	$51.77	$43.12	$94.88	$145.56
4	5.93	$61.64	$60.21	$52.44	$112.65	$174.29
5	6.77	$70.41	$53.54	$59.91	$113.44	$183.86
6	4.57	$72.80	$61.29	$40.41	$101.69	$174.50
7	6.94	$110.61	$88.29	$61.39	$149.68	$260.30
8	6.81	$108.61	$89.04	$60.28	$149.32	$257.93
9	1.85	$115.99	$102.09	$56.54	$158.63	$274.62
	4.55					
10	2.54	$139.65	$116.33	$68.53	$184.85	$324.50
	5.21					
11	2.54	$139.65	$116.33	$68.53	$184.85	$324.50
	5.21					

Assumptions: Tractor R&M - 100% of purchase price over 10,000 hours
Oil and filters - 15% of fuel cost

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