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AN ECONOMIC EVALUATION OF CONSERVATION TILLAGE IN NORTHERN NEW SOUTH WALES : A DYNAMIC PROGRAMMING APPROACH

Evaluasi Ekonomi Pengolahan Konservasi di New South Wales : Suatu Pendekatan Program Dinamis

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ABSTRAK

Studi ini menganalisis hubungan antara erosi tanah dengan produktivitas tanaman pada tingkat petani individual. Tujuan utamanya adalah untuk melihat pengaruh erosi tanah, sistem rotasi tanaman dan sistem pengolahan tanah terhadap fungsi tujuan petani.

Analisis mencakup lima jenis tanaman, tiga sistem pengolahan tanah, dan dua sistem pengolahan konservasi. Ketiga hal tersebut kemudian dikombinasikan menjadi tiga sistem analisis. Program dinamis digunakan untuk menganalisis permasalahan tersebut. Program memperhatikan satu *state variabel* dan melibatkan 15 variabel keputusan.

Hasil analisis menunjukkan bahwa tanaman pada sistem pengolahan konvensional, walaupun menyebabkan tingkat erosi tertinggi, tetapi menghasilkan nilai fungsi tujuan tertinggi dibandingkan dengan dua sistem konservasi lainnya. Tingkat erosi kumulatif dapat ditekan hingga 17-55 persen dengan mengubah sistem pengolahan tanah dari konvensional ke konservasi. Namun, hal tersebut menimbulkan biaya opportunitas kepada petani yang besarnya antara 1.3-2.4 persen dari total nilai fungsi tujuan. Apabila tingkat produksi dengan kedua sistem konservasi tersebut meningkat masing-masing sebesar 5 persen, maka tanaman dengan sistem konservasi akan lebih menguntung-kan dibandingkan dengan sistem konvensional.

INTRODUCTION

The extent of soil erosion is by far the most important problem in the northwest of New South Wales. Indeed, the Namoi Valley area contains one of the few significant areas of highly fertile soils in Australia. However, Junor *et al.* (1979) reported that rapid erosion of this important resource is now occurring as a result of increased areas of previously grassed lands being brought into cultivation for both winter and summer crops.

The extent of soil erosion in that area increases drastically from 1945 to 1984. During the first 22-year period from 1945 to 1967 the area affected by erosion increased by 8 per cent, leaving about 53 per cent of non-eroded land. However, from years 1967 to 1975 and 1975 to 1984 the area not eroded fell to 31 and 15 per cent, respectively.

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Thus, soil erosion is now a far worse problem than it has ever been. This may represent a significant threat to the future agricultural production in the region.

Increased soil erosion implies losses both for the individual and for society. There are 3 potential sources of losses for the individual farmer: (1) crop production may be expected to decline and consequently farm profit, (2) production costs may be expected to increase, and (3) the value of agricultural land can be expected to decline in proportion to increased land degradation (Baffoe et al. 1987). Land degradation has been shown to influence the value of land in this area (King and Sinden 1988). The market has clearly recognised land condition, with better- conserved land selling for higher prices.

Crop productivity is a function of soil resource endowment, and management practices. The soil endowment is relatively stable, while the practices can often be changed. Therefore, the farmer is faced with the problem of choosing which management practices to use in order to maintain the productivity in response to soil erosion. At one extreme, the farmer can choose management practices which degrade the soil resource in the short term with some consequent effects on the future productive capacity of the farm. At the other extreme, the farmer can conserve the soil resource so that productive capacity is retained through time. The farmer's choice of management practice affects profit in the short term as well as the long term, particularly when soil productivity is reduced gradually over time.

In this study, two types of crop management practices are considered, namely *conventional tillage* and *conservation tillage*. While conventional tillage results in severe soil erosion, conservation tillage reduces the rates of erosion; therefore, the crop productivity can be expected to be maintained in the long run. Therefore, it is expected that, through the use of conservation tillage, the farmer's income can be maximised and reduction in the value of farmland can be minimised due to lower level of soil loss. Two types of conservation tillage are considered in the study: *minimum tillage* and *no tillage*.

The objective of this paper is to analyse the relationship between soil erosion and production at the individual farm level. This study attempts to estimate the impact of soil erosion, crop rotations and cultivation systems, on the farmer's objective function, that is maximisation of the net present value (NPV) of annual farm cash surpluses plus the present value (PV) of changes in the land prices.

AN ECONOMIC MODEL OF SOIL CONSERVATION

Farm-level Soil Conservation Model

McConnell (1983) developed an optimal control model suitable for analysing the theory of optimal private and social use of land. The focus of the model is the intertemporal path of soil use, and the determination of circumstances when the private path of erosion differs from the socially-optimal path. The two model solutions suggest that, under most institutional arrangements, the social and private rates of erosion would generally converge.

McConnell assumes the components of the model of the private decision are a maximisation of the PV of profits stream plus the PV of farm land at the end of planning period. He has shown that, in the absence of externalities, farmer decisions on investment to reduce farm soil loss can be socially optimal. He concluded: 'increasing soil loss does not imply that the farmers ignore physical production relations ... if farmers know that the soil base affects farm resale value, they will conserve it. ... It suggests that the impact of soil depth on the value of farms be investigated' (p. 88).

Soil Conservation and Land Value

In addition to the quality of the land resource base, there are likely to be several factors involved in the determination of farm land values. These include location factors, institutional factors, and other factors of government policy, and personal factors associated with particular purchasers and/or sellers. These factors have different relative importance in determining value of a unit of land, and therefore it would be difficult to isolate general effects of land degradation (Kirby and McCallum 1988).

Gardner and Barrows (1985 and 1987) investigated the relationship between investment in soil conservation practices and land price in Wisconsin. They argued that soil productivity is an important determinant of farmland prices. Since erosion control affects productivity, it might be tempting to conclude that the investment in conservation practices is capitalised into land prices. However, their study showed that the hypothesis that the value of soil conservation investments is capitalised into land value should be rejected, at least tentatively.

Recently, King and Sinden (1988) analysed the effects of soil conservation on farm land values in Manilla Shire, NSW. The hedonic approach was applied to cross-sectional data from an actual market under the competitive market assumptions. Their study showed that the market for land has clearly recognised land condition, with better-conserved land selling for higher prices.

The Farmer's Decision Model

A rational farmer will maximise profits from his farm activities over his working life. Two things are considered in achieving this an objective, (1) the PV of expected farm net income and (2) the PV of the change in value of the farm over the planning horizon. In brief, the economically-rational farmer will choose a plan which maximises his total NPV.

Decisions whether or not to adopt the soil-conserving practices rather than the conventional practices depend on the effects of such practices on the total NPV. If a soil-conserving practice raises both the PV of net income and the PV of farm, it would be rational for the farmer to adopt it.

Soil Erosion and Crop Productivity

Soil loss brought about by soil erosion can cause loss in productivity (Crosson 1984, Miranowski 1984, Sinden and Yapp 1987, Watt 1990, and Hall and Hyberg 1991).

In many cases, yield decline is related only to soil loss or soil erosion. There is no mention about soil depth, even though it is remaining soil depth rather than soil loss which is the critical factor influencing crop yield and productivity; and in the context of long-term productivity, erosion rates alone are not good indicators of soil degradation (Larson et al. 1983).

Crosson and Stout (1983), and Barrows and Gardner (1987) argued that erosion's effects on productivity depend in part on previous erosion. On some soils, over some considerable range of topsoil depth, erosion does not greatly affect yields because the depth is adequate for the plant's rooting zone and other characteristics are suitable for plant growth. At some point, further topsoil losses greatly affect yields as the subsoil begins to be plowed into the topsoil and rooting depth exceeds topsoil depth. As topsoil continues to decrease, the effect on the already-low yield becomes less dramatic.

Although soil erosion may often deplete productivity, the relationship between erosion and productivity is not generally well established. Sinden and Yapp (1987), Watt (1990), and Hall and Hyberg (1991) study the effects of land degradation on farm output in NSW. Their results suggest that land degradation caused a 4 to 7 per cent reduction in the total output.

Soil erosion, that reduces the productive capability of the soil, may be offset to some extent by deposition of material from elsewhere and by formation of new soil materials. However, even the limited available data suggest that the soil formation rates in Australia are very low. Edwards (1988) reports that soil formation rate in Australia is approximately 0.4 t/ha/y. This is obviously insignificant compared to the erosion rates.

Conventional and Conservation Farming

Conventional (traditional) tillage systems are used by most landholders throughout the country for crop production. Such practices can result in severe erosion which causes a significant reduction in crop production. This is because organic matter is not available for the improvement or maintenance of soil structure, nor is plant residue available to protect the soil from raindrop splash erosion and surface sealing (Charman 1985).

Conservation tillage is worthy of special mention, not only due to the soil-conservation advantages of the practice, but also due to the increased farming flexibility and energy savings which can be achieved with it. In addition, conservation tillage also ensures continued farm productivity and economic viability (Charman 1985). The essential elements of such system are reduction in the intensity of tillage, and retention of plant residue.

No-tillage and minimum-tillage systems are considered in this study because these systems are applicable and increasingly important to the arable land in northern NSW. Both systems involve the use of herbicides for weed control during the intercrop period. The advantages of both systems are not well known, but research on both systems, such as Herridge and Holland (1984), Colles (1983), and Colles and Popovic (1983), has showed that crop yields can be maintained in the long run.

METHODS TO ANALYZE THE SOIL EROSION PROBLEM

Review of Methods

Resolution of problems of soil erosion involve decisions on the intertemporal use of resources, and such decisions are usefully analysed by various types of mathematical programming, simulation, and benefit-cost analysis. Some applications of these methods are now reviewed.

Alt and Heady (1977), De Boer and Gaffney (1974, 1975), Saygideger *et al.* (1977) and Pope III *et al.* (1982) developed linear programming models to analyse the economic effects of soil erosion and soil (and water) conservation. The models are able to incorporate various tillage and conservation methods, crop rotations, different types of soils, and conservation policies. However, they are static-deterministic models which cannot analyse the full intertemporal effect of soil erosion on production.

Multiperiod linear programming (MLP) uses a linear programming model which incorporates time-dependent variables. In this framework, the activities are modelled and solved simultaneously within the time period. Pearse and Cowie (1986), Baffoe et al. (1987), Miranowski (1984) and Smith and Shaykewich (1990) developed MLP models which allow for an economic assessment, from a landholder's point of view, of implementing the various soil conservation programmes, structural works or management practices. The objective of the models are usually maximisation of PV of annual net returns or PV of farm networths over a certain year of planning horizon.

Most applications of dynamic programming (DP) have used an optimal control model, that is, a mathematical model to develop optimal strategies for resource use over time. Examples of these applications are McConnell (1983), Burt (1981), Bhide *et al.* (1982), Segarra and Taylor (1987), and Pagoulatos et al. (1989).

Segarra and Taylor (1987) developed a conceptual optimal control theory model which considers farm level decision making with respect to soil management. The model is an improvement, in both the theoretical and empirical application of control theory to soil erosion analysis, on previous studies. The theoretical model is more comprehensive than previous efforts, especially with respect to its treatment of investment in soil conservation capital and soil productivity. A simplified version of the model is then applied to the Piedmont area of Virginia.

Pagoulatos *et al.* (1989) developed an intertemporal profit function to determine optimal conservation-adoption strategies under alternative scenarios with respect to crop prices, relative yields, and discount rates. Special emphasis was placed on determining when the switchover from conventional to soil-conserving practices should take place.

Choice of the Method

Problems of soil erosion and conservation are both dynamic and multiperiod. They are dynamic because the optimal course of action over a period of time cannot be determined without considering the action taken in each period collectively. Thus, a static framework is incapable of considering the intertemporal impact of soil erosion and conservation on productivity and income. Consequently, the modelling procedure must incorporate the dynamic elements of the problem.

In this study DP is chosen, because it has several advantages compared to the MLP and MNP (multiperiod nonlinear programming). Firstly, since DP employs backward induction, it generally saves a number of calculations (Kennedy 1981). Whilst the number of calculations increases exponentially with MLP, it increases linearly with DP. Secondly, since DP requires computation of returns for every possible decision at each stage, it provides an automatic sensitivity analysis in addition to specifying the optimal decision policy. Thirdly, DP can be useful where there is no optimum decision or there are tied decisions at any stage (Kelly 1981). As all the possible decisions at every stage are enumerated, the results from selecting alternative decision paths can be easily evaluated. Finally, while MLP model is incapable of overcoming the problem involving a large number of integer variables, MNP is capable of solving it. However, since DP is more capable for handling dynamic natures of the problems at hand and it results in a more efficient solution, DP is chosen in this study.

Application of the Method

Cropping Activities

Many farming systems involve crop rotations. However, for the most part, crop rotations have been modelled using explicit predetermined rotations, such as a wheat-wheat-barley-barley rotation. An attempt is made to relax this requirement, allowing the model to determine freely the optimal long-run rotation. Such an analysis has been conducted by El-Nazer and McCarl (1986).

In this study, both fixed (predetermined) rotations and free rotations are considered. Since the alternative cultivation systems are also considered, there are three possible systems: free-rotation and free-cultivation systems; fixed-rotation free- cultivation systems; and fixed-rotation and fixed-cultivation systems. In the first system, crop rotation and cultivation are not predetermined, so the model 'chooses' any rotation, and any cultivation in order to maximise the objective function.

In the second system, fixed rotation free cultivation, sequences of crop activities for a certain period are predetermined, but the model chooses the cultivation system for each activity at each stage to maximise the objective function. In the last system, fixed rotation and fixed cultivation, both crop activity and cultivation system are predetermined at each stage.

In this study, only one state vaiable in considered, namely soil erosion, but there are 15 decision variables which result from combinations between 5 crop activities and 3 cultivation systems. The 5 crop activities are wheat (W), barley (B), chickpeas (C), sorghum (S), and sunflower (F); and the 3 cultivation systems are conventional, minimum, and no tillage. Three fixed rotations are considered, namely: WWFF, BBSS, and WCFS. The study concentrates on the effects of crop rotations (both free and fixed rotations) and choice of cultivation systems on soil erosion, and with it crop yield, farm profit, and land value.

Formulation of the Model

(a) Free-rotation and free-cultivation system

The model allows only one crop activity to be chosen from the all possible activities at any stage, that is from the 15 decision variables. The total area of the crop activity at any year (A_{ijt}) must, of course, not exceed the area of land available (L). In this study, the analysis is performed on a one hectare basis because such model can be adapted to other farmers who have different size of land but have the same structure of costs and geographical conditions.

The function to be maximised for the free-rotation and free- cultivation system is stated as follows:

$$\text{Max. } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=0}^{T-1} [P_i Y_{ijt} - C_{ij}] A_{ijt} (1+r)^{-t} + \qquad (3.1)$$

$$LNDVAL_T (1+r)^{-T} \qquad (3.2)$$

subject to:

$$E_{ij} \quad A_{ijt} \; - \; SL_t \; = 0, t = 0, 1, \ldots, T\text{-}1 \qquad (3.3)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} A_{ijt} \leq L, \; t = 0, 1, \ldots, T\text{-}1 \qquad (3.4)$$

$$SL_t \geq 0, t = 1, 2, \ldots, T\text{-}1 \qquad (3.5)$$

$$BCSL_0 = a \qquad (3.6)$$

$$BCSL_{t+1} = BCSL_t + SL_t, t = 1, 2, \ldots, T\text{-}1 \qquad (3.7)$$

where P_i is price of commodity i; Y_{ijt} is actual yield of commodity i under cultivation j at year t, and is a function of cumulative soil loss ($Y_{ijt} = f(CSL_t)$); E_{ij} is soil erosion coefficient for commodity i under cultivation j which is generated from SOILOSS; A_{ijt} is total area of commodity i under cultivation j at any year t; $LNDVAL_T$ is change in land value at the end of planning horizon T, and is a function of cumulative soil loss at that period ($LNDVAL_T = g(CSL_T)$); SL_t is soil loss at year t resulting from a specific crop activity at that period; $BCSL_0$ is beginning cumulative soil loss at year 0; $BCSL_t$ is beginning cumulative soil loss at year t; r is level of discount rate; a is mid point of range of cumulative soil loss for a particular year; m is the number of crops (5); and n is the number of cultivation systems, (3).

The objective function would, ideally, take into account both onsite and offsite effects of erosion. However, there is a lack of information on the offsite effects.

Therefore, only the onsite effects are considered in the study. The objective function Z represents the net present value of annual cash surpluses plus the present value of change in farm land at the end of planning horizon T ($LNDVAL_T$). Change in land value is negative and represents the cost to the farmer due to soil loss resulting from crop activities.

The actual yield for a specific crop at a specific year (Y_{ijt}) is a proportion of the maximum yield of that crop (Y^0_{ij}). In this case, the actual and maximum levels are linked by the erosion-productivity function which was developed by Watt (1990).

$$Y_{ijt} = Y^0_{ij} \ (a - \beta \, CSL_t) \qquad (3.8)$$

where and ß are the intercept and slope of the yield-damage function, and CSL_t is cumulative soil loss at year t.

Change in land value at the end of planning horizon ($LNDVAL_T$) is derived from King and Sinden (1988). Their results indicated that the land value of eroded properties using conventional tillage is $90.00/ha lower than the value of similar fully-conserved properties. Suppose that cumulative soil loss from wheat-wheat- pasture-pasture rotation under conventional tillage at the end of planning horizon T is CSL_c tonnes per hectare (1 mm/ha of soil is equivalent to 12 tonnes). This CSL_c is therefore the benchmark which is associated with a full $90 decrease in value. The change in value is set proportional to the loss of soil following, for example Baffoe *et al.* (1987), so the changes in the value of land resulting from different crop-rotation and cultivation systems are estimated from the following formula:

$$\begin{aligned} LNDVAL_T &= CSL_T/CSL_c * \$90 \text{ or} \\ LNDVAL_T &= CSL_T * h \end{aligned} \qquad (3.9)$$

where h (= $90/$CSL_c$) is soil loss penalty, that is the change in the value of land due to one millimetre loss of soil. Since the CSL_c is about 36 t (3 mm) in a 20-year period, the value of soil loss penalty (h) is $30 per mm.

Until recently there were no readily-available general- purpose computer programmes for DP. Therefore, this DP model was written in a computer programming language (FORTRAN), and solved on a personal computer.

(b) Fixed-rotation and free-cultivation system

For each of crop rotation, the cultivation system to be applied to a particular crop activity, at any stage, is a decision variable under this system. The model selects a cultivation system for each activity to maximise the cash surplus from that activity. The objective function and constraints of the model of fixed-rotation free-cultivation system are presented as follows:

$$\text{Max. } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=0}^{T-1} [\, P_i Y_{ijt} - C_{ij} \,] A_{ijt} (1+r)^{-t} + LNDVAL_T (1+r)^{-T} \qquad (3.10)$$

subject to:

$$E_{ij} A_{ijt} - SL_t = 0, t = 0, 1, \ldots, T\text{-}1 \qquad (3.11)$$

$$\sum_{j=1}^{n} A_{ijt} \leq L, t = 0, 1, \ldots, T\text{-}1 \qquad (3.12)$$

$$SL_t \geq 0, t = 1, 2, \ldots, T\text{-}1 \qquad (3.13)$$

$$BCSL_0 = a \qquad (3.14)$$

$$BCSL_{t+1} = BCSL_t + SL_t, t = 1, 2, \ldots, T\text{-}1 \qquad (3.15)$$

where P_i, Y_{ijt}, A_{ijt}, $LNDVAL_T$, and others are the same as those for free-rotation system.

The objective function and constraints are the same as those from previous model, except one for the constraint on total area of land (3.12). Under the previous model, there are 15 areas of crop activities (A_{ijt}) included in constraint (3.12). Here, only 3 areas are included.

(c) Fixed-rotation and fixed-cultivation system

The fixed-rotation and fixed-cultivation system does not involve choice of activities, and so can be solved using a spreadsheet. The objective function is similar to that for the two previous systems.

Sensitivity Analysis

Sensitivity analysis is undertaken to examine the effects of changes in some key variables on the objective function and choice of crop and its cultivation system. The key variables will be soil loss, soil loss penalty, yield, and discount rate.

RESULTS AND DISCUSSION

Basic Solutions

The basic solutions comprise the three crop rotation systems, a 10 per cent discount rate, a 20-year planning horizon, a \$30/mm of soil loss penalty, and basic yields and prices.

The solution to the free-rotation and free-cultivation system shows that conventional-tillage chickpeas (CC) and conventional- tillage wheat (CW) are the most desirable activities (Appendix Table 1). While, conventional-tillage chickpeas is one of the most profitable crop, it is also the most erosive crop. Its erosion coefficient is 14 t/ha/y, so it becomes less profitable if the farmer continues with that crop in the longer period. Consequently, the farmer should switch his crop from CC into a less erosive one. In this case, the switch is to CW with a 2.8 t/ha/y loss of soil, starting at year nine.

Cumulative soil loss at the end of year 20 is 12.13 mm or 145.60 t, at an average of 7.28 t/ha/y. Total NPV is $1381.40 which consists of PV annual cash surpluses of $1435.50 and PV of change (decrease) in land price of $51.40.

Among the three rotations under the fixed-rotation free- cultivation systems, WWFF is the most profitable, with a total net present value of $1214.94. The next most profitable rotation is WCFS ($1168.23), followed by BBSS ($1037.78).

For the WWFF rotation, the solution is conventional- tillage wheat and sunflower (CW and CF) for the whole 20 year period. This indicates that annual cash surpluses generated from both CW and CF are superior to those of minimum and no tillage. For BBSS and WCFS rotations, all crops are sown under conventional tillage, except for sorghum. Sorghum is grown under minimum tillage from the first up to the fourth four-year rotation sequence, and under no tillage in the last sequence (Appendix Table 1). Conventional-tillage sorghum (CS) is not chosen in either solution. This indicates that, in general, minimum- and no-tillage sorghum (MS and NS) are preferable to the conventional one.

All solutions from the fixed-rotation and fixed-cultivation systems (not presented here) show that for each crop rotation conventional tillage results in higher total net present value compared to minimum and no tillage. This indicates that, for a specific rotation, under a 20-year planning horizon, conventional tillage will be preferable to both alternative tillages. For example, total net present value resulting from WWFF rotation under conventional, minimum, and no tillage are $1214.94, $1128.34, and $1108.42, respectively.

Conventional tillage, for each specific rotation in the fixed- rotation and fixed-cultivation system, generates a higher total NPV than the two alternative tillages. A decision to choose either minimum or no tillage practice, rather than conventional tillage, therefore results in an opportunity cost. The farmer can trade off total NPV and CSL by switching cultivation system. When he switches the cultivation system from conventional to minimum tillage (for example BBSS rotation), the total NPV falls by $54.71 ($1031.66-$976.95), but he can reduce the loss of soil by 2.66 mm. This implies that the farmer loses $20.57 of net present value for saving one millimetre of cumulative soil loss. In other words, the opportunity cost of minimum tillage relative to conventional tillage, in BBSS rotation, is $20.57 per mm loss of soil. As another alternative, when he switches the cultivation system from conventional to no tillage, he could save 6.75 mm of soil loss, but it causes a reduction of the total NPV of $84.99. This is a loss of about $13.33 per mm. Values of all opportunity costs of the minimum and no tillage relative to the conventional tillage are presented in Appendix Table 2.

The values of the opportunity costs of no tillage practices, for each rotation, are less than those of minimum tillage practices. These indicate that switching from conventional to no tillage entails lower costs than those of conventional to minimum tillage.

Sensitivity Analysis

Effects of Zero Soil Loss

It is now assumed that all crop activities result in zero soil loss. Therefore, actual levels of crop yield in any year are the same as their maximum levels. This means that there is no yield reduction nor change in the value of land due to soil loss. The results are presented in Appendix Table 3.

The free-rotation and free-cultivation system, of course, results in the highest total NPV, \$1550.76. The decision variables here are CC_1 ... CC_{20}, indicating that conventional-tillage chickpeas is the most profitable crop at any time.

Under the fixed-rotation and free-cultivation systems, conventional tillage is also chosen for the decision variables for every crop in the rotations. This is because conventional tillage results in the lowest total variable costs compared to those of minimum and no tillage, while yield of each crop under those three tillage systems are assumed similar. Thus, conventional tillage results in the higher cash surpluses than minimum and no tillage. These results are also applicable under the fixed-rotation and fixed-cultivation system, and are also presented in Appendix Table 3. Solutions from this system indicate that for each rotation, the total NPV resulting from conventional-tillage system is always greater than that under minimum and no tillage.

If solutions under zero soil loss are compared to those under basic conditions, the PV of total user costs of having soil erosion can be enumerated. Total user cost indicates change in the value of objective function associated with the soil loss. For example, for the free-rotation and free-cultivation system, the value of having a 12.13 mm loss of soil is \$169.36, that is the difference in values of the total NPV (\$1550.76 - \$1381.40). Therefore, average user cost is about \$13.96 per mm of loss of soil. Values of average user costs for each system are presented in Appendix Table 4.

The values of average user costs vary from \$6.92 per mm to \$13.96 per mm loss of soil. The free rotation and free cultivation results in the highest (\$13.96). This is because under this system the solution allows choice of crops to maximise the objective function, regardless of the soil losses resulting from them.

The average value of average user costs resulting from fixed-rotation systems, with both fixed and free cultivations, is \$7.38 per mm. This value indicates that every mm loss of soil contributes \$7.38 to the decrease of the objective function, in present value terms. If this value is transferred in to current value, it equals to \$49.65. There are two components included in this value, that is change in value of land (LNDVAL) and change in cash surplus of production due to soil loss. Since the analysis is conducted under a soil loss penalty of \$30.00 per mm, thus every millimetre loss of soil contributes to the decrease in the objective function at \$19.65 (\$49.65 - \$30.00) through the decrease in crop production.

Effects of Change in Soil Loss Penalties

Since the value of the objective function is determined by the cash surplus and the change in land value, and since the soil loss penalty affects land value, any change in soil loss penalty (SLP) will affect the value of objective function. The effects of change in the value of soil loss penalty on the decision variables and the objective function are presented in Appendix Table 5.

When the value of SLP is zero, which implies there is no change in the value of land associated with soil loss, cumulative soil losses are maximised. For example, the CSL are 23.33 mm for the free-rotation and free-cultivation system, and 11.50 mm for WWFF rotation under the fixed-rotation free-cultivation system. With a zero SLP, crop yield changes with the associated soil loss, but the calculated value of land does not change even though the soil loss exists. Therefore, the NPV of cash surplus are equal to the overall objective functions (the total NPVs).

Cumulative soil loss decreases when the value of soil loss penalty increases. This occurs because cumulative reduction in the value of land increases with higher values of the SLP. Thus, the farmer switches from an erosive to a less-erosive crop, in order to maximise the objective function. By planting a less- erosive crop, in fact, the NPV of the cash surplus decreases, but the rate of change (reduction) in land value can be reduced. Thus, the less-erosive crops may result in higher net cash surpluses than the erosive ones. For example, under the basis SLP, \$30.00 per mm, the CSL and NPV generated from the free-rotation and free-cultivation system are 12.13 mm and \$1381.40, respectively. When SLP decreases from \$30.00 per mm to \$0.00 per mm, CSL and total NPV rise to 23.33 mm and \$1469.25, respectively. Next, when value of SLP increase from \$30.00 per mm to \$60.00 per mm, CSL decreases substantially to 4.30 mm, and total NPV falls to \$1348.20. From these three solutions, it can be seen that cumulative soil loss and total net present value decrease with an increase in soil loss penalty. Such a relationship is also applicable for solutions under fixed-rotation free-cultivation system.

The relationship between CSL and total NPV due to changes in the value of SLP can be analysed using elasticities. In this case, an elasticity is the percentage change in the NPV for one per cent change in CSL. The elasticities for the free-rotation and free-cultivation and the fixed-rotation and free-cultivation systems are presented in Appendix Table 6.

The elasticities vary between 0.037 to 2.688. All signs are positive, which implies that CSL and NPV are positively related, that is, total NPV increases with CSL. This relationship is applicable only for each specific rotation, not for the whole system.

Most of the values of the elasticities are less than one (inelastic), except that for WWFF rotation when the soil loss penalty changes from \$30.00 to \$60.00 per mm loss of soil. This means that a 10 per cent change in CSL will result in a 0.37 per cent change in NPV, in the same direction. Inelastic values imply that it is still profitable to have more soil loss since the percentage change in the NPV is less than the percentage change in CSL. This occurs mainly because of the low rate of change in Watt's yield-damage function.

Effects of Change in Yields

The effects of changes in crop yields on decision variables, CSL, and total NPV are now examined. The yields are assumed to increase and decrease by 5 per cent with conservation tillage, while yields under conventional tillage are assumed constant. This addresses the uncertainty in yields of crops under both minimum and no tillage.

When crop yields increase by 5 per cent with conservation tillage, minimum-tillage wheat (MW) is chosen for the whole period under the free-frotation and free-cultivation system, resulting a CSL of 2.83 mm and total NPV of $1491.94 (Appendix Table 7). On the other hand, when crop yields decrease by 5 per cent under conservation tillage, conventional-tillage chickpeas and wheat (CC and CW) are chosen. This system results in a CSL of 12.13 mm and a total NPV of $1381.40.

Under the fixed-rotation and free-cultivation system, a 5 per cent increase in yield with conservation tillage has caused both minimum and no tillage to enter the solutions for many crops. The only exception is sunflower in WWFF and WCFS rotations, which remains under conventional tillage (CF). When yields decrease by 5 per cent with conservation tillage, all crops under conventional tillage become superior to those under both minimum and no tillage. Thus, the solutions choose conventional tillage for each crop included in each rotation.

Solutions for the changes in yield under fixed-rotation and fixed-cultivation system indicate that if the crop yields can be increased by five per cent with both conservation tillages, the minimum- and no-tillage practices become preferable to the conventional one (the results are not presented).

Effects of Change in Discount Rates

Changes in discount rates affect the decision variables and consequently the total NPV. When the discount rate is 5 per cent, CSL is reduced substantially. The CSL is only 4.67 mm as compared to 12.13 mm under the basic discount rate. Under this condition, the model chooses the less erosive crops. On the other hand, when the rate increases to 15 per cent, the future income become less valuable relative to the case when discount rate 10 and 5 per cent. Thus, increasing net cash surpluses during the current and immediate future becomes an optimal strategy compared to the strategy oriented towards obtaining significant levels of future income by sowing less-erosive crops. From both conditions, it can be seen that solutions under different discount rates show that the CSLs increase (decrease) with higher (lower) discount rates.

Testing Hypothesis

Both conservation tillages, that is minimum and no tillage, result in a lower soil loss. So it might be expected that long- term reduction in crop yield and change in land value can be minimised by their use. In general, they might be expected to generate higher values of the objective function than conventional tillage. Therefore, it is hypothesised that 'crops under conventional tillage will result in lower total NPV than those under conservation tillage'.

The results from most solutions, however, indicate that crops under conservation tillages result in lower NPV than those under conventional tillage. The exception is for sorghum in the BBSS and WCFS rotation under the fixed-rotation and free-cultivation systems. The results from the fixed-rotation and fixed-cultivation system indicate that the total NPV from crop rotations under conventional tillage are more profitable than those under both conservation tillages. Thus, the hypothesis is rejected.

There are some possible reasons for the rejection of the hypothesis. First, although yield loss and loss in the land value are lower with conservation tillage, the variable cost associated with the conservation tillage is much higher, that is, between 1 to 14 per cent with minimum tillage and from 5 to 18 per cent with no tillage. The latter effect might have dominated the farmer to result in a lower total NPV with conservation tillage.

Second, although conventional tillage results in higher soil loss than conservation tillage, the adopted yield-damage function has a low coefficient of yield reduction due to soil loss. This has caused the crops under conventional tillage to result in higher NPV than those under conservation tillage.

Third, adoption of a low value of soil loss penalty. With a higher value, it is expected that the farmer will switch from soil-erosive crops to less soil-erosive crops. Solutions with different value of soil loss penalty under the free-rotation and free-cultivation, and the fixed-rotation free-cultivation systems indicate that the farmer switches the crop cultivation from conventional to conservation when the value of soil loss penalty increases from $30.00 per mm to $60.00 per mm loss of soil.

Finally, relatively 'short' planning horizon. With a longer-term period, it is expected that the farmer will switch from conventional to the conservation tillage. Thus, cumulative reduction in land value can be reduced and total NPV can be increased. However, total net present value will possibly decrease with the longer time period due to the effect of discount rate. Therefore, the effect of the longer time span depends on magnitude of reduction in the land value and effect of discount rate.

CONCLUSIONS

The solutions suggest that the quantity of soil erosion may not be as significant, at least in economic term, as is often suggested. Under the basic conditions, the solutions to the three systems indicate that crops under conventional tillage result in higher total NPV than those under conservation tillages although they result in greater soil loss. Market forces could not, therefore, be relied upon to encourage the adoption of a less-erosive crop production system.

Switching the cultivation system, from conventional to either minimum or no tillage, entails an opportunity cost. The present value of the opportunity cost of switching from conventional to minimum tillage ($71.10 per hectare), in terms of NPV, is lower than that of switching from conventional to no tillage ($95.36 per hectare).

These two values are averages over all three rotations in the fixed-rotation and fixed-cultivation system. However, in terms of per millimetre saving of soil loss, the cost of switching from conventional to no tillage, is greater than switching from conventional to no tillage, that is, $27.62 per mm rather than $14.40 per mm. These values mean that a one millimetre saving in the soil loss, resulting from the switch from conventional to minimum and no tillage entails a 2.40 and 1.26 per cent reduction in the total NPV, respectively.

For each of the three specific rotations, total NPV increases with CSL. Values of elasticities of total NPV with respect to CSL indicate that the percentage changes in the CSL are less than percentage changes in total NPV. This, again, does not encourage the adoption of less soil-erosive crop production system.

When crop yields of both conservation tillages are raised by 5 per cent, both minimum and no tillage become more profitable than conventional tillage. This occurs because the increase in revenue, due to the increase in yield, compensates for the difference in the total variable cost due to adoption of the conservation tillage relative to the conventional one. Therefore, if this yield does increase by 5 per cent the rational farmer will switch from conventional to either minimum or no tillage, particularly to minimum tillage.

With a higher discount rate, increasing net cash surpluses during the current and immediate future becomes an optimal strategy, compared to the strategy oriented towards obtaining higher levels of future income by planting the less-erosive crops.

One policy implication which can be deduced from the results is that sizeable reductions in the CSL can be accomplished by switching from conventional to conservation tillage, particularly to no tillage. More specifically, the reduction in the CSL varies between 17.39 and 22.86 per cent for switching to minimum tillage, and between 49.33 and 54.74 per cent for switching to no tillage. But, switching from conventional tillage to either minimum or no tillage will reduce the value of objective function.

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Appendix Table 1. Basic Solution for Free-rotation and Free-cultivation System, and Fixed-rotation Free-cultivation Systems

System	Solutions
(1) Free rotation and free cultivation	
Decision variables[a]	$CC_1 \ldots CC_8\, CW_9 \ldots CW_{20}$
Cumulative soil loss (mm)	12.13
NPV of cash surplus ($)	1435.50
Change in land value ($)	-51.40
Total NPV ($)	1381.40
(2) Fixed rotation free cultivation	
a. W W F F	
Decision variables[b]:	5 x (CW CW CF CF)
Cumulative soil loss (mm)	11.50
NPV of cash surplus ($)	1266.22
Change in land value ($)	-51.28
Total NPV ($)	1214.94
b. B B S S	
Decision variables[b]:	4 x (CB CB MS MS); 1 x (CB CB NS NS)
Cumulative soil loss (mm)	9.90
NPV of cash surplus ($)	1081.93
Change in land value ($)	-44.15
Total NPV ($)	1037.78
c. W C F S	
Decision variables[b]:	4 x (CW CC CF MS); 1 x (CW CC CF NS)
Cumulative soil loss (mm)	15.37
NPV of cash surplus ($)	1236.75
Change in land value ($)	-68.52
Total NPV ($)	1168.23

[a] subscripts indicate years within the planning horizon
[b] codes in brackets indicate choice of crop within a four-year rotation

Appendix Table 2. Opportunity Costs of Switching from Conventional to Minimum and No Tillage for Fixed-rotation and Fixed-cultivation System

Rotation and cultivation	Saving in CSL[1] (mm)	Loss in NPV ($)	Opportunity cost ($/mm)
(1) W W F F			
Conv. - Min.	2.00	86.60	43.30
Conv. - No till.	5.67	106.52	18.79
(2) B B S S			
Conv. - Min.	2.66	54.71	20.57
Conv. - No till.	6.75	84.99	13.33
(3) W C F S			
Conv. - Min.	3.79	71.97	18.99
Conv. - No till.	8.54	94.58	11.07

[1] cumulative soil loss

Appendix Table 3. Effects of Zero Soil Loss on Decision Variables and Total Net Present Value for the Three Rotation Systems[1]

Rotation system/ cultivation	Decision variables	Total NPV ($)
(1) Free rotation and free cultivation	$CC_1 \ldots CC_{20}$	1550.76
(2) Fixed rotation free cultivation		
a. W W F F	5 x (CW CW CF CF)	1297.25
b. B B S S	5 x (CB CB CS CS)	1116.97
c. W C F S	5 x (CW CC CF CS)	1285.97
(3) Fixed rotation and fixed cultivation		
a. W W F F		
Conventional tillage		1297.25
Minimum tillage		1200.14
No tillage		1152.41
b. B B S S		
Conventional tillage		1116.97
Minimum tillage		1047.53
No tillage		982.39
c. W C F S		
Conventional tillage		1285.97
Minimum tillage		1191.47
No tillage		1132.39

[1] Zero soil loss results in no cumulative soil loss and no change in land value.

Appendix Table 4. Comparison of Solutions under Zero Soil Loss and Basic Conditions

Crop rotation and cultivation	Zero soil loss CSL(mm)	NPV($)	Basic conditions CSL(mm)	user cost NPV($)	Average ($/mm)
(1) Free rotation and cultivation	0	1550.76	12.13	1381.40	13.96
(2) Fixed rotation free cultivation					
a. W W F F	0	1297.25	11.50	1214.94	7.16
b. B B S S	0	1116.97	9.90	1037.78	8.00
c. W C F S	0	1285.97	15.37	1168.23	7.66
(3) Fixed rotation and fixed cultivation					
a. W W F F					
Convent.	0	1297.25	11.50	1214.94	7.16
Minimum	0	1200.14	9.50	1128.34	7.56
No till.	0	1152.41	5.83	1108.42	7.55
b. B B S S					
Convent.	0	1116.97	12.33	1031.66	6.92
Minimum	0	1047.53	9.67	976.95	7.30
No till.	0	982.39	5.58	941.67	7.30
c. W C F S					
Convent.	0	1285.97	16.58	1164.92	7.30
Minimum	0	1092.95	12.79	1092.95	7.70
No till.	0	1132.39	8.04	1070.34	7.72

Appendix Table 5. Effects of Various Soil Loss Penalties on Decision Variables and Total Net Present Value for Free-rotation and Free-cultiva- tion System, and Fixed-rotation Free-cultivation Systems

	Soil Loss Penalty ($/mm)		
	0.00	30.00	60.00
(1) Free rotation and free cultivation			
Dec. vars.:	$CC_1 \ldots CC_{20}$	$CC_1 \ldots CC_8$ $CW_9 \ldots CW_{20}$	$CW_1 \ldots CW_{15}$ $MW_{16} .. MW_{20}$
CSL (mm)	23.33	12.13	4.30
NPV (cash surplus)	1469.25	1435.50	1386.55
LNDVAL ($)	-0.00	-54.10	-38.35
Total NPV ($)	1469.25	1381.40	1348.20
(2) Fixed rotation free cultivation			
a. W W F F			
Dec. vars.:	5x(CW CW CF CF)	5x(CW CW CF CF)	4x(CW CW CF CF) 1x(MW MW CF CF)
CSL (mm)	11.50	11.50	11.32
NPV (cash surplus)	1266.22	1266.22	1264.74
LNDVAL ($)	0.00	-51.28	-100.92
Total NPV ($)	1266.22	1214.94	1163.82
b. B B S S			
Dec. vars.:	5x(CB CB CS CS)	4x(CB CB MS MS)	2x(CB CB MS MS)
1x(CB CB NS NS)	3x(CB CB NS NS)		
CSL (mm)	12.33	9.90	8.53
NPV (cash surplus)	1086.66	1081.93	1073.51
LNDVAL ($)	0.00	-44.15	-76.11
Total NPV ($)	1086.66	1037.78	997.40
c. W C F S			
Dec. vars.:	5x(CW CC CF CS)	4x(CW CC CF MS) 1x(CW CC CF NS)	2x(CW CC CF MS) 2x(CW CC CF NS)
CSL (mm)	16.58	15.37	13.97
NPV (cash surplus)	1238.87	1236.75	1227.60
LNDVAL ($)	0.00	-68.52	-124.56
Total NPV ($)	1238.87	1168.23	1103.04

Appendix Table 6. Elasticities of Total Net Present Value with Respect to Cumulative Soil Loss

Rotation system	Change in soil loss penalty ($/mm)	
	$30.00 - $0.00	$30.00 - $60.00
(1) Free rotation and free cultivation	0.069	0.037
(2) Fixed rotation free cultivation		
a. W W F F	und.	2.688
b. B B S S	0.192	0.281
c. W C F S	0.767	0.613

und. = undefined, due to a zero per cent change in cumulative soil loss (denominator).

Appendix Table 7. **Effects of Change in Yield on Cumulative Soil Loss and Total Net Present Value for Free-rotation and Free-cultivation System, and Free-rotation Fixed-cultivation Systems**

Crop rotation/ cultivation	Change in yield with conservation tillage	
	Increase 5 %	Decrease 5 %
(1) Free rotation and free cultivation		
Decision variables:	$MW_1 \ldots MW_{20}$	$CC_1 \ldots CC_8$ $CW_9 \ldots CW_{20}$
CSL (mm)	2.83	12.13
NPV[a] ($)	1504.58	1435.50
LNDVAL ($)	-12.64	-54.10
Total NPV ($)	1491.94	1381.40
(2) Fixed rotation free cultivation		
a. W W F F		
Dec. vars.:	5 x (MW MW CF CF)	5 x (CW CW CF CF)
CSL (mm)	10.58	11.50
NPV[a] ($)	1325.80	1266.22
LNDVAL ($)	-47.19	-51.28
Total NPV ($)	1278.61	1214.94
b. B B S S		
Dec. vars.:	4 x (MB MB MS MS) 1 x (MB MB NS NS)	5 x (CB CB CS CS)
CSL (mm)	8.98	12.33
NPV[a] ($)	1139.31	1086.66
LNDVAL ($)	-40.06	-55.00
Total NPV ($)	1099.25	1031.66
c. W C F S		
Dec. vars.:	4 x (MW MC CF MS) 1 x (MW MC CF NS)	5 x (CW CC CF CS)
CSL (mm)	12.99	16.58
NPV[a] ($)	1297.20	1238.87
LNDVAL ($)	-57.93	-73.95
Total NPV ($)	1239.27	1164.92

[a] net present value of annual cash surpluse