An economic approach to soil fertility management for wheat production in New South Wales and Queensland

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Abstract

Soil fertility decline and soil management for crop production are important issues for grain growers in northern New South Wales and southern and central Queensland. In this paper a stochastic dynamic economic analysis of soil fertility management is presented to derive optimal fertility levels, and the management practices to achieve them. A sequential analysis of first deriving the optimal nitrogen stock and application, *ceteris paribus*, was followed by an assessment of tillage, stubble and fertiliser strategies to obtain an optimal level of soil organic carbon in the soil. The recommended management practices are compared with levels of current usage in the region. The derivation of optimal levels of soil fertility for agricultural purposes may have other policy implications.

Key words
Soil fertility, economic, dynamic, stochastic, nitrogen, carbon

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1. Introduction

Soil fertility decline in the cropping region of north-eastern Australia has been an important issue for scientists (Dalal and Mayer 1986a, b, c, Whitbread *et al*. 1998, Chan *et al*. 2003) and for the grains industry (Grains Research and Development Corporation (GRDC) 2003). The major component of soil fertility is soil organic matter (SOM), which has important biological, chemical, physical and environmental roles (Franzluebbers 2002). Chemically, SOM comprises the organic forms of carbon (C), nitrogen (N) and other nutrient elements (eg phosphorus, sulphur) that can be transformed into inorganic forms which are available to plants. Leaving aside soil erosion, these components can be both depleted and built up by cropping practices; hence soil fertility is a renewable natural resource when used for agricultural production.

Measured declines in soil fertility have been identified as a cause of declining wheat quality (particularly protein content) in the region (Hamblyn and Kyneur 1993). Hence there are potential benefits to individual farmers from managing investments in soil fertility remediation. The building up of soil C associated with improved soil fertility could also provide benefits to farmers and others in terms of C sequestration and the greenhouse effect (Lal 1997), although in a policy context land use change and forestry projects to offset emissions of carbon dioxide must consider the permanence of such changes (Cacho *et al*. 2003). For either the individual farmer or a carbon credit market, the economics of building up soil fertility for wheat production is an important question.

Some soil scientists (eg Whitbread *et al*. 1998) have recognised that SOM concentrations measured in their reference soils (representing the original soil status) are not necessarily considered to be at an optimal level; 'SOM concentrations at which favourable soil physical properties are maintained, nutrient supply capacity is optimised, and crop yields are stable and sustainable needed to be identified' (p. 679). Carter *et al*. (1997) noted that soil quality has two components, an intrinsic part covering a soil's inherent capacity for crop growth, and a dynamic part influenced by the soil manager. Marcellos *et al*. (1996) observed that there are carryover effects of N from one year to the next, so that 'fertilizer N, like soil fertility itself, should be treated like an asset' (p. 405). Pandey and Hardaker (1995) defined sustainability 'in a somewhat narrow sense as an improvement in the productive performance of a system without depleting the natural resource base upon which future performance depends' (p. 440). For questions of sustainability in agriculture, Cacho (1998) noted that measurements must include economic as well as biological measures, and that the dynamic nature of the production system must be accounted for. Hence soil fertility is a stock or asset and there are annual flows which can be manipulated in ways that are economically important.

Dynamic economic analysis based on the biological response of soil to alternative management strategies is becoming more commonly used to address such problems of the management of natural resources through time (eg Kennedy *et al*. 1973, Stauber *et al*. 1975, Godden and Helyar 1980, Taylor 1983, Kennedy 1981, 1986, 1988), but no contemporary use of such an approach for managing soil fertility has been reported (see for instance, Babcock 1992, Llewellyn and Featherstone 1997, Smith *et al*. 2003 and de Koeijer *et al*. 2003). In this paper an economic approach to soil fertility management under wheat production in north-eastern Australia is presented. A bio-economic approach is detailed based on simulated responses to N and C management for wheat production. The analysis focuses on farm-level issues of soil fertility management without considering environmental issues. The question is whether such an approach provides advantages for individual farmers or information useful in a wider policy sense.

Until recently recommendations by NSW Department of Primary Industries and other providers (eg Lawrence *et al*. 1996, Martin *et al.* 1996) concerning fertilizer use have been based largely on static N budgeting approaches which don't include prices and handle the carryover effects of fertilizer use inadequately. Using more sophisticated techniques of economic analysis our results suggest that farmers in general have a strong economic incentive to use significantly higher rates of N which will also maintain soil fertility stocks.

2. Soil fertility decline and renewal

Nutrients are essential for plant growth, and soil is the main source of nutrients for crop production. SOM contains macro-nutrients which can be converted into forms available for uptake by plants, and also provides other benefits (eg soil structure, reduced erosion potential, water infiltration and water-holding capacity). As well as being a natural source of these nutrient elements, SOM has a role in retaining cations and is also important in making available micro-nutrient elements (eg copper, zinc and magnesium). Soil organic carbon (SOC) is a good measure of SOM, and N is the most important nutrient for wheat production (Angus *et al*. 1994).

Dalal and Mayer (1986a, b, and c) measured long-term declining trends in the fertility of soils under continuous cultivation and cereal cropping in southern Queensland. They attributed the declines in soil fertility to cropping with traditional cultivation methods (little or no fertilizer applications, substantial tillage for weed control and, sometimes, stubble burning for disease control). The declines were measured in terms of SOM and its constituents, including SOC, total and mineralisable N, and other soil properties such as bulk density. Similar declines have been measured in northern New South Wales (NSW) (Daniells *et al*. 1996, Kirchof *et al*. 2001).

In considering such fertility declines, relevant questions for soil fertility are whether, and if so by how much, N and SOC in cropping soils would rise, and by how much profit would increase, under better crop management (use of stubble retention, minimum or zero tillage and use of fertilizer to replace nutrients lost through crop removal). In the case of N, added synthetic fertilizer (i.e. N as urea or ammonium gas) is equivalent to inorganic (or mineralisable) N in the soil; therefore soil N fertility can be readily built up through fertilizer applications. For SOC, the agronomic and soil science literature offers some evidence that this measure can be built up by active management. Wang *et al*. (2004) reported results from a 33-year trial in Queensland, and found a significant effect of no till, stubble retention and N fertilizer application on SOC. These effects were only observed on the top 10 cm of soil, and only when they were practiced together. This and other studies by the Cooperative Research Centre for Greenhouse Accounting (CRCGA) suggest the potential for increasing carbon levels in Australian soils is modest (CRCGA 2005).

Grace *et al*. (1995) considered that it is the amount of residue, whether it is from above or below ground sources, which governs C storage in fertile soils. Previous agronomic trials (eg as discussed by Grace *et al*. 1995) have recorded changes in SOC associated with improved crop management, but the N application rates were relatively low compared to what some contemporary farmers are applying (Schwenke and Young 2004). Farquharson *et al*. (2003), using relatively high rates of N applications in a simulation analysis, showed that theoretically it is possible to change the direction of SOC trends by adopting better management practices for wheat production, but did not investigate how to achieve the best outcome.

With respect to higher SOC, there may be benefits apart from improved soil fertility associated with this outcome. Bell *et al.* (1998) evaluated one measure of SOC and developed a relationship between frequency of runoff events and management practices for Ferrosol soils in Queensland. At increased levels of their carbon fraction measure, aggregate soil stability and resulting rainfall infiltration were improved. There are other soil benefits such as water holding capacity, or improved water infiltration and less erosion, than just soil fertility arising from improved SOC (Connolly *et al*. (1998)).

The analysis was conducted for a wheat-fallow crop sequence, which is a simple system to analyse. Both winter and summer crops can be grown in northern Australia. Other crop sequences (including different winter and summer crops, and different cropping frequencies) are sometimes used by farmers, although wheat is the dominant winter crop. The results are specific for a short fallow-wheat sequence on the main soil type in the Liverpool Plains region of northern NSW.

A two-stage approach to analysing soil fertility management for a particular agricultural purpose, and from a wheat grower's perspective, was adopted for this analysis. In the first stage the question of how much input to use in a production process is addressed; N is investigated as an input to short-fallow wheat production *ceteris paribus*. In the second stage other important crop practices (relating to tillage and stubble) are included to address the question of long-term soil management, in terms of SOC, for wheat production. Increases in measured SOC were assumed to be associated with improvements in soil water-holding capacity, providing a potential agronomic benefit. Using an optimal N input strategy from the first stage and simulated responses of wheat crops to different N inputs and tillage and stubble treatments, the second analysis determined the best crop management mix for wheat production and an associated optimal level of SOC.

The economic optimizing methodology used in the analysis (detailed below) determines optimal management to maximize wheat profits when considered over a long time horizon. It accounts for changes in the particular stock of soil fertility from year to year, as affected by management decisions and crop outcomes. In the process an optimal stock of the soil fertility resource (N in the first case and SOC in the second) is generated. The question arose, in using the sequential approach to fertility management, of whether determining the optimal SOC management in the second stage would affect the optimal N decision rule developed in the first stage. However, the SOC analysis, incorporating as it does improvements in soil water-holding capacity, did not, in the opinion of a soil scientist, affect the N decision rule previously developed (Dr G. Schwenke, personal communication).

Dryland crop production in this environment is subject to substantial climatic uncertainty, and irregular rainfall and temperature patterns can influence processes of soil fertility change. Wheat growers have developed soil moisture conservation methods and crop sowing rules to take advantage of soil moisture variability when making decisions about wheat production. At the time of sowing growers can estimate soil moisture and measure soil N using an inexpensive test. They do not know the climatic outcomes within the growing crop, or in the subsequent fallow. With respect to wheat price, the presence of grain marketing firms offering forward selling contracts means that uncertainty in wheat price can be eliminated for the crop year.

3. Analytical approach

The problem faced by a producer who wishes to manage his soil resource optimally is to determine control decisions over time to maximize the present value of net returns subject to the state of the soil. The control variable is defined as u_t, and the state variable as x_t. The state space X enumerates all possible states attainable by the system and the decision space U enumerates all the actions that can be taken by the producer. The Bellman equation for this problem is:

$$V_t(x) = \max_{u \in U(x)} = \left\{ f(x,u) + \delta \sum_{x' \in X} P(x' | x,u) V_{t+1}(x') \right\}, \quad x \in X, \quad t = 1,,2,...\infty \qquad (1)$$

where the net annual return is $f(x,u)$, $\delta = (1+r)^{-1}$ is the discount factor for the discount rate r, and $P(\bullet)$ are transition probabilities describing how the system evolves over time. This formulation applies when the state of the system is a controlled Markov process, where the probability distribution of the state in the next time period depends only on the current state and the producer's action:

$$P(x' | x,u) = \Pr(x_{t+1} = x' | x_t = x,\ u_t = u) \qquad (2)$$

This shorthand notation (Miranda and Fackler, 2002) indicates the probability that the state variable will take on a value x' in the next time period, given that its current value is x and that the control method u will be applied during the current time period. Solution of the Bellman equation (1) results in the optimal policy $u^*(x_t)$, prescribing the action that should be taken at any given state in order to maximise the present value of current plus expected future rewards.

In the case of wheat there are two economically important outputs: yield (y_1) and protein (y_2). These outputs are jointly determined by temperature and moisture interactions in the final stages of crop growth. They are not separable in terms of inputs (Anderson *et al*. 1977), nor are they priced and sold separately. Therefore the net return function is expressed as:

$$f(x,u) = p_W(y_2) \cdot y_1(x,u) - c(x,u), \qquad (3)$$

where p_W is the price of output, c is the cost of deriving the output, and y_1 and y_2 are determined by a multi-output production function derived from a simulation model as described later.

This general model was applied to wheat production in northern NSW. Two separate state variables were considered: soil N and SOC. The two variables were analysed separately because they have different attributes, accumulate in the soil at different rates, and are influenced by different control variables. In particular, N can be readily restored by applying fertiliser, whereas C can only be built up slowly by increasing the amount of organic matter in the soil through selected management actions.

3.1 Numerical Model

The use of stochastic dynamic programming (SDP) to assess soil fertility management involves a number of assumptions. These include that the process of change in resource stocks over time can be represented by a Markov process and that the stage return and transformation functions are stationary. Given these assumptions, the state transformation function for a given action *u* is represented by a state transition matrix, as represented in equation (2). This matrix can be derived from biological simulation models which generate results over extended time frames using weather data as inputs. Essentially, the state transformation function $x_{t+1} = g(x_t, u_t)$ is simulated for a large number of weather events, and the probabilities represented in equation (2) are derived from the simulation results.

The APSIM model (McCown *et al*. 1996, Probert *et al*. 1998) was used to generate transition probability matrices. APSIM is a cropping-systems simulation model developed for use in the cropping regions of north-eastern Australia. The major factors affecting production addressed by this model are climate variability, soil water characteristics, soil N fertility, phenology, planting time and planting density. APSIM is a relatively complex, daily-time-step model capable of simulating soil water and nitrogen dynamics in wheat production over relatively long time spans. The model uses historical climate data to simulate growth according to user-defined sowing and management rules. APSIM was configured to simulate continuous wheat with summer fallow. The soil type analysed was a black Vertosol (i.e. deep cracking clay, Isbell 1996) and the wheat variety, Hartog, was sown on a common sowing date with Gunnedah, NSW, climatic records. The model does not deal with phosphorus cycling, so phosphorus supply was assumed to be non-limiting.

The wheat varieties grown in the case study location (generally Australian Hard or Australian Premium White) are valued according to their protein characteristics. The wheat price is applied to the wheat yield, but it is based on quality attributes (predominantly protein content). Figure 1 contains three schedules of farm-gate wheat prices according to protein content. The 5-Aug 2002 schedule was used in the analysis, the others were tested in a sensitivity analysis. The cost of fertiliser (urea) was $1/kg N. The discount rate (*r*) was set at 7%.

3.2 Nitrogen

For the N analysis, APSIM simulations were controlled by resetting soil fertility and soil moisture at predetermined levels for each season, following a 5^3 factorial design. Yields and nitrogen use were simulated over a 90-year historical period for Gunnedah, NSW. The APSIM outputs of interest were crop yield (y_1), protein content of wheat (y_2) and soil N at harvest (x_H).

To represent carryover of soil N from one crop season to the next, the crop year was defined to consist of a crop period, of about six months, followed by a fallow of six months. The carryover effects depend on what happens during both these periods. Three factors were specified to capture the effects of climatic variability in the model: soil moisture at sowing (*SM*); in-crop rainfall (*ICR*); and fallow rainfall (*FR*). The levels of *SM* were set to represent very dry, dry, medium, wet and very wet soil conditions after fallow (63, 97, 124, 180 and 222mm). These five *SM* levels were set within APSIM for the same sowing date each year. Five percentiles of *ICR* and *FR* were estimated from the simulation results and used to describe the impacts of climatic variability for each *SM* category. The probability functions implicit in the percentile values result from different rainfall and temperature patterns from year to year. The five *ICR* and *FR* percentiles were selected so as to have an equal probability of occurrence (0.2).

A total of 125 different response surfaces for the three variables of interest were generated through simulation to represent variability in the cropping system. We assume that N applied (i.e. u) is the same as N in the soil (i.e. x). The total N available to the wheat plant is $x + u$, and this is the horizontal axis in Figure 2, which presents selected results. The yield response to added N and increased moisture is positive. The protein responses are characterised by increases as N fertility rises and moisture falls. These yield and protein responses are as expected, since the wheat plant changes the relative partitioning of carbohydrate and protein with temperature and moisture conditions in the final crop stages. The soil N left after harvest also varies directly with soil N and inversely with moisture.

Holford *et al*. (1992) found that wheat yield responses were well fitted by the Mitscherlich equation. A modified Mitscherlich form was found to be a suitable functional form for both yield and protein:

$$y = \alpha + (\beta - \alpha)\left[\frac{1 - k\exp\left(\frac{(x-1)(x+u-100)}{100}\right)}{1 - k\exp(x-1)}\right] \tag{4}$$

The parameters of the estimated yield and protein equations are shown in Table 1. The smoothed response equations were the basis of the datasets used to generate transition probability matrices.

In the N model, the state variable was the kg/ha of plant available N, with $x \in X = \{25, 35, \ldots, 250\}$, and the control was N fertiliser application (kg/ha) with $u \in U = \{0, 5, \ldots 180\}$. Apart from the wheat price schedule (Figure 1) and the price of N, other variable costs used in the analysis were \$170/ha. The model (1) to (4) was implemented in MATLAB and solved by backward induction until policy convergence was obtained. The solution represents the optimal fertiliser policy for an infinite planning horizon.

3.3 Carbon

In a cropping system, C is found both above ground, as plant residues, and below ground, as incorporated plant residues, plant roots and SOM. Flows of C from plant residue pools to SOM pools, and from one organic matter pool to another, involve loss of C from the soil system to the atmosphere (as CO_2 respired by micro-organisms). C may also be lost from the soil system by burning of plant residues and cultivation. To maintain organic matter concentrations in the soil, these C losses need to be balanced by plant C inputs in the form of photosynthesis.

The basis of this analysis is that soil C can be managed through strategies for fertilization, tillage and stubble management. Farquharson *et al*. (2003) used crop simulations to show that it is theoretically possible to reverse the decline in soil C using contemporary best management practices, but did not determine the ‘best’ combination of practices. The present analysis extends their work by using an economic optimising analysis.

In the soil C model six possible management options were considered. These involved combinations of soil fertilisation, stubble treatment, and tillage methods for moisture retention and weed control (Table 2). The options considered were zero tillage (ZT), conventional cultivation (CT) and burning stubble (BT). ZT (or no till) allows stubble to be retained and relies on chemical sprays for weed control and soil moisture accumulation during fallow. Specific crop planting machines (allowing sowing into heavy stubble) and spray rigs are required for ZT. CT requires several passes of different types of machinery. In a direct cost sense, ZT involves extra spray chemicals compared to the predominantly diesel and machinery cost under CT. The costs of BT are lower. Soil outcomes under CT are likely to be poorer soil structure (including the chance of severe soil erosion), less soil moisture and lower soil organic matter levels. Burning of stubble (BT) reduces replenishment of soil organic matter and uses cultivation for weed control. The same adverse soil outcomes for CT are likely for BT.

The management of SOC was investigated for the site of a long-term agronomic trial on the Liverpool Plains Field Station near Breeza in northwest NSW, for which climatic, soil and agronomic data were available. Breeza is 40 km south of Gunnedah. The soil was a Vertosol (black earth), initially under grassland, now extensively used for continuous summer and winter cropping. More detailed descriptions of the Liverpool Plains soil and climatic conditions are given by Webb *et al.* (1997).

The costs associated with the management options (derived from Scott 2002) are also presented in Table 2. Variable costs are used in the analysis because the focus is at the enterprise rather than the farm level. Machinery costs were derived based on all tillage and spray options being available to the grower. Some graingrowers have equipment enabling cultivation, stubble sowing and spraying operations, as conditions require. Soil moisture is the major factor, apart from soil fertility, in wheat crop establishment. Crop management to utilise soil moisture is well understood by growers, who can use push probes to estimate soil moisture as a basis for crop planting. The crop planting rules used in the simulations for this soil C analysis are based on a minimum level of soil moisture during the crop planting window.

The APSIM model was again used to simulate responses to management and climate using 100 years of historical climate data. The simulation results provided were used to estimate the transition probabilities associated with equation (2) for each management strategy. The simulation approach was to run APSIM for 10 years, then reset the parameters to keep them within reasonable bounds. For longer-term SOC observations, each year incorporates the breakdown of previous year's residues. In the longer term the changing SOC contents are measured by the change in the combined microbial biomass and humus amount over a ten-year period. The transition probabilities were calculated for a stage of one year.

APSIM results for the management strategies set out in Table 2 are shown in Figure 3. Trends in SOC over 10-year periods for each management strategy from the simulations are presented. These are averages of ten 10-year cycles from initially 'low', 'medium' and 'high' levels of SOC. At each fertility level the plus N strategies lead to increases in SOC, whereas the zero N strategies exhibit flat trends.

In conducting the SOC analysis, we found that the N-fertiliser optimal rules (according to *SM*) needed to be modified. The N rules were developed based on sowing at a specific date, but the more usual practice is that farmers use a time window (from 1 June to 15 August at Breeza) to make the wheat sowing decision. Within this period APSIM checks daily for soil moisture conditions as a basis for crop sowing. When running APSIM with separate N strategies for the SOC analysis it became apparent that in some years both the dry and medium *SM* conditions could be met within the same sowing window. As a result it was decided that for the SOC analysis only one plus-N strategy would be tested. This strategy was for medium *SM* conditions, i.e. to add fertiliser N so that plant-available N was 205 kg/ha at sowing. The alternative fertilizer strategy was to apply zero N.

Connolly *et al*. (2001) used APSIM to simulate the effects of increased cropping activity (including wheel track compaction, smearing and tillage disturbance) on the water-holding capacity and hydraulic conductivity of soil. They predicted that soil water-holding capacity would degrade as a result of continued traditional cropping practices. In a similar way, the use of improved crop management practices was considered likely to have beneficial impacts on soil water-holding capacity or plant available water content (PAWC).

There were no published experimental or simulation analyses of how changes in tillage and stubble management are likely to affect PAWC. After discussions with a soil scientist, a set of parameter values representing soil PAWCs at different levels of SOC was derived for testing in this analysis. As SOC increases the PAWC of the Vertosol soil is assumed to improve, with associated potential agronomic benefits. The parameter values in Table 3 were suggested by Dr M. Probert (CSIRO, personal communication). Changes in soil PAWC were considered to apply to the top three soil layers (down to 30 cm). Interpolation was used to derive values for soil water-holding capacity for SOC levels between the highest and lowest in the table.

The crop simulations required selecting a range of SOC contents in soil. Soil measurements taken at the Breeza site showed that organic carbon measures in the top 10 cm of soil were 1.72% in native grassland, 1.52% in soil with no-till and stubble retained for 15 years, 1.33% in stubble cultivated soil, and 1.26% in stubble burned and cultivated soil (Dr G. Schwenke, personal communication). These percentages can be converted to tonnes of C per ha using the bulk density of the soil (Table 3).

In the C model, the state was represented as tonnes/ha of SOC, with $x \in X = \{14, 15, \ldots, 24\}$, and the control was a given combination of fertiliser application and stubble management (Table 2), with $u \in U = \{\mathrm{ZT0, ZTN, CT0, CTN, BT0, BTN}\}$. Changes in SOC measured in the top 10 cm of soil were used in developing the transition probabilities. The model was implemented in MATLAB and solve by backward induction until policy convergence was achieved. The solution indicated the optimal policy, in terms of tillage, stubble management and fertilisation, for an infinite planning horizon.

Examples of state transition matrices ($P(x'|x,u)$ in (2)) derived from 100 years of simulation results for BT0 and BTN are shown in Tables 4 and 5. The probability of moving between SOC states from any year *t* to *t+1* is read across the row. The BT0 probabilities generally cluster around the diagonal, whereas the pattern of BTN probabilities promotes build-up of SOC over time.

4. Results

4.1 Optimal level of N input to wheat

The optimal N management according to level of *SM*, and the associated Net Present Values (NPV), from the SDP analysis are shown in Table 6. In each case the results consist of: (i) an optimal N application; (ii) an optimal soil N stock x_{LT}; (iii) an optimal total soil N level required for the crop at sowing (the sum of (i) and (ii)); and (iv) the NPV of the optimal decision strategy if followed for 10 years from an initial soil N level of 100 units. The optimal x_{LT} is prior to sowing, with the optimal application being added as the crop is sown.

The optimal total N applied to the crop at sowing (eg 205 units for medium *SM*) should be made up of 124 units in the soil and 81 units applied by the grower. The results for increasing *SM* levels are in line with accepted practice, that is, apply more N as soil moisture levels improve. They also exhibit increasing levels of both N stocks and application, and NPV, as soil moisture conditions at sowing improve.

The derivation of these results is shown in Figure 4. For each *SM* level, the solid line in Figure 4(a) shows the optimal state transition from any year to the next. The point at which this line intersects the dotted 45^0 line (the set of steady states where $x_{t+1} = x_t$) is the optimal long-term stock level (x_{LT}). In Figure 4(b) the corresponding optimal decision rules are shown. At any measured soil N_t (stock) level the optimal rule (optimal N application or u_t^*) can be read from the graph. The total of the existing soil N level and the corresponding application is the total amount of input applied to the crop.

In comparison with these dynamic results a static analysis of an individual wheat crop (i.e. with no N carryover) using the same response surfaces and prices resulted in an optimal N input (for medium SM and average ICR) of 115 kg N/ha and an NPV over 10 years of $256/ha. This is substantially less than the NPV for medium SM from the dynamic results ($2813/ha), indicating that farmers are potentially much better off. However, in making this comparison we must remember that there is less N in the static soil-crop system, since there are no gains and losses associated with the fallow period.

Sensitivity analyses were conducted to check whether a variation in specific items would affect the results in Table 6. Sensitivity analyses of financial variables indicated that a higher discount rate only affected NPV. The effects of increasing the N price by 20% were small, with the optimal N stock and decision being slightly reduced for the medium and wet *SM* cases. The effects of changed wheat prices were more interesting, although still not large. With no premium for protein content, the optimal N stock was reduced by between 2 and 10 kg/ha. For the higher wheat price schedule, there was an increase in the optimal N stock and decision only in the case of very dry *SM*. In general, the results did not appear to be very sensitive to changes in input or output prices.

The results of changes in biological parameters were more substantial. The amount of carryover of soil available N from one crop to the next via fallow was reduced, by parameterising the losses of x_H from 10% (base case) up to 100%. In general, as the amount of soil N carried over the fallow was reduced the optimal total N at sowing and the optimal stock of soil available N were reduced substantially, with the optimal amount applied rose. These results are reasonable – the plant still requires N according to the response functions, and if there is less in the soil then more must be added externally.

4.2 Carbon results

The first set of results is derived from solving the SDP model using the transition probabilities as shown in Table 4 and 5. The solution allows derivation of the optimal set of decisions for any initial value of SOC, and shows the optimal state path and NPV. The optimal decisions and NPVs are shown in Table 7, and some optimal state paths are in Figure 5.

From the results in Table 7, the optimal decision converges by year 3 to a stable strategy for each initial soil fertility level. All optimal management involves applying N, and the optimal final management always involves ZT. Finally, as expected, the NPV figures generally trend upwards with initial SOC levels, but the differences are not large. The optimal fertiliser strategy in each case would be to adjust N inputs according to initial soil fertility, so fertiliser applications would vary. Also, following the optimal strategy over a 10-year period means that there is little difference economically between soils of initial SOC differences.

Examination of Figure 5 shows that the optimal level of SOC is a minimum of 20-21 t/ha, equivalent to 2.0% SOC with a bulk density of 1.01 in the top 10 cm of soil. At higher initial levels of SOC it is optimal to maintain the SOC at its original level rather than let it run down. This result may be due to interactions between management costs and the state transition equations.

The interpretation of these results is that, at high initial levels of SOC, and given the optimal management decision (maintain stubble, use no tillage, and add N fertiliser), there is an associated minimum SOC outcome of 2.0%. This SOC percentage is higher than the measurement in native grassland at the Breeza site. However, it is feasible that a higher optimum be derived since the growing of wheat provides a greater economic return than the pasture alternative.

The state transition matrices express the probabilities that SOC states will change from one decision period to the next, based on particular management strategies. However, the results in Table 6 are deterministic, they do not incorporate the stochastic nature of these transitions. Simulations of results which incorporate stochastic transitions were conducted as follows. A Monte Carlo simulation of the optimisation process was implemented by expressing each row in the transition probability matrices as a cumulative distribution function. A sampling process was implemented, which consisted of generating a series of random numbers (between 0.0 and 1.0) which were used as probabilities on the vertical axis of the function, and then reading associated SOC outcomes on the horizontal axis. The optimal decision rule was applied to each resulting state.

Using the range of initial SOC values and the optimal decisions (which generated the optimal adjustment paths shown in Figure 5), the stochastic state transition was simulated over 6 years - twice the time period to achieve convergence in the deterministic simulation. For each initial SOC level, 1000 random draws were generated using the same series. The results consisted of a pattern of state paths and a histogram of final SOC outcomes. The results for an initially low and an initially high SOC level are shown in Figure 6.

The results indicate that, rather than the precise optimum state paths from the deterministic simulation seen in Figure 5, there is a distribution of outcomes after 6 years. With an initially low SOC content the mean of the distribution of the final level of SOC (Figure 6(b)) is 23.2 t/ha, or 2.3%. However, despite the best efforts to follow optimal management there is a positive probability that SOC will be as low as 16 t/ha (1.6%). For initially high levels of SOC the mean level of SOC after 6 years is 21.7 t/ha (2.1%), with some outcomes of 20 t/ha (2.0%).

An important result from the Monte Carlo analysis of the state transition processes is that the distribution of SOC outcomes was wider for lower rather than higher initial SOC states. Maintenance of high SOC appears to promote lower variability in this attribute.

5. Discussion

Two questions can be asked about the results of this analysis – are wheat growers likely to be better off by following the recommendations, and are there wider policy implications? In general the issue is whether the extra effort in conducting a dynamic economic analysis is worthwhile, compared to the alternative static approach.

5.1 Implications for wheat growers

The results in Table 6 indicate relatively high rates of N usage, compared to previous levels of usage. Martin *et al*. (1988) reported that in the early 1980s the average amount of N applied annually, by those farmers who did use it before sowing, was 30 kg/ha, with a further 9 kg/ha at sowing. But not all farmers used fertilizer; the average over all farms was only 5.3 kg N/ha, although N usage did increase from 1983 to 1985. McLeish and Flavel (1996) reported, from another survey of the Liverpool Plains in 1995, that for those using fertilizer on long-fallow wheat grown on black soil the average application rate was 62 kg N/ha. Hayman and Alston (1999) reported that the average N fertilization use on the Liverpool Plains was 36, 64 and 72 kg N/ha in 1992, 1996 and 1997 respectively. In developing advisory recommendations for northern NSW an example calculation from Hayman (2001) shows that for an initial 30 kg soil N/ha recommended fertilizer applications were 24, 67 and 105 kg N/ha in poor, average and good seasons respectively. In contrast the results in Table 6 recommend that total N at sowing should be 185, 205 and 245 kg N/ha for dry, medium and wet SM respectively.

There is evidence that farmers are now applying higher rates of N fertilizer. Results from a survey of agricultural consultants in the Gunnedah district (Schwenke and Young 2004) indicate that wheat growers are now applying 100 to 150 units of N to wheat and sorghum crops. Further, growers that are intensively managing their crops consider the optimal total available N rate (applied fertilizer plus soil N test) to be 200 kg/ha when sowing a particular crop at the best time on a full profile of moisture. This is closer to the results from this analysis.

How much financial improvement might be experienced by individual wheat growers depends on what they are currently applying. The results in Table 6 are from an optimizing analysis, which is not designed to value non-optimal behaviour. The comparison between static and dynamic results in section 4.1 indicated that there may be substantial improvements in financial returns from the dynamic approach, although there is a different amount on N in the two soil-crop systems.

The farm-level results for the SOC analysis (Table 7) advocate the use of ZT with N, and the financial results show a substantially higher level of NPV compared to the N results. This analysis was based on hypothesised improvements in PAWC associated with higher levels of SOC. There are no soil experimental results to provide a basis for this scenario. Hence these financial results are not emphasised, except to indicate the potential benefit from a soil-agronomy research trial on this topic.

The use of conservation farming methods (stubble retention and substituting of herbicides for cultivation) has been promoted by Research and Development agencies in northern Australia mainly to combat the threat of erosion. Uptake of this technology has varied: Scott and Farquharson (2004) reported that in 2002 the percentage of northern NSW cropping area sown using ZT was 24%, with a further 47% sown using reduced tillage. These percentages have grown from zero in 1985. They indicate that there is substantial potential for further uptake of conservation farming methods in the region.

5.2 Potential policy implications

Apart from the implications for individual wheat growers, a policy issue that might arise from increased fertilizer use involves potential leaching of N into groundwater. This is an important issue in Europe and North America because of high fertilization rates, the use of manures and the relative permeability of the soils. Analyses of these issues have been conducted by Zhu *et al*. (1993), Yadav (1997) and Blombach *et al*. (2003). This issue does not appear to be as important in Australia, but further work could be done on this issue.

A second policy issue arising from this analysis is the identification of optimal stocks of some components of soil fertility. For those interested in sustainability issues, such results might be of interest as a policy target. In this respect the analysis is an illustration of the potential for using the methodology to derive similar results for other characteristics of interest.

An important policy issue from this analysis is that levels of SOC might be raised by on-farm management, with potential implications for carbon accounting and trading in greenhouse gas abatement. Three points can be made here. First, the analysis is based on a hypothetical improvement in PAWC, and more attention to measurable improvements associated with increased SOC would be valuable. Second, the permanence of such changes has been noted as an important issue (Cacho *et al*. 2003), and it appears possible that SOC could be depleted more easily than built up. This leads to the third point, which relates to measurement of SOC levels in soils.

A practical issue for the question of SOC management relates to the accuracy with which SOC can be measured in fields by commercial soil tests. Schwenke *et al*. (1997) estimated sampling coefficients of variation for SOC over a number of cropping sites in northern NSW. In their study they took soil measures on 10 farms near Breeza, finding an average SOC content of 1.68% in the top 10 cm, with an average standard error of 0.05%. The results in Farquharson *et al*. (2003) showed that the greatest change in surface SOC in their results equated to 0.03% per year, hence it may be impossible to distinguish short-term responses of SOC to management from sampling error. This might cause difficulties in validating changes in SOC for carbon accounting and trading purposes.

In terms of greenhouse gas abatement, the use of crop management practices which include the use of N fertilizer has an additional problem. Although adding N fertilizers boosts plant growth, some of the N is released to the atmosphere as nitrous oxide, a gas with 310 times the global warming power of carbon dioxide (CRCGA 2004).

6. Conclusions

Managing soil fertility is a complex dynamic problem for farmers with long term consequences for the flow of income from cropping and for land values. Important dimensions of soil fertility include stocks of N and SOC. There is evidence that soil fertility in Australia’s northern cropping region declined in the past. Soil erosion has also been a major problem in the development of a cereals industry in the region. Significant numbers of farmers are applying N fertiliser and using conservation farming technologies to manipulate these two important dimensions of soil fertility.

Yet there are many farmers who are not using these technologies, either because they do not find them profitable or because they find it difficult to appreciate the impact on stock levels and profitability over time of alternative farming practices.

The optimal levels of N and SOC in the soil for particular farms depend on a range of biological and economic factors and on the cropping system analysed, as well as on the farmers' attitudes to risk. Our objective has been to analyse optimal levels of N and SOC for two sites in northern NSW for a range of starting levels of these stocks and for a range of SM levels at planting. From this analysis optimal rates of N application and usage of conservation farming techniques can be derived and compared to common practice in the region. Clearly this analysis can not be prescriptive of farming practice for individual farmers, but it will provide an indication of whether it is likely that maintaining soil N and SOC levels is in the long term interests of a significant group of farmers in the region. We have not assessed environmental off-site consequences for the community of changes in soil N and SOC.

We found that it is profitable for wheat growers to maintain soil N levels at around 124 kg/ha under conditions of medium SM at sowing. This amount varied, according to SM, between 81 and 142 kg N/ha. For soils already at this level of soil N, this will require maintenance applications of N to the wheat crop at sowing at the rate of 81 kg/ha. Rates of N application will be higher (lower) for soils where measured levels of soil N are lower (higher) than this optimal level. There is survey evidence that N applications have increased over time, and that the some farmers are now applying fertilizer in this order of magnitude.

Higher rates of N application imply growing larger crops with increased bio-mass returned to the soil if conservation tillage methods are used for stubble management. Based on an improvement in soil water holding capacity, the use of ZT and fertilizer management in this analysis has demonstrated a build-up of SOC over time. There is evidence that use of conservation tillage methods of crop establishment have grown substantially since 1985, but there are substantial areas still cultivated.

In a policy sense the potential leaching of N into groundwater does not appear to be as important in Australia as elsewhere. The crop establishment methods used by some farmers (opportunity cropping rather than long fallows) can reduce the amount of deep drainage by using the soil water when it becomes available.

The sustainability of renewable natural resources in agricultural uses can be investigated using dynamic bio-economic methodologies. This analysis provides an example.

Finally, the build-up of SOC in agricultural soils has potential implications for a global carbon management system. This analysis has shown that there may be private benefits in managing SOC. However, issues of SOC measurement and the permanence of changes are important in a practical sense for such considerations.

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Table 1. Parameter values of the Mitscherlich equation (4) for selected yield and protein responses

Soil moisture at sowing	In-crop conditions	α	β	k	Number of data points
Yield response parameters					
Very dry	Very poor	n.a.	1.01	n.a.	10[a]
	Average	2.20	2.29	0.58	9[b]
	Very good	3.51	3.78	0.64	10
Dry	Average	2.78	2.82	0.47	10
	Very poor	2.00	2.15	0.25	10[c]
Medium	Average	3.15	3.28	0.60	10
	Very good	3.94	4.68	0.77	10
Wet	Average	3.70	4.15	0.73	10
	Very poor	3.38	3.67	0.67	10
Very wet	Average	3.76	4.39	0.76	10
	Very good	4.24	5.65	0.84	10
Protein response parameters					
Very dry	Very poor	15.19	15.32	0.42	10
	Average	11.35	12.73	0.79	10
	Very good	9.88	11.13	0.84	10
Dry	Average	10.77	11.76	0.76	10
	Very poor	12.84	16.54	0.63	10
Medium	Average	10.27	11.59	0.82	10
	Very good	9.31	10.98	0.92	10
Wet	Average	9.61	10.98	0.87	10
	Very poor	10.52	11.92	0.82	10
Very wet	Average	9.61	10.98	0.87	10
	Very good	9.08	10.57	0.94	10

n.a.: Not Applicable

[a] Flat response, intercept only

[b] One data point omitted

[c] Functional form:

$$Y = \alpha + (\beta - \alpha)[(1 - k\exp((N-1)(TotalN - 60)/140))/(1 - k\exp(N-1))]$$

Table 2. Crop management options and variable costs for C analysis

			Variable costs ($/ha)		
Option	Description	Code	Fallow	Wheat[a]	Total
u_1	zero tillage, zero N	ZT0	43	177	220
u_2	zero tillage, plus N	ZTN	43	177	220
u_3	conventional till, zero N	CT0	25[b]	145	170
u_4	conventional till, plus N	CTN	25[b]	145	170
u_5	burn and till, zero N	BT0	14[b]	145	159
u_6	burn and till, plus N	BTN	14[b]	145	159

[a] Urea N cost of $1/kg not included

[b] Fallow costs for CT and BT involve3 and 2 workings with chisel plough

Table 3. Parameter values for soil water holding capacity, Vertosol (black earth) at Breeza NSW, C analysis

		Highest SOC			Lowest SOC		
Soil layer		1	2	3	1	2	3
Soil depth	cm	0-10	10-20	20-30	0-10	10-20	20-30
Bulk density	gm/cm^3	1.01	1.17	1.23	1.01	1.17	1.23
PAWC	mm/layer	26	26	26	20	20	20

Source: Dr M. Probert CSIRO (personal communication)

Table 4. State transition matrix for SOC: BT0 strategy

SOC_t	SOC_{t+1} category (t/ha)									
(t/ha)	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
14-15	0.88	0.12								
15-16	0.11	0.71	0.18							
16-17		0.31	0.47	0.22						
17-18			0.29	0.56	0.15					
18-19				0.23	0.64	0.14				
19-20					0.16	0.67	.017			
20-21					0.01	0.24	0.58	0.17		
21-22							0.27	0.62	0.11	
22-23							0.06	0.48	0.39	0.07
23-24								1.00		

Table 5. State transition matrix for SOC: BTN strategy

SOC_t	SOC_{t+1} category (t/ha)									
(t/ha)	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
14-15	0.20	0.50	0.30							
15-16	0.17	0.03	0.53	0.27						
16-17	0.05	0.13	0.23	0.50	0.09					
17-18		0.10	0.10	0.28	0.42	0.09				
18-19			0.15	0.09	0.33	0.37	0.06			
19-20				0.11	0.09	0.40	0.32	0.08		
20-21					0.06	0.12	0.45	0.30	0.07	
21-22						0.09	0.10	0.44	0.39	
22-23							0.11	0.09	0.46	0.35
23-24								0.14	0.08	0.78

Table 6. Stochastic dynamic results: expected results for all *ICR* and *FR* conditions, N analysis

Soil moisture at sowing *SM*	Optimal N application kg/ha	Optimal N stock x_{LT} [a] kg/ha	N required at sowing[b] kg/ha	Net present value[c] ($/ha)
Very dry	54	81	135	2657
Dry	71	114	185	2738
Medium	81	124	205	2813
Wet	105	140	245	2960
Very Wet	103	142	245	3005

[a] Optimal soil N stock at sowing

[b] Optimal total crop requirements - sum of applied fertiliser and optimal soil N stock

[c] Calculated over 10 years at 7%

Table 7. Optimal decisions[a] and NPVs[b] for initial levels of SOC, deterministic C analysis

Year	Initial SOC levels (t/ha)									
	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
1	CTN	CTN	CTN	CTN	CTN	ZTN	ZTN	ZTN	ZTN	ZTN
2	CTN	CTN	CTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN
3	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN
4	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN
5	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN
6	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN	ZTN
NPV	5549	5499	5493	5591	5528	5590	5650	5721	5856	5866

[a] Management strategies from Table 2

[b] $/ha at 7% discount rate over 10 years

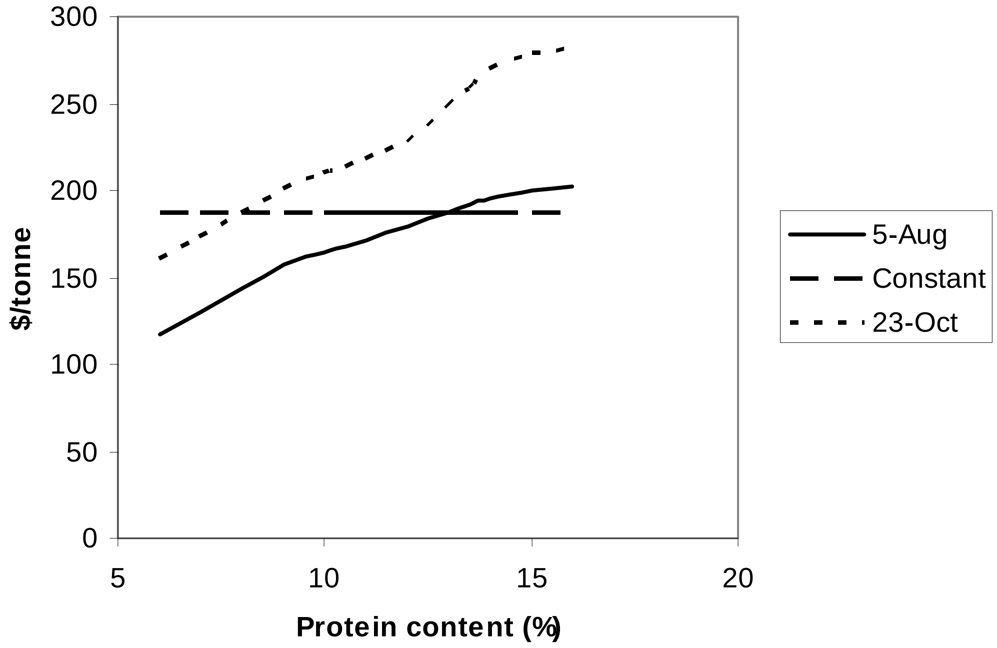


Figure 1. Wheat price schedule according to protein level

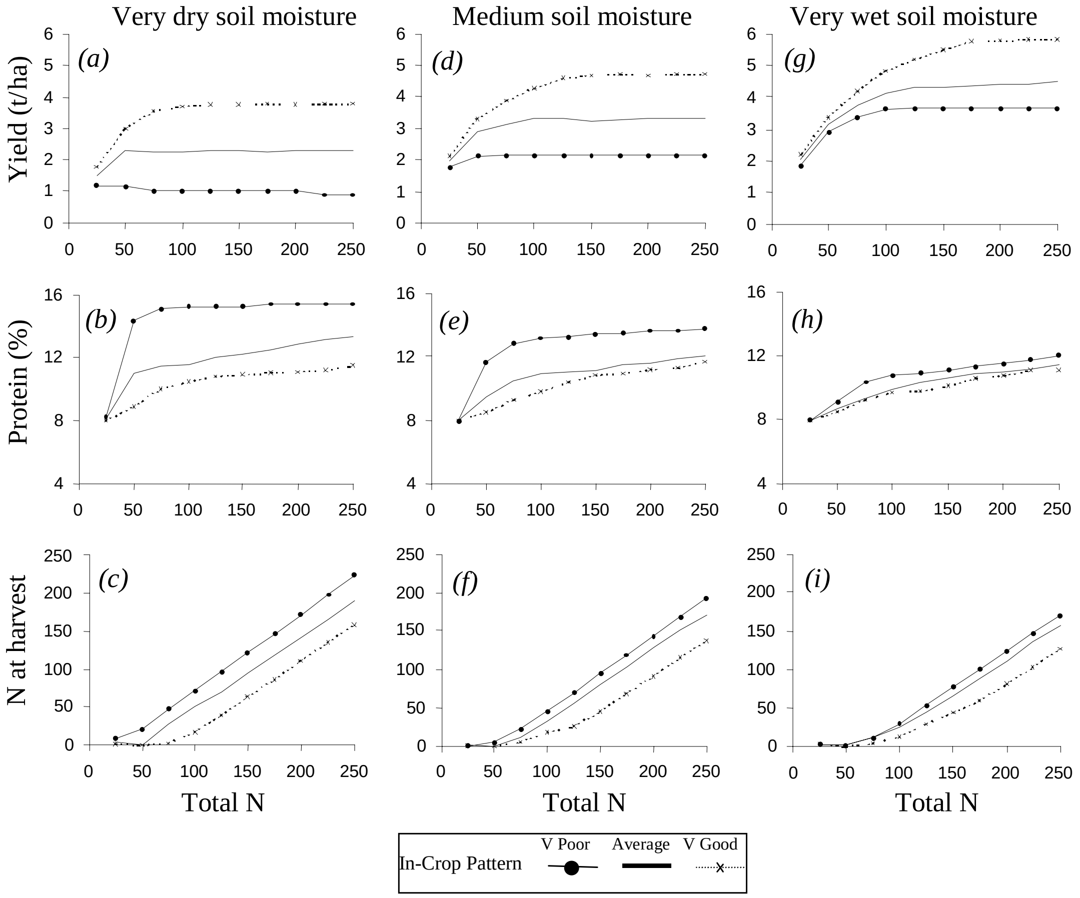


Figure 2. Selected responses generated by APSIM for yield, protein and soil available N after harvest

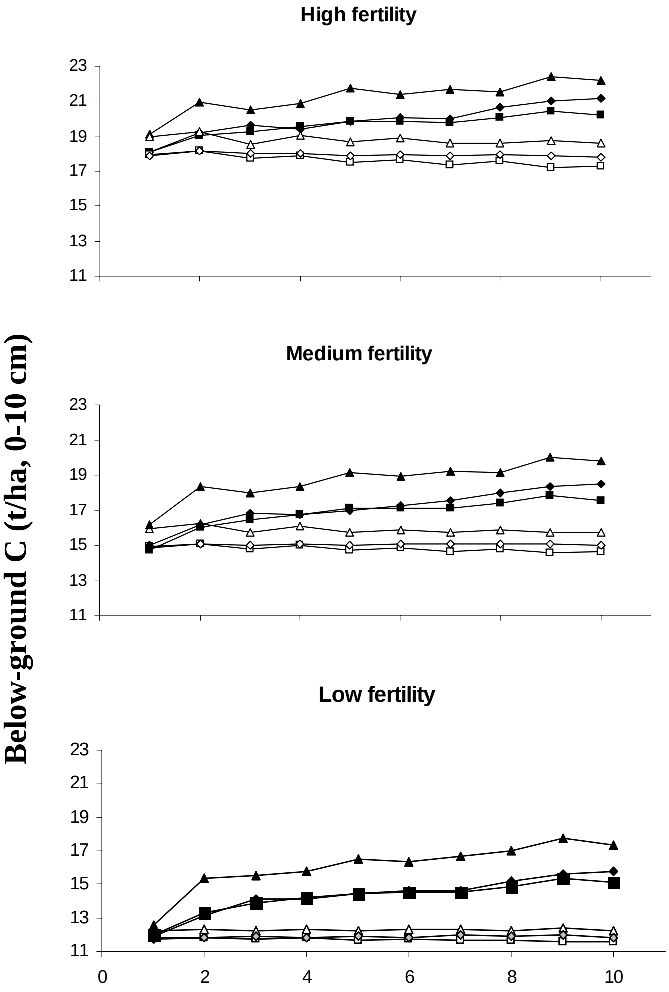


Figure 3. Simulated levels of below-ground carbon (0-10 cm) in wheat crops at Breeza, averaged over 10 years, for initial soil fertility levels under different crop strategies (triangles, wheat cultivated; diamonds, wheat no-till; squares, wheat burn-till; solid shapes, plus N; blank shapes, zero N)

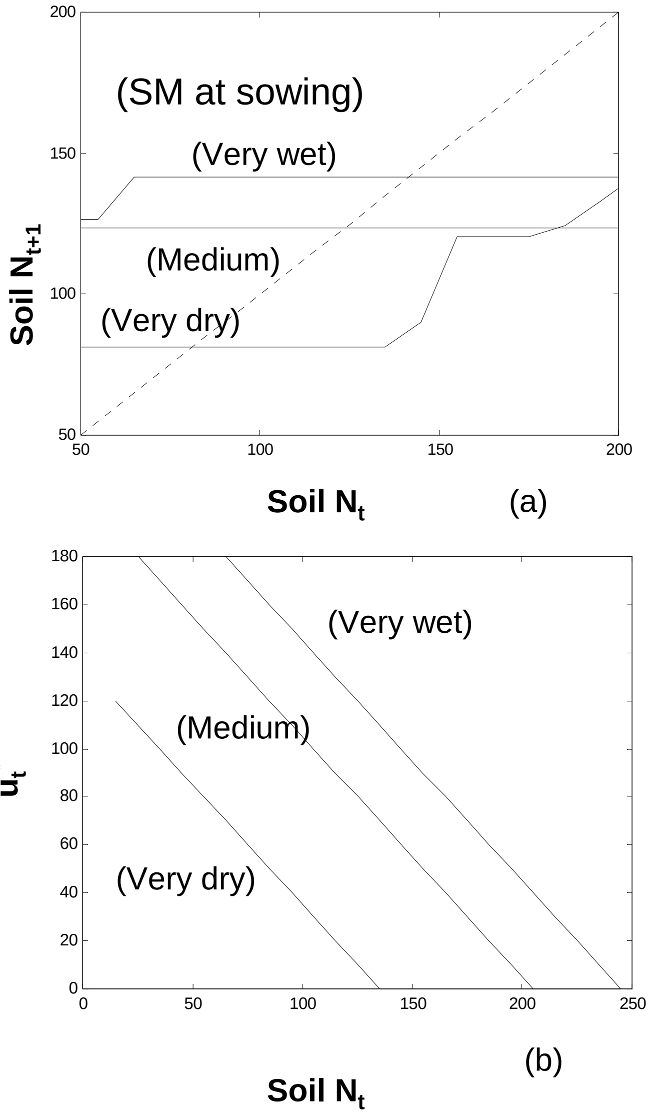


Figure 4. Optimal soil nitrogen state transition and optimal decision rule at three initial levels of SM at sowing

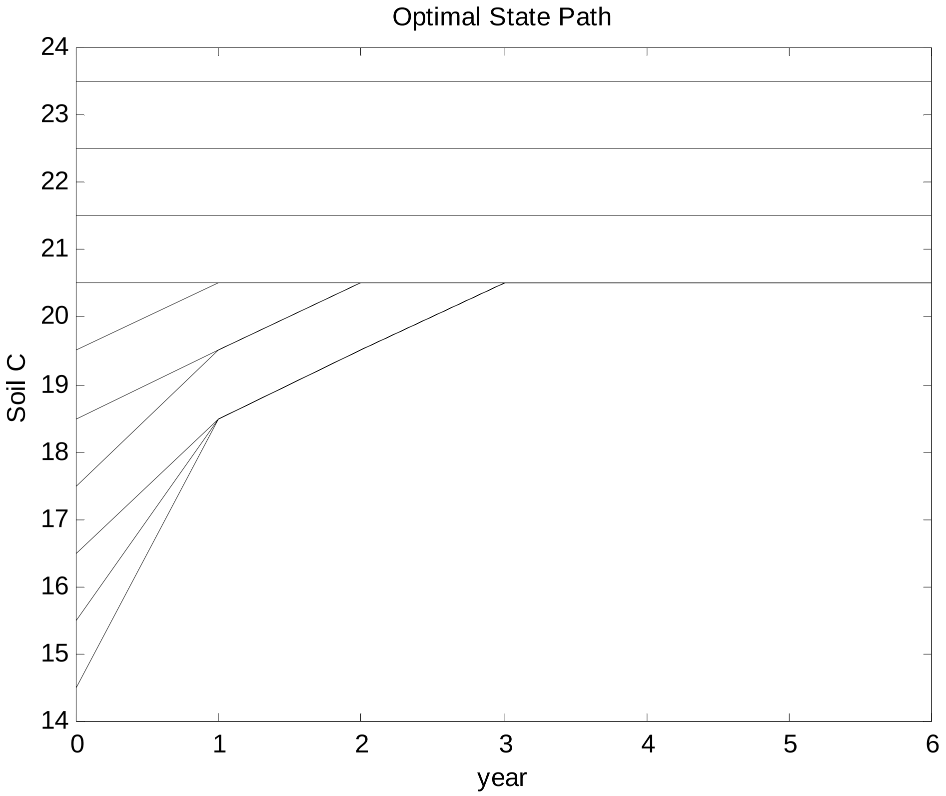
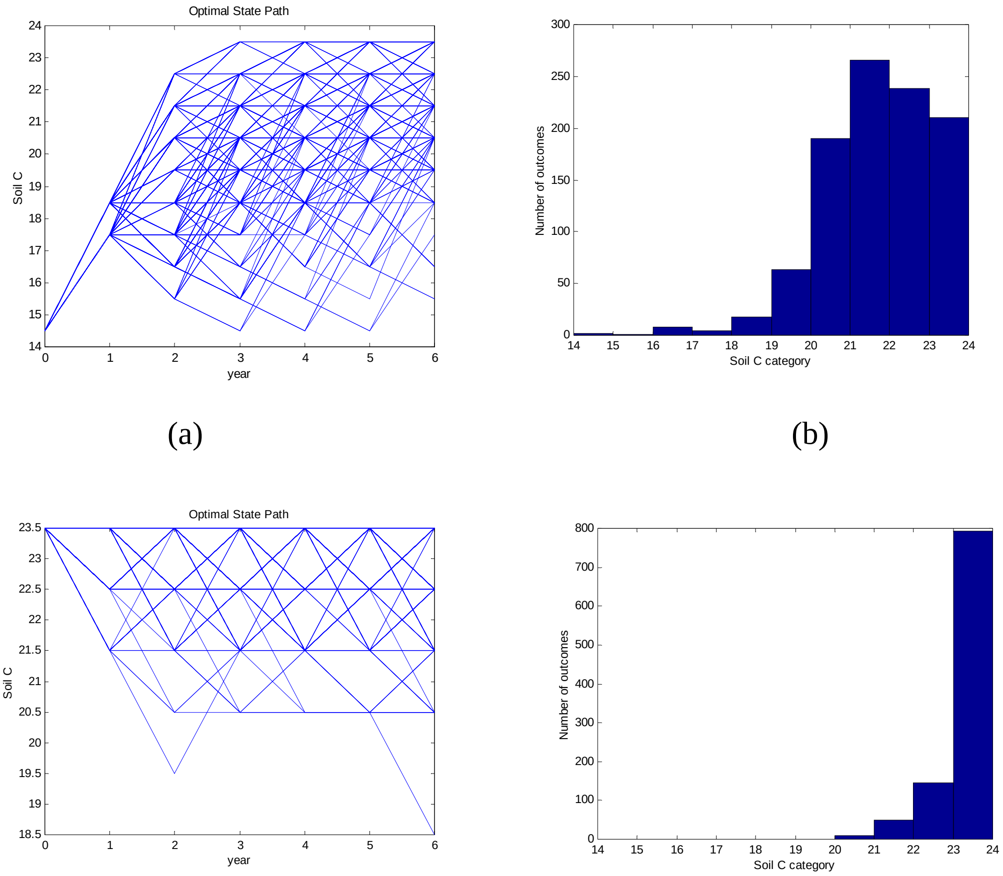


Figure 5. Optimal paths for SOC from initial values



(a) (b)

(c) (d)

Figure 6. Stochastic results for low and high initial SOC levels, temporal pattern of change and histogram of final values after 6 years