1. Introduction

Over the past 50 years there have been consistent economic pressures on farmers in Australia. A decline in the terms of trade arising from Australia's international trading environment and domestic policy settings has been an important historical underlying influence, although this downward trend has recently levelled off. Australia is a small open economy with low levels of agricultural industry protection, surplus domestic production traded on export markets, and a general inability to influence world prices. The resulting pressures on farm-level profits have been offset, at least partly, by productivity improvements arising from research and development (R&D) and through macro- and micro-economic policy changes.

More recently there have been other pressures which have arisen from changed environmental and natural resource conditions, and the associated increase in public or community awareness of these issues. There has been increased evidence of longer term changes in the condition of natural resources used in association with agricultural industries. These resources include soil, water, vegetation and other natural inputs to production. The impact of these changes has been felt both on and off the farm, and some commentators have worried about the 'sustainability' of current agricultural activities.

The wheat industry in northern New South Wales (NSW) and southern Queensland is important and prosperous, but it is a relatively young industry compared to others (eg wool). The industry in this region only began to develop in the 1960s and 70s. This was a new environment for wheat production for reasons relating to both soil and climate. The soils were fertile self-mulching clays which required more powerful machinery for tillage and sowing operations. Climatically, the rainfall patterns were distributed throughout the year (having slight summer dominance) and with, on average, evaporation being greater than precipitation in every month. Rainfall events were less frequent and often larger than in Mediterranean climates, so that new means of soil moisture management needed to be explored for successful crop establishment.

Methods of measuring soil moisture content were developed, and soil moisture sowing rules were tested for the variable rainfall patterns.

As with any new system, there were unforseen problems as wheat production grew. At first crop production methods from other areas were adopted; these involved substantial tillage of the soil for weed control. The result of sudden and severe storms on tilled soil surfaces was soil erosion, and these soil losses were severe. This problem was addressed through the development of stubble retention methods, adoption of reduced tillage practices, and the use of herbicides to control weeds in crops and fallows, all of which protected the soil surface from wind and water forces. Pest and disease problems also emerged, against which the breeding of new varieties and adoption of crop rotations have been successful. Soil compaction problems are being addressed by the use of common wheel-tracks, or tramlining.

Another major problem has been a declining trend in soil fertility under wheat production. Given that the soils were initially fertile, it is ironic that a soil fertility problem would emerge. Some R&D programs have been conducted for this issue, but the analyses and recommendations have not generally been based on economic principles. Improved management of soil fertility under wheat production is still considered by growers in the region to be an important research subject, and is the subject of this study.

1.1 Problem statement

Nutrients are essential for plant growth, and soil is the main source of nutrients for crop production. Organic matter contains macro- (nitrogen (N), phosphorus (P) and sulphur) and micro-nutrients which can be converted into forms available for uptake by plants, and also provides other benefits (eg structure and water holding capacity) to soil. Soil organic carbon (SOC) is a good measure of the organic matter content of soil (SOM) and N is the most important nutrient for wheat production (Angus *et al.* 1994). Therefore soil fertility (including SOC and N) is indispensable for wheat production in Australia.

Soil fertility levels have declined dramatically in northern NSW and southern Queensland over the last 30 to 40 years (Dalal and Mayer 1986a, b, c, Whitbread *et al.* 1998, Chan *et al.* 2003). This has been due to the particular crop management practices used to grow wheat as the industry developed. The question arises as to whether the current levels are too low, and if they should be raised, then by how much? 'Sustainability' concerns have been expressed about what can be done for this problem and how to develop a better strategy for soil fertility management.

There are new stubble and tillage management practices which can be used to improve soil condition for crop production. N and SOC levels can be built up within the soil by retention of stubble, use of less tillage and N applied from both external sources and legume crops or pastures (Farquharson *et al.* 2003). The issue of 'how much soil fertility is best' has been, and remains, an important question. This is an economic question since there are benefits and costs associated with different management practices and crop input decisions.

The way in which soil nutrient processes change over time (the N and carbon (C) cycles) means that there are responses in soil fertility stock levels arising from management decisions and subsequent crop outcomes. These stock effects are what have been observed in the soil fertility trends presented below, and such effects are expected to be important in considering desirable future soil fertility levels.

The general economic and sustainability question from these soil fertility trends is whether new fertiliser, stubble and tillage management practices are profitable to farmers (and the community) in the long term? If so, are there optimal soil fertility levels for wheat production on particular soil types in northern NSW, and are there associated optimal depletion and renewal patterns? Of methodological interest is whether the inclusion of soil fertility stock effects improves the economic analysis and provides more and better information to decision makers.

1.2 Aim

Soil fertility is a renewable natural resource use in agricultural production, and the aim of this study is to use economic analysis to develop soil and crop management practices that are profitable for farmers in a sustainable sense. The analysis will particularly investigate whether there are improvements in management recommendations when resource stock and carryover effects are included. Information from such analyses will be evaluated for its value in decision making for crop production. Two case studies are conducted to demonstrate the analysis and type of results that can be obtained.

The study region is the north-west plains area of NSW, which contains substantial crop and livestock industries. The case studies are conducted for two locations in one part of the study region. However, the choice of location and soil type means that the results are likely to be widely applicable in northern NSW and in Queensland areas with similar soils and climates.

The Grains Research and Development Corporation (GRDC) utilises independent Research Advisory Committees which consist of grain growers. These Committees develop and communicate research, development and extension priorities to research funders and providers. There are eight such Committees in Queensland and northern and central NSW. In 2003 four of these eight committees nominated soil fertility, soil health, nutrient depletion, and soil biology of sub-soil constraints as their top priority issue, as shown in Table 1.1 (GRDC 2003).

Table 1.1. Top priority issue for each Research Advisory Committee of the GRDC in 2003

Region	Top priority issue
Central Queensland	Soil fertility decline
Western Downs/Maranoa	Wheat improvement
Darling Downs	Improved IPM of pests
South east Queensland	Deteriorating soil health and nutrient depletion
North east NSW	Soil biology
North west NSW	Improved understanding of long term soil biology and sub-soil constraints
Central east NSW	Pulse and oilseed improvement
Central west NSW	Development of farming systems for the Western Plains

1.3 Scope of the study

The scope of this investigation is the state of soils used for crop production in north-west NSW. There is substantial evidence of long-term soil fertility decline in the study region. Questions of fertiliser, stubble and tillage management for crop production are investigated to address the study aim in a general economic context. The 'sustainability' term is widely used in the community, but subject to a variety of interpretations which makes it difficult to apply in any quantitative sense. An important component of the analysis is to define sustainability in a way that allows empirical analysis.

Despite the growing importance of sustainability objectives, it is the basic production economics of crops, livestock and farms that is the primary driver for decisions made by farm owners and managers. The profitability of farm enterprises is the basis for business survival, and farmers need to make decisions that are economically sound. It may be that decisions which led to the observed decline in soil fertility were based on short-term objectives, without considering any long-term implications. The sense in which sustainability is incorporated is that the economic decisions are developed within a longer-term (temporal) perspective. The interpretation of sustainability used here incorporates the natural resource characteristics which are beneficial for agricultural production (as expressed by an individual's profit from growing a crop), but excludes any aspects of the farmer's decision on third parties. 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.' It is the sustainable resource use in an inter-temporal context which is the focus of this work.

Therefore the analysis focuses on soil and farm enterprise-level impacts of crop management practices, and does not investigate potential impacts of, for instance, excess levels of N and P upon groundwater or streams and rivers. The build-up of soil carbon associated with improved soil fertility could also provide wider benefits in terms of carbon sequestration and the greenhouse effect (Lal 1997). Although such impacts may be important and could be added into subsequent analyses, the scope of analysis is restricted here to agricultural impacts. The analysis focuses on decisions made at an individual farm level and does not address issues of aggregate responses for regions or catchments. The justification for this approach is that enterprise-level impacts must be understood before larger-scale analyses are conducted. However, it must be borne in mind that profitable management strategies that reduce on-farm resource degradation may still be a source of externalities to present and future communities.

1.4 Contribution to the literature

This thesis aims to make a contribution to the literature in a number of ways. The subject of soil fertility is of interest to soil scientists. In a northern Australian context, declining soil fertility levels have been identified (Dalal and Mayer 1986, Whitbread *et al.* 1998, Chan *et al.* 2003). With respect to N, the inclusion of prices when developing recommendations for farmers has sometimes (Hayman 2001b), but not always (Lawrence *et al.* 1996, Martin *et al.* 1996), been included. The thesis addresses this issue. With respect to soil SOM, Whitbread *et al.* (1998) noted that SOM concentrations at which soil characteristics and crop yields were stable and sustainable needed to be identified. This thesis has also addressed this issue.

The literature on economic fertilizer input levels (Kennedy *et al.* 1973, Stauber *et al.* 1975, Godden and Helyar 1980, and Kennedy 1981) has been extended in this thesis. The analysis incorporates wheat crop responses derived from a biological simulation model, an economic objective, carryover functions, and stochastic effects for a multi-output production function with prices varying according to a quality measure. Outputs from the analysis are optimal input and other management strategies and tactics to achieve optimal soil fertility levels for SOC and N under wheat production in northern NSW. Use of the dynamic bio-economic approach with two constraints (production function and stock carryover) has allowed two outcomes – an optimal stock of the resource and an optimal input strategy for its substitute. This has not previously been applied to the soil fertility question.

With respect to sustainability, the thesis has taken a particular view of the concept to develop an analysis which will address the stated priorities of wheat growers in northern Australia. One aspect of sustainability is that a natural resource stock used in agricultural production should last indefinitely – the term 'temporal sustainability' has been used to describe the focus of this work. While this specifically excludes the effects of agricultural production on the environment or communities, it is an important production-economic issue.

Another area of the literature that the thesis addresses is that of 'flatness of economic response' (Anderson 1975, Perrin 1976, Pannell *et al.* 2000). These references relate to the flatness of profit response between the production- and short-term-economic maximizing input levels. In this thesis a comparison is made between the short-term (static) and long-term (dynamic) optimal input levels.

1.5 Overview of the study

The problem, as stated above, relates to the management of natural resources (soils) in agricultural production, which has led to a decline in the level and/or quality of natural resources stocks (i.e. soil fertility). The aim of the thesis is to test whether alternative management practices and policies can be developed for situations where the use of natural resources for agricultural production involves carryover effects on resource stocks, i.e. the inter-temporal management of soil fertility.

This issue relates to what many people would call sustainability issues. But how useful is this terminology in general and, in particular, for the purpose of this thesis? Chapter 2 contains a review and discussion of economics and sustainability in terms of developing a relevant focus for analysis. It concludes by developing working hypotheses about predicted outcomes from analyses with and without carryover effects.

In Chapter 3 the particular agricultural study region and farming systems are described. Homogeneous sub-regions were identified. Farming systems issues and practices are reviewed to provide further context for analysis. The general analytical approach of the study is described, including the two-stage analysis of soil fertility. The case studies were conducted for two sites in the Liverpool Plains sub-region.

Given that the focus is on soil fertility, Chapter 4 presents evidence of soil fertility decline and discusses possible causes through examination of the C and N cycles in Vertosol soils of northern NSW. A discussion of soil fertility, soil quality and soil health is presented, and soil fertility change is described in terms of stocks and flows. The soil management questions to be investigated are then presented and justified. Finally a brief discussion of fertiliser replacement strategies is presented to provide context for subsequent analyses.

There is an established suite of theory involving dynamic optimisation methodologies that have been used to investigate these types of issues in the past, and these are briefly reviewed in Chapter 5. The optimality conditions for input use in a single (or separable) time period (the static case) and over non-separable time periods (the dynamic case) are presented. Solution methods and interpretations of economic results are discussed as an introduction to the results presented later.

Chapters 6 and 7 include a model and analysis of nitrogen inputs to wheat production. N is the most important nutrient deficiency for wheat production from Vertosol soils in the region, and the analysis is based on plant response functions to total available N and carryover of soil N through subsequent fallows.

The optimal N input level derived from the dynamic bio-economic analysis is then used in an analysis of other crop management strategies in Chapters 8 and 9. Here SOC is the soil fertility stock which is manipulated by stubble, tillage and fertiliser management. A 'best' level of SOC is derived to answer questions about optimal management of soil fertility and soil quality.

Finally, in Chapter 10, the results are discussed and conclusions drawn about the advantages of the dynamic bio-economic approach to soil fertility management.

2. Economics and sustainability: issues in problem definition

2.1 Introduction

A literature review is used to identify and discuss various issues relating to economics and sustainability, and to help justify and refine the topic of this thesis.

The context for the study is observable natural resource changes, eg erosion, salinity, soil fertility decline and pesticide resistance, and other environmental effects. The particular question of interest is whether these impacts can be improved by better inter-temporal decisions about resource use. One way to think about natural resources is as stocks which may be depleted and replenished over time, the management of which can be evaluated in an economic framework. A naive decision might involve excluding the stock effects (ignoring that the stock needs to be managed according to depletion and renewal processes) or the feedback effects (that decisions now may have implications in the future). How much better can we do than this simple approach?

Although this issue can in one sense be defined more narrowly as an economic efficiency question, the issues that are addressed have been considered by many as relating to sustainability, or sustainable development. The main purpose of this chapter is to acknowledge the sustainability concerns, to review what other writers have said about economics and sustainability, and to consider whether any of these issues are relevant in developing and refining the problem as outlined in Chapter 1.

An initial section deals with how economists have dealt with sustainability in abstract, conceptual or aggregated frameworks. Then concepts of weak and strong sustainability are considered, including the ability to substitute man-made for natural capital, and the place of markets and economic evaluation in managing future resource use. Another aspect is the question of defining sustainability in terms of 'sustaining what' and 'for whom', which is the subject of the following section.

Various writers have discussed ecological/environmental, economic and social aspects of the concept. This leads to a discussion of scale or definition of boundaries beyond which no effects are observed.

In some ways threats to sustainability can be characterised as resulting from externalities. Either spatial (removed in distance) or temporal (removed in time) externality effects, or a mixture of the two, can occur. However, issues giving rise to changes in natural resources are likely to include more than just externalities and indeed some authors argue that a classification according to rivalry and exclusion characteristics provides a more realistic scope for explaining the causes of the observed natural resource degradation and environmental effects of agriculture. The section concludes that there is a wide variety of causes of 'unsustainable' management.

Then follows a discussion of stationarity and sustainability, and of the effects of prices on sustainable agricultural management. A section on the many possible definitions and meanings of sustainability then follows. Some writers have noted that it is a strength that a variety of concepts of sustainability have emerged, but that it is important to specify the ideas carefully and distinguish between them. The relationship between productivity measures and sustainability is considered. Sustainability issues in an Australian context are reviewed.

The difficulties with the sustainability debate are then put in a different context by noting that past actions, practices and outcomes are redundant. An approach to improved farm-level resource use is then developed, which owes more to an economic efficiency objective than to sustainability. Finally the planned approach is set in an informal working-hypothesis framework.

2.2 Economics and sustainability in aggregated frameworks

Pezzey and Toman (2002) discussed post-1987 concerns of economists stemming from the Brundtland Report (World Council on Environment and Development (WCED) 1987). For their purposes the economics of sustainability was defined to include any work with concern for intergenerational equity or fairness and some recognisable use of economic concepts. Economists' work in this period has addressed two components of the sustainability question: the possibility of technical or physical limits to maintaining conditions over time, and the nature of possible obligations to future generations.

The theory and models that these authors presented are characterised by:

- an aggregate whole-of-society or whole-of-country approach;
- incorporation of sustainability constraints in terms of aggregate welfare or utility;
- exclusion of issues of population change (through use of representative agent models);
- a deterministic rather than stochastic approach;
- inclusion of production functions in their models, although they exclude aspects of changing natural resource stocks as constraints. This derives from their focus on intergenerational equity and not on the technical/physical limits side of sustainability; and
- not focusing on sustainability within particular resource sectors (eg agriculture, forestry).

Heal (1998) in his book 'Valuing the Future' stated that the central question giving rise to sustainability concerns is whether current or existing levels of human activity can safely and sensibly continue unaltered over the long term, or whether such continuation would lead to unacceptable circumstances. Since it is economic forces that drive decisions on the issues, the environmental economic approach of considering whether prices reflect private and social costs remains valid. However, he argued that there are two dimensions in which sustainability issues differ from environmental economics. One was the time dimension where frames of 50 to 100 years or more are possible, and the other was the need to address the interaction between economic systems and a range of natural ecosystems.

Quiggin (1997) stated that concern with sustainability raised a number of issues for economic analysis in general and benefit-cost analysis in particular. These were the problem of discounting the effects of current decisions on future generations, the appropriate treatment of uncertainty, and the inadequate accounting for environmental goods and services.

Tisdell (1999a) considered that the principal economic concept of sustainable development is that income per capita of future generations should be no less than that of current generations. Income could be defined in terms of some measure of standard of living or economic welfare. This is an anthropocentric point of view; a broader (ecocentric) view might include the welfare of other sentient beings (Blackorby and Donaldson 1992).

Tisdell (1999a) also observed that neo-classical growth theory (Solow 1974, Stiglitz 1979) and new growth theory (Romer 1986) assumed that economic growth was not limited by the natural environment, and that assumptions about functional forms allowed unlimited substitution of capital for labour so that capital accumulation could offset economic scarcity. Other writers emphasised the entropy of resources (Georgescu-Roegen 1971) and the interdependence of economic activity with the biosphere (Daly 1980). The ecological economics position is that the growth of the economic system depends on the natural environment. Tisdell presented the example of increased waste from economic activity affecting the quality of natural resources and so reducing economic production or welfare.

According to Heal (1998), sustainability is not part of the economist's language; as it has no accepted economic meaning or consensus. However, he asserted that the essence of sustainability lies on three axioms:

- treating the present and future so as to put a positive value on the very long run;
- recognising all the ways in which environmental assets contribute to economic well-being; and
- a recognition of the constraints implied by the dynamics of environmental assets.

Both Heal (1998) and Pezzey and Toman (2002) affirmed the neoclassical economic approach of discounted utilitarianism which has the advantages of allowing trade-offs to be analysed (i.e. providing valuable flexibility in analysis) and incorporating discounting of future values (which represents rational preference behaviour).

However, Heal noted that the traditional discounting method (constant discount rate, exponentially declining discount factor) is problematical for very long-term effects (eg greater than 100 years). This might be the case when analysing issues such as climate change, species extinction and disposal of nuclear waste. At any positive constant discount rate, discounting over those time frames effectively means that no weight is given to future values.

Heal (1998) proposed two ways of overcoming the problem of including very distant future effects into conventional analysis. First he proposed the study of optimal resource-use problems using a generalised discount factor, one with a discount rate that declines over time rather than remaining constant. This can be characterised by hyperbolic discounting (Ainslie and Haslam 1992). Heal (1998) presents a discount factor that replaces time with the natural log of time, so that the effective discount rate declines asymptotically to zero. Hence, the discount factor declines at a slower rate than in the standard case, in which the discount factor declines exponentially. Second, he drew on work by Chichilnisky (1996) to add a term to the objective function which enables ranking of future paths according to their very long-term characteristics (or limiting behaviour). The combination of a generalised discounted utility-maximising term with an appropriately weighted long-term limiting value was described as combining 'no dictatorship of the present' and 'no dictatorship of the future'.

In summary, abstract considerations of sustainability issues by economists have emphasised the need to consider distant future values and outcomes, include an appropriate treatment of uncertainty, account for environmental goods and services, and recognise the constraints implied by the dynamic interaction between economic decisions and environmental assets. Use of the neo-classical economics approach of discounted utilitarianism was affirmed but the need to incorporate limits associated with the natural environment was emphasised.

2.3 Weak versus strong sustainability

The question of substitutability between natural and man-made capital, goes to the heart of economic responses to sustainability questions. Natural resources include renewable, non-renewable and flow resources, whereas man-made capital includes produced physical capital (such as machines), the stock of knowledge or human capital, and institutional/cultural capital.

Pezzey and Toman (2002) noted that the mainstream neoclassical economic view centres on the concept of weak sustainability. This holds that potential substitutability between man-made capital and an environmental resource is more or less unlimited (evidenced by common usage of the Cobb-Douglas or Constant Elasticity of Substitution production functions). Therefore degradation of specific natural resources (natural capital) is in itself not a cause for concern as long as there are offsetting increases in other forms of capital, so that overall well-being can be maintained or increased over time. However the composition of the consumption bundle will change. This view derives from utilitarian objectives, and is common in models of inter-temporal growth. Adherents to this view hold that substitutability, technical progress and conventional policy measures to internalise environmental externalities will together be enough to make conventional optimal development sustainable, so that is there is no need for a specific sustainability policy.

An alternative (less confident) view is that policy intervention (over and above the correction of conventionally defined externalities) will be needed. This is a variant of the strong sustainability view, that capital-resource substitutability is either self-evidently impossible, or subject to strict and fairly imminent limits. It implies that economic growth over centuries inevitably requires higher material throughput (not just improved efficiency) and that these inputs are inherently limited in availability. Therefore strong sustainability leads to a positive (what is) and normative (what should be) problem in balancing the aspirations of the population for more output to improve living standards in a physically binding world (O'Connor 1998).

The combination of this doubt about technical/physical substitution limits and the rights-based approach (obligations to future generations deriving from Rawls 1972) implies the need for strong measures to protect or replace specific natural resources. There may be unknown risks from future environmental degradation that will compromise the rights of future generations, which leads to the precautionary principle of *a priori* constraints on resource degradation or depletion to limit such risks. For Pezzey and Toman (2002) the key issues are if, when, where and how these limits might show themselves and these are empirical, rather than an ideological or theoretical, questions.

Tisdell (1999a) discussed this issue in terms of the ratio of man-made to natural capital, with utility depending on this ratio. The optimum ratio will differ according to views about weak and strong sustainability, and the ratio is also dependent on available technology.

Stoneham *et al.* (2003) reviewed weak and strong sustainability concepts in the context of Australian agriculture. They concluded that despite any degradation of the natural resource base, the agricultural sector is more productive now than in the past. This has occurred because the rate of investment in R&D (resulting in increased reproducible capital) has more than offset the rate of degradation in the natural capital stock. However, with respect to the environment they argue that a strong version of sustainable development may be appropriate. In this thesis the renewable resource of soil fertility is investigated with external effects excluded, hence consideration of weak or strong sustainability concepts is not required.

2.4 Sustainability and system boundaries

Tisdell (1999b) stated that in order to integrate sustainability appropriately into meaningful economic measures two questions must be asked: sustainability of what and in what sense? He also noted (Tisdell 1999c) that the sustainable use of an agricultural technique depends on three factors – economic viability, social acceptability and biophysical sustainability.

According to Lynam and Herdt (1989) sustainability can be considered at different system levels - plant, cropping system, farming system, regional catchment or marketing system, and international marketing system. Except for the highest level system, each of the lower systems may be open to influences from outside.

Because of these different dimensions to the sustainability concept, it seems that any detailed discussion or analysis must start by defining boundaries for definitional and practical purposes. A boundary can be defined as the limit beyond which no further sustainability impacts (however defined) can be felt. Lynam and Herdt (1989) noted that the conceptual problem involved specifying boundaries of the system and the time period involved. The need for boundary specification arises in choosing the system level at which sustainability becomes a relevant characteristic.

The openness of system levels and the needs of economic, social and biophysical factors create the problem of determining when sustainability is an inherent property of a defined system and when it is dependent on external forces. Lynam and Herdt (1989) stated that the system level should be adjusted to define sustainability adequately. Their formal proposition was that "sustainability is first defined at the highest system level and then proceeds downward". The corollary is that the sustainability of a system is not necessarily dependent on the sustainability of all sub-systems.

Hardaker (1995) took a farming system perspective for policy making in sustainable agriculture and rural development (SARD), in a developing country context. He noted Lynam and Herdt's point that the level of aggregation is important for examining these issues and commented that the more narrowly defined is the sub-system, the more difficult it is to ensure its sustainability. It need not be a requirement that every farming system be sustainable for the goal of SARD to be attained, but global sustainability depends on performance of all sub-systems (i.e. they must be sustainable in aggregate). He also noted that resource management decisions are taken at various levels, these decisions may often be poorly coordinated and sometimes in conflict.

This discussion indicates that even before addressing the issue of specifically defining sustainability (see Section 2.8), the possible levels of analysis and other influencing factors give rise to problems in boundary definition. To analyse the impacts on some system of a set of forces according to an objective there is a need to draw a boundary beyond which no other impacts are felt, and making such delineations can be difficult.

2.5 Externalities, market failure and sustainability

As discussed earlier, sustainability issues mentioned by economists and others have included the nature of possible technical or physical limits to maintaining conditions over time, and any (long term) obligations to future generations. The availability of natural resources for production and consumption and the maintenance of environmental services (eg waste assimilation) have received much attention. Threats to these natural resources include pollution and resource degradation, and economists have often described the actions leading to these phenomena as externalities.

Typically, externalities have been characterised as the actions of A (who initiates the externality effect) on B (the recipient), the incidence over which B has no control. In a land degradation context Mullen (2001) characterised off-site effects as having both a spatial and temporal dimension, and defined an externality as a sub-set of offsite effects where the effects are not confined to those who cause them. For a spatial impact that is non-point in nature, there may be no apparent mechanism to internalise the externality. In the temporal context, the externality can occur if the impact of current resource use is not reflected in the price of the asset (eg land) when it is transacted between current and future owners. There may be inefficiency in resource use but this is not necessarily an externality if the relevant market works.

The existence of externalities can drive a wedge between the interests of the individual and the community, which may be expressed in terms of implicit prices. Templet (1995) noted that in the presence of an externality there is a cost imposed by A on B, and there is an implicit subsidy gained by A (consisting of costs avoided). If the aggregate costs of the externality borne by recipients are greater than the subsidy gained by the initiator(s) then the externality gives rise to a net loss in public welfare. The divergence between private and social prices is the basis for environmental economics concerns.

A point from the previous section can be re-emphasised here. At lower levels of aggregation (eg farm or farming system) the existence of spatial externalities may influence where boundaries can be drawn, and limit what can be said about sustainability at that level of aggregation. This issue also arises depending on what is included in a sustainability definition – if social impacts are included then it is difficult to decide where to draw a boundary.

What, then, is to be done about externalities? Traditional economic solutions to a spatial externality are for the imposition of a tax on the polluter (Pigou 1946) according to some damage function, or bargaining by affected parties to reach some mutually agreed solution (Coase 1960). In an agricultural context the first of these is often precluded by the existence of non-point pollution and the second is sometimes hampered by high transaction costs. These approaches to spatial externalities are not dealt with in this thesis; the focus here is on temporal externalities or inefficiencies.

The conventional economic conceptualisation of externalities has been questioned, and it is likely that externality-type effects are not the only causes of unsustainability. Randall (1983) argued that the conventional wisdom notions of market failure were inadequate, whereas the use of the concepts of non-exclusiveness and non-rivalry was precise and led to correct analysis. If a resource is unowned then the rights to it are non-exclusive. If a good can be enjoyed by some without diminution of the amount effectively available to others, then it is non-rival (Randall 1983, pp. 133-144).

Tisdell (1999b) pointed out that environmentally-related market failures which could result in a lack of sustainability included: externalities, pure public goods, open access to resources, and crown commodities. Using a classification according to exclusion and rivalry he categorised the above market failures, but noted that there are many mixed cases with different degrees of rivalry and excludability. Discussion of this theme is continued in the next section.

2.6 Stationarity and sustainability

Does an approach based on the principle of stationarity have anything to say about sustainability? In the sense that a stationary process has the property of being invariant with respect to time, then it does have similar connotations to sustainability. For Y, a variable to be forecast, the stochastic properties of being invariant with respect to time *(t)* are that the mean of Y_t, its variance, and its covariance with other values of Y do not depend on time (Judge *et al.* 1988). These are desirable attributes of sustainability in an inter-temporal sense.

These stationarity properties are often applied to time-series (or Box-Jenkins) analysis for forecasting purposes, whereby predictions of future behaviour are made based on the past behaviour of the variable being predicted. However, the aim of sustainable resource use is to identify management strategies that will allow agricultural production in the current period while allowing future production to continue. Declining trends in soil fertility are predicted to change and a new optimum obtained by changed management. This is more than just using past levels of soil fertility to predict future levels; it requires active management of fertilizer, tillage and stubble to bring the previous levels of soil fertility to an optimal level which can be maintained into the future. As a means of developing sustainable resource management rules the time-series approach would not be adequate.

2.7 Effect of prices

In Australian agriculture the response by farmers to environmental concerns (in terms of implementing conservation measures) has been examined. Clarke (1992) found that investment in soil conservation activity will increase when product prices and farm profitability are favourable and economically viable conservation measures exist. LaFrance (1992) concluded that where both the cultivation intensity and the level of conservation activity respond to market forces, policies that subsidise crop prices or the prices of inputs may contribute to land degradation.

2.8 Definitions and meanings of sustainability

Many authors have tried to define sustainability or sustainable development, while some others have argued that these concepts are flawed and impossible to define meaningfully. Hardaker (1995) quoted broad definitions of sustainable development in the Brundtland Report (WCED 1987) and by the Food and Agriculture Organisation (FAO) (1989), and of sustainable agriculture by the Technical Advisory Committee of the Consultative Group on International Agricultural Research

(CGIAR) (1988). He noted that there was considerable ambiguity, subjectivity and uncertainty regarding sustainable agriculture and rural development. Pezzey (1992) quoted 27 different definitions of sustainability.

Lynam and Herdt (1989) noted that sustainability includes a broad range of concerns about the maintenance of the resource base to ensure future levels of agricultural production. They pointed out that sustainability is essentially a set of concerns about future conditions, but that the concept is ambiguous. Conway (1987) defined sustainability as the ability of a system to maintain productivity in spite of a major disturbance, such as is caused by intensive stress or a large perturbation. That is, it is a property of a system operating over time. Lynam and Herdt (1989) also subscribed to this, but for them the problem came back to the issues of specifying the boundaries of the system and the relevant time frame. Pretty (1994) stated that "sustainability is not so much about a specific farming strategy as it is a systems-oriented approach to understanding complex ecological, social, and environmental interactions in rural areas" (p. 39), although he argued that attempting to define sustainability is flawed.

On the other hand Beckerman (1996) stated that the principle of sustainable development is not only logically incoherent, but also could prejudice the standards of living of future generations. He argued that the proper objective of society is the maximisation, over whatever time period is regarded as relevant, of human welfare, and that the imposition of rules on human behaviour according to some sustainable development criteria would ultimately be more costly.

NSW Agriculture separates the concepts of profitability and sustainability with a vision of "profitable agriculture for a better environment", and a mission of "leading agriculture in NSW to a profitable, environmentally-sustainable future" (NSW Agriculture 2001). One corporate goal of the organisation is "sustainably managing natural resources for agriculture and the community, specifically encouraging adoption of practices and policies that improve the State's environmental sustainability and the health of its natural resource base".

In a contemporary agricultural R&D (cropping systems) context, a Grains Research Update (GRDC 2002) included sessions on sustainable farming systems. Freebairn

(2002) stated that there is no such thing as a sustainable system and that indicators can be useful to measure things quickly as a basis for decisions. He noted that measures of management practice that are well related to resource condition are more likely to demonstrate change than measuring physical properties. Felton (2002) focused on methods and technologies to address problems in crop systems of soil degradation through erosion, soil fertility decline, acidity and salinity. Contamination of the water table is also of concern. McDonald (2002) noted the role of pastures in improving the sustainability of cropping rotations, but he also noted that high levels of management are necessary. These commentators are agronomy based, but they make a distinction between sustainability in a natural resource sense (basis for future production, as did Lynam and Herdt) and profits.

Lynam and Herdt (1989) defined sustainability as the capacity of a system to maintain output at a level approximately greater than or equal to the historical average, i.e. a non-negative trend in measured output. A technology adds to system sustainability if it increases the slope of the trend line. They further defined the relevant measure of output at the crop, cropping system or farming system level as total factor productivity (TFP). This is the total value of all output produced by the system during one crop cycle divided by the total value of all inputs used by the system in one cycle. They also acknowledged the problem of defining the time frame, and suggested that most decision makers choose a time period of up to 20 years.

Ehui and Spencer (1993) noted a problem with the TFP approach: that agriculture uses natural resources (such as soil nutrients) and the stock and flow of these resources affect agricultural production. In many cases the stock of these resources is beyond the control of the farmer and must be accounted for in an agricultural sustainability and economic-viability measurement. They computed inter-temporal and inter-spatial total factor productivity indices for four cropping systems in south-western Nigeria using the stock of major soil nutrients as the natural resource stock. Their results showed that the sustainability and economic viability measures were sensitive to changes in the stock and flow of soil nutrients as well as the material inputs and outputs. Whether their analysis could be extended to more than one natural resource stock is unknown.

Other authors have considered the relationship between agricultural productivity growth and resource quality. Gollop and Swinand (1998) evaluated the effects on farm productivity growth of environmental regulation in US agriculture. Byerlee and Murgai (2001) considered a measure of total social factor productivity, which is TFP estimated with both market and non-market inputs and externalities, and with all factors valued at social prices, as a single all-embracing measure of agricultural sustainability. They showed that no one measure alone will be theoretically or empirically robust as an indicator of sustainability. Ali and Byerlee (2001) considered measures of TFP in Pakistan's Punjab province, and related those to trends in resource quality. Concerns were expressed about degradation of the irrigated land base, despite growth in TFP over time.

In summary, there is no generally-agreed definition or measure of sustainability. This should not be surprising given the different perspectives and system levels than can be considered and the implications of these for defining boundaries. In an agricultural context, the need to maintain the natural resource base is widely acknowledged. However, a narrower definition of sustainability in economic terms can be stated.

2.8.1 Sustainable resource use in an economic context

For renewable resources used in agricultural production, and without spatial or environmental externalities, a definition of sustainable resource use can be developed. The optimal inter-temporal use of a resource involves recommendations for an optimal stock level and an associated stock management strategy for economic production purposes. Optimal inter-temporal economic resource use occurs when there is no net benefit from extra units of the resource. This is the case where the maintained resource stock is sufficient to maximise profits from agricultural production in the current and future periods, provided the optimal management decisions are implemented. In an economic sense this situation is defined by the shadow value of the resource stock being zero; i.e. after the marginal costs of managing, supplementing or renewing the resource are accounted for there is no net benefit from an extra unit beyond the optimal stock. This is a production-economic definition of sustainability in a relatively narrow context of zero externalities and a renewable resource. Hence this definition of sustainable temporal management only applies to individual producers deciding how to adjust their production system.

2.9 Sustainability issues in the Australian context

In Australia the debate has considered both land degradation and sustainability issues. The collection of papers within Chisholm and Dumsday (1987) considered land degradation problems in Australia. An issue noted was that neither the rural sector nor the government at the time had adopted an integrated approach to the question of what approaches were appropriate to the whole area. Chisholm (1992) found that productivity growth over the previous four decades had led to an impressive increase in the productive capacity of Australian agriculture. The foregone productivity attributed to land degradation appeared to be very small compared with that productivity growth. Walpole *et al.* (1996) developed a general approach to analysing the effect of changes in land quality, and tested and applied it to land degradation. An approach that incorporated bio-physical causes of land degradation, the economic effects on farms and the incentives farmers faced to avoid or ameliorate land degradation was developed by Gretton and Salma (1997). They found that there are incentives for farmers to co-exist with certain forms of land degradation, while there are also incentives to avoid some other forms.

The Standing Committee on Agriculture and Resource Management (SCARM) developed sustainability indicators to provide an assessment of how well Australian agriculture is meeting the principles of ecologically sustainable development (the balance of economic, ecological and social needs) (SCARM 1998). The indicators showed that the economic performance of the agricultural sector is highly variable, but here are real concerns about the ability of some industries to sustain their resource base. Improved management practices such as conservation farming were contributing to a decrease in the level of wind erosion, but soil sodicity and acidity were increasing and stream water quality was decreasing. On-farm investment in sustainable practices was inadequate, contributing to an increase in on-site and off-site impacts on the natural resource base. Farm managers needed to be skilled in managing the sustainability and profitability of their farms; skill levels were improving but education levels were still below those of business managers in other industries. The social infrastructure of the agricultural sector was declining, and these factors led to concerns about future sustainability of the sector.

2.10 Possible questions

Pezzey and Toman (2002) raised two possible questions about sustainability:

1. Is a particular society, sector or farming system sustainable?
2. If not, what can be done about it?

Whether the first question even needs to be considered is doubtful. Firstly, as seen above there is no universally agreed definition of sustainability or sustainable development. Second, Lynam and Herdt's question of scale and open boundaries remains. Third, as Pezzey and Toman noted, in an economic sense the derivation of some economically sustainable system would need to be based on a set of "sustainable" prices. Such prices are likely to be different from observed market prices because of the implicit subsidies associated with spatial externalities (Templet 1995) and pricing inefficiencies associated with sub-optimal inter-temporal resource use.

The first question may also be redundant because past actions, practices and outcomes are a sunk cost; they are irrelevant to what happens in the future. Mullen (2001) gives the example of land degradation in Australia and previous attempts to value its impact in terms of production foregone. Apart from raising awareness about the possible scale of the problem, such methods provide little insight into how the resource could be managed in the future. The value of foregone production is not related to any practical or feasible strategy for future land use, although it is an activity required to justify arguments for funding of further research.

The relevant question seems to be a version of the second question: 'What is the best way to manage natural resources in an agricultural production context for present and future resource users?' This question can incorporate some of the concerns expressed in the sustainability literature. The question of how to make better agricultural production economic decisions, including accounting for natural resource stocks and flows is important in this study.

2.11 An approach to improved farm-level resource use

From the foregoing discussion an approach to problem definition and analysis is now developed. The primary subject of this work is enterprise-level analysis of crop production in northwest NSW. The 'sustainability' of these systems has sometimes been called into question, but for the reasons given above this will not be pursued as a specific question.

However, the fact that there are such calls indicates some concern about aspects of those agricultural production systems. These concerns include issues of soil decline (fertility, structure and erosion), stream and dryland salinity, riverine ecosystem quality and biodiversity loss. The solution to these problems involves both government policy development and R&D. Progress is being made on both these fronts, through development of catchment management, water management and native vegetation conservation plans for the former, and through farming systems, agronomy, soil science and economic R&D for the latter.

This thesis will consider aspects of R&D as a means of overcoming knowledge-based deficiencies in natural resource management for agricultural production. It will focus on decision making for managers with economic or financial objectives, but who must consider the interactions of physical and biological systems as decisions are made and stochastic climatic patterns are considered. In these production systems it is often the case that resources and other stocks are used as inputs to production. These stocks may be renewable (e.g. soil fertility) or exhaustible (e.g. soil quantity; pest, disease and weed susceptibility to pesticides). The management of these stocks over time is one aspect of concern for those industries and individuals. Market failure can, in part, be ascribed to a lack of knowledge about these processes, which governments have addressed through developing policies allowing groups to self-impose R&D funding levies, and through conducting R&D themselves.

As proposed by Lynam and Herdt (1989) the analysis will be forward looking, and will illustrate an approach to evaluating alternative resource management strategies with an economic objective. It will account for existing resource conditions, available technologies and the state of knowledge about physical and biological interactions and relationships.

This type of approach addresses inter-temporal effects of natural resource use. It will be undertaken at the micro (enterprise) level to provide information to farm decision-makers. There is a well-developed theory (optimal control) and methodology (dynamic programming) which can be applied. There are a number of past applications of optimal control theory and dynamic programming to agricultural resource questions in Australia, although most have not had a specific sustainability/resource use focus. Pandey and Hardaker (1995) and Cacho (1998) advocated this approach for sustainability-type questions.

Consequently this thesis includes an outline of optimal control theory and dynamic programming as a basis for optimal inter-temporal resource management for agricultural production in a profit-maximizing framework. This will be illustrated by two case studies relating to soil fertility: on nitrogen as a wheat-crop input when carryover of soil nitrogen from one crop to the next is important; and on the use of stubble management, tillage and fertilization strategies in considering general soil fertility and soil carbon for wheat production.

In the first case study the traditional question of how much input to use in a production process is addressed. Nitrogen is investigated as an input to short-fallow wheat production. The model considers two outputs (yield and protein content), as well as nitrogen carryover effects in the fallow phase. The analysis uses output from a crop simulation model to investigate optimal input levels in the presence of stochastic climatic effects, and illustrates the difference in optimal input use between the static (no carryover) and dynamic (carryover) cases. The issue is that the dynamic nature of the problem implies a marginal user cost, which may influence optimal input levels.

In the second case study the questions of long-term soil fertility decline and the use of contemporary best management practices are evaluated in terms of soil quality and soil health for wheat production from the farm decision-maker's viewpoint. Using simulated responses of wheat crops to different nitrogen inputs, tillage treatments and stubble management, the analysis determines the optimal input mix, and in the process determines the optimal level of soil organic carbon associated with such management.

2.12 Hypothesis tests

The premise underlying the discussions above is that observed detrimental natural resource outcomes are due to a lack of information on the part of decision makers, or that wheat growers do not fully appreciate the magnitude of these effects, relating to long-term consequences of alternative management strategies. This thesis advances the idea that both R&D practitioners and farm decision makers could improve their understanding and information base by conceptualizing the natural resource descriptive framework in a stock-and-flow representation. It proposes that specifically accounting for dynamic feedback processes in natural resource stock management will provide a more useful approach to developing recommended management actions. Growers may not be aware of these effects in principle, or they may not fully appreciate the magnitude of the effects or how to handle them; in either case it is the aim of this thesis to analyze these issues.

In a classical hypothesis test, as an econometric analysis might perform, the analysis aims to decide whether the data in a sample would likely have been generated by a particular population (e.g. Greene 1993). A null or maintained hypothesis should be rejected if a sample estimate lies within a critical region. The present analysis is a case study, and so the question of interest is more a working hypothesis or question of interest to be evaluated, rather than a formal acceptance or rejection of a null hypothesis.

The issues to be tested therefore involve comparison of the predicted outcomes of decisions with and without considering resource stocks and feedback effects. The subjects of investigation are two case studies involving a wheat enterprise chosen to be 'representative' of a farming system with particular soil and climate characteristics.

In general, the situation without considering these effects is assumed to be the status quo. In each case the working hypothesis is questioning whether it makes any difference to the individual decision-maker whether dynamic effects (i.e. use of dynamic models) are considered. This is important because, if the working hypothesis is accepted for a specific case, it means that the more complicated (expensive) conceptual framework for decision making is worthwhile. The basis for judging whether the outcomes are different enough to be important or significant, is discussed separately in each case.

3. The agricultural region: characteristics and issues

3.1 Introduction

The first two chapters have identified a particular issue relating to natural resource use in the northern agricultural region of NSW. To address this issue the approach proposed is to focus on improving management decision making through provision of better information from R&D processes. The particular management focus is inter-temporal decision making regarding use of natural resource stocks.

In this chapter the agricultural region of interest is described and perceived agricultural problems within that region are discussed. Two sites within the Liverpool Plains sub-region were used in the analysis. Evaluations of new technologies or management practices can be conducted at different levels. These include the individual activity or production enterprise; the crop sequence or farming system; the whole farm; more aggregated levels of catchment, industry or sector; and conceivably the whole economy. At each evaluation level different methodologies are available.

It is argued that even though management considerations at aggregated levels (eg the whole farm or whole catchment) are considered very important, the technology must first be understood and evaluated at lower levels. The important point for R&D processes is to be clear about the purpose of evaluation, the level at which decisions are made, and the information needed to make these decisions.

3.2 The northern cropping region of NSW

In defining the region of interest a crop focus was considered important because a number of the resource use and degradation issues relate to cropping practices. The summer-rainfall-dominant crop areas within the State of NSW are the main focus, with the southern geographical boundary being the latitude of Quirindi and Coonabarabran. The soil types associated with successful cropping comprise the fertile clays and loams. Precipitation levels from less than 500 to more than 700 mm rainfall per annum define the region, with limits in the west being the 450 mm rainfall isohyet and in the east being the smaller areas of arable land with rising slope.

The region of interest is the northern cropping region of NSW. Similar cropping areas are located in southern Queensland, and although these were not included in the analysis the results could also apply there. Agricultural areas of the northern tablelands and parts of the slopes of NSW are not included in the region because they do not include cropping enterprises.

The region contains both dryland and irrigated cropping areas. Irrigation water and infrastructure associated with dams in the Namoi and Gwydir Catchments, and from groundwater sources, allow irrigated cropping in the region. Cotton is the principal irrigated crop and the cotton industry has developed rapidly in the last 30 years. The main focus in the thesis is on dryland agriculture, however the management principles apply to all natural resource use.

These regional characteristics fit into a statistical classification of the State. The region is contained within the north-west slopes and plains topographical areas, and consists of parts of the Northern and North Western Statistical Divisions of the Australian Bureau of Statistics (ABS). These can also be defined by Local Government Area (LGA) groupings. The region comprises the LGAs of Inverell, Yallaroi, Moree Plains, Bingara, Barraba, Manilla, Tamworth City, Parry, Quirindi, Gunnedah, Narrabri, Walgett, Coonamble and Coonabarabran. Figure 3.1 shows the defined region, including the main towns, roads and rivers.

Regional soil and rainfall characteristics are shown in Figure 3.2. Around and between the 500 to 700 mm rainfall isohyets is a large area of relatively fertile soils with flat topography. Areas to the west with less than 500 mm rainfall become more marginal for dryland cropping.

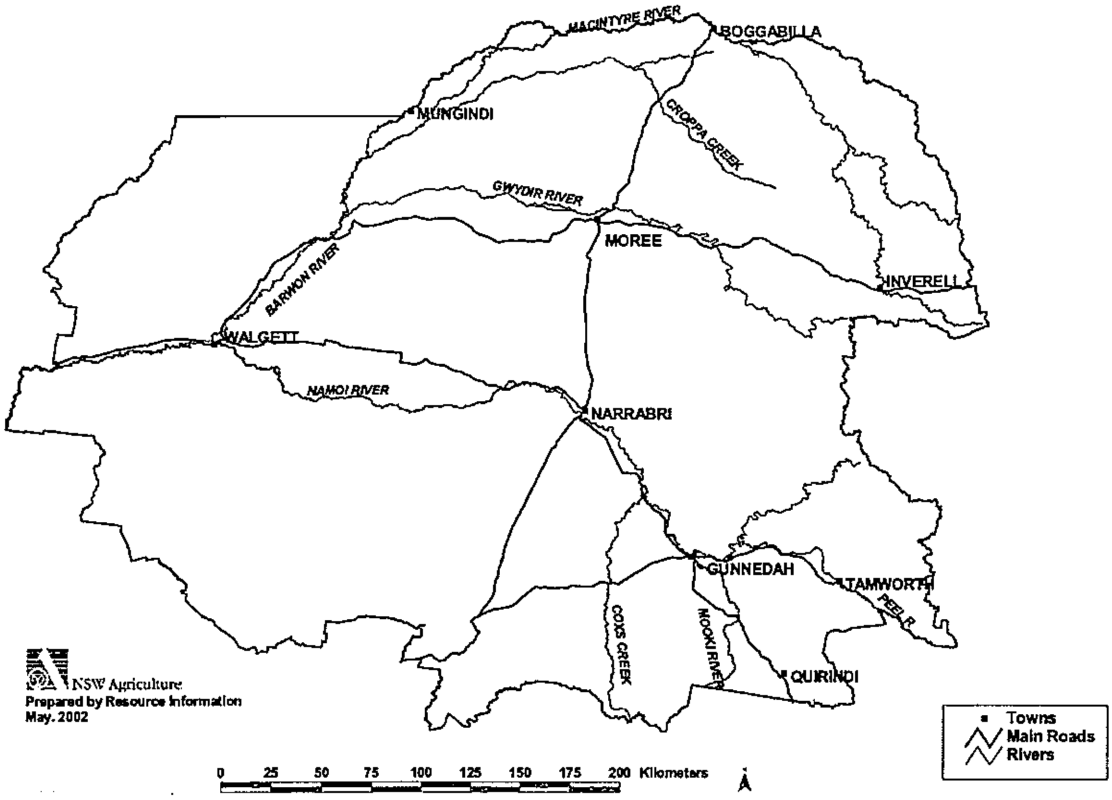


Figure 3.1. The Northern Cropping Region of NSW

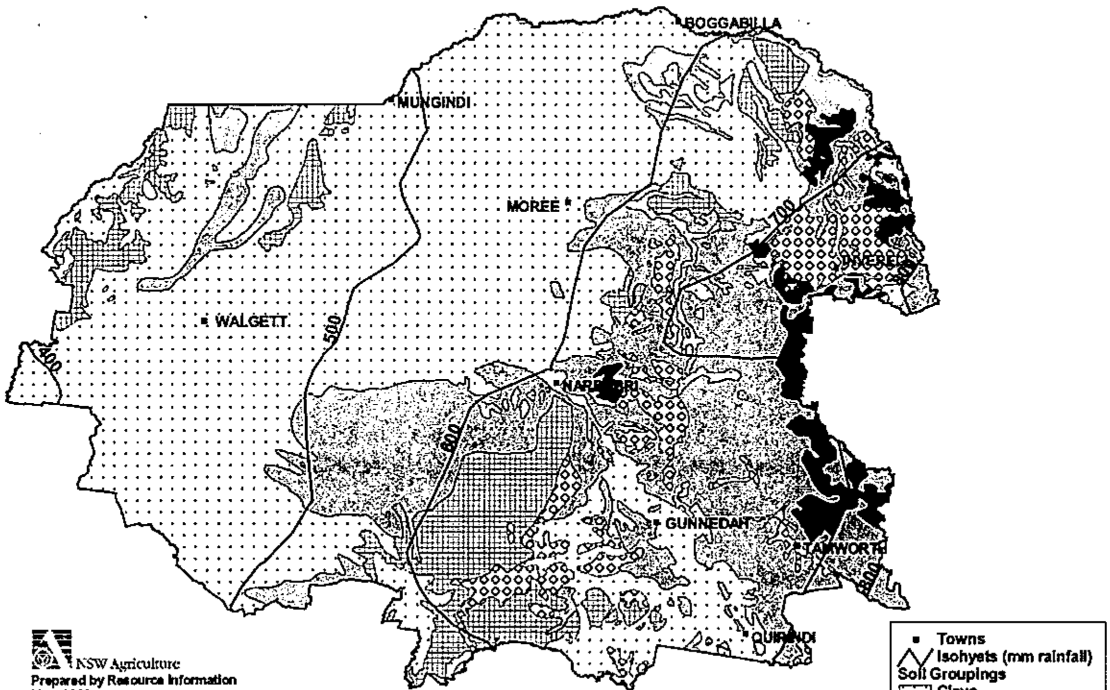


Figure 3.2. Soil and rainfall characteristics of the Northern Cropping Region

About two-thirds of the rainfall in the region occurs between October and March. Rainfall is increasingly summer dominant in the north of the region. High intensity storms may occur during this period. The lowest and most variable rainfall occurs during autumn, which is the sowing time for winter crops. Planting times for both winter and summer crops are highly variable, and greatly affect potential yields (Holland *et al.* 1987, Marcellos and Felton 1992). The region has traditionally produced high quality prime hard wheat, but other (durum) wheat, oilseeds and pulse crops have more recently been produced as well.

The soil groupings in Figure 3.2 relate to the Factual Key classification (Northcote 1979). This classification includes sands; loams; dark, grey and brown clays; red and yellow massive earths; friable earths; and duplex soils classified according to soil and sub-soil types. An amalgamation into five broad soil groups (clays, loams, massive earths, sands and duplex soils) is shown in Figure 3.2, based on suitability for agricultural and cropping activities. The clays and loam soil amalgamations are most favourable for cropping enterprises.

There is a new soil taxonomic classification which can be used for comparing and communicating about soils nationally, but not for mapping purposes. This is the Australian Soil Classification (ASC) (Isbell 1996). Clay soils are called Vertosols under the ASC. They have shrink-swell properties that exhibit strong cracking when dry. Australia has the greatest area and diversity of cracking clay soils of any country in the world. The best cropping soils in the region range from neutral to alkaline grey clays to black and red earths, often self-ameliorating due to their shrink-swell properties (Marcellos and Felton 1992). Large amounts of fallow rainfall can be stored in these soils for subsequent use by a crop.

3.2.1 Case study locations

Two case studies were conducted for the analytical component of this thesis. Analyses of soil fertility management in the context of wheat production were conducted at two locations with Vertosol soils in the Liverpool Plains sub-region in Figure 3.3.

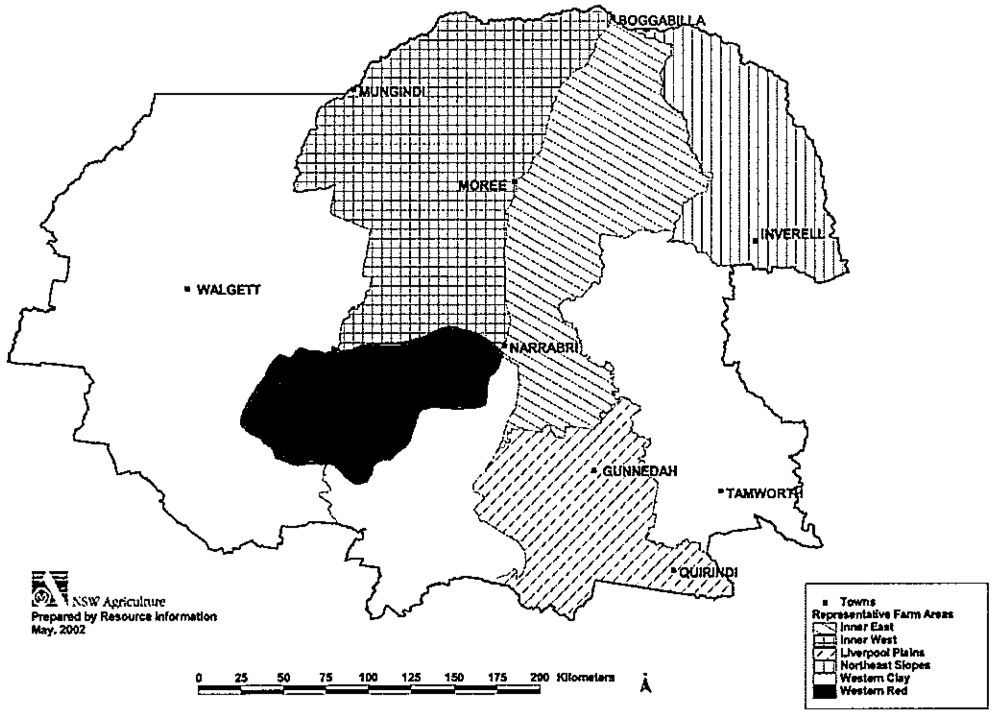


Figure 3.3. Representative farm areas in the Northern Cropping Region

While these are case studies, and so we should be careful in extrapolating the results, the studies do provide useful information for the northern cropping region. The analyses were for wheat on Vertosols, which is the major cropping enterprise and soil combination in the region. It is likely that the results will be relevant for other sub-regions with similar climatic and soil characteristics. As rainfall decreases to the west, the results become less valuable but still remain broadly relevant.

3.3 Farming practices within the region

3.3.1 Historical development

Agricultural practices in the region have developed and become more sophisticated over the last 50 years. During the 1950s tillage by shallow cultivation with disc ploughs and scarifiers drawn by low-powered tractors was the most common practice. 'Crop rotation' during this period usually meant continuous wheat with short fallow (i.e. between each annual wheat crop). Some farmers occasionally grew lucerne, oats or sorghum or used long fallow (Marcellos and Felton 1992).

In the 1960s cropping expanded rapidly as returns from grain increased relative to those of sheep, and tractor horse-power increased. The wheat variety Gabo was released in 1960; it was an early-maturing variety with high quality (prime hard) characteristics, and was widely grown in the northern cropping region. Large areas of native vegetation were cleared between 1962 and 1975 (Marcellos and Felton 1992). Conventional cultivation for seedbed preparation and weed control was traditionally practised, but erosion was always a risk with this land preparation method.

During the 1970s tyned trash-working implements were introduced. The implications of this were that stubble retention and reduced tillage practices became more practical. Reduced tillage practices were recommended because they were more efficient at storing water in the profile during fallow periods and lessened erosion potential during rainfall events. Weed control during fallow was carried out to maintain fallow moisture; this was achieved by spraying with weedicides. Fallowing was also important for soil fertility renewal via nitrogen mineralisation through break down of organic matter.

Strip cropping (growing crops in rotation in alternative strips) was more widely adopted in the Liverpool Plains (south of Gunnedah) during the 1970s to combat erosion damage caused by flood events. Fences were removed to avoid water channelling and runoff problems. The strips were between 20 to 100 metres wide and alternated between fallow, crop stubble and growing crop, using mostly wheat, sunflowers and sorghum.

In the 1980s a survey of crop rotation, tillage, fertiliser use and weed control was undertaken (Martin *et al.* 1988) covering the Shires of Moree, Narrabri, Yallaroi, Gunnedah, Inverell, Quirindi, Parry, Manilla, Bingara and Barraba. The authors found that adoption of new wheat varieties and herbicides was rapid, but adoption of the use of nitrogen fertilisers was slow. They concluded that the change in crop rotation practices since the 1940s was only marginal, meaning that cropping paddocks were mostly kept in continuous production, particularly in the more western Shires. Eighty-one percent of farmers surveyed cultivated three to five times every year, implying a high cropping intensity and cultivation fallowing. Rotations with pastures or with cereals grown every second year were more common in the eastern part of the area surveyed, which on average receives more annual rainfall.

The survey indicated 74% of farmers in the northern wheat belt practised conventional tillage, 14% practised reduced tillage and used herbicides and 1% used no-till. In the same survey, less than 30% of growers burned stubble. It was also found that 66% of farmers included sorghum, 28% lucerne, 20% grazing oats, 18% sunflower and 14% barley as alternatives to wheat. About half of the farmers surveyed used fertilisers, but the more northerly shires used the least.

Hamblin and Kyneur (1993) observed that crop rotations with pastures, or with a cereal crop every two years, were more common in the higher rainfall areas in the north-east. Flavel and McLeish (1996) presented survey results for the Liverpool Plains and reported that 57% of respondents included pasture in a rotation. Fixed crop rotations were used by 56% of respondents, 35% of respondents using response cropping and 4% used other rotations. Only 5% reported continuous monoculture. Martin and Edwards (2001) reported results of a 1999 survey of cereal growers in the Warren/Narromine, Coonamble and Walgett areas of NSW. Average sizes of surveyed farms in the Coonamble and Walgett areas were 2917 and 6081 ha. The percent of farm area under crop was 45 and 20, and the percent under sown pasture was 4 and zero percent respectively. These figures imply that pastures as part of crop rotations are more likely in the eastern (higher rainfall areas) than to the west.

A formal measure of productivity growth in the general region was presented by Knopke *et al.* (2000). They reported annual growth in total factor productivity on crop farms from 1978-79 to 1998-99. Average rates of productivity growth for NSW North East/Queensland South East and NSW North West/Queensland South West were 2.7 and 3.7 % per annum, respectively. The average for all northern farms was 3 %.

3.3.2 Cropping activities and representative farm areas

Developments in soil moisture measurement and opportunity crop sowing rules have been important in the growth of cropping activities and rotations in the region. With the ability to measure soil moisture content by simple mechanical probes or water budget estimation techniques, the practice of fallowing to fill a soil profile with moisture and then planting a crop in the next sowing window has improved crop management. This has been called opportunity or response cropping and involves using the water when it is available. Both winter and summer crops can be grown, and although this is an intensification of land use it has also been considered to be an improvement in water-use efficiency. Stubble retention, chemical weed control and minimum or zero tillage practices have continued to be important for erosion control.

Wheat is the principal dryland crop in the region, while barley, sorghum, chickpeas and sunflower are the crops generally used in rotation with wheat. Cotton is the main irrigated crop. For both dryland and irrigated crop production the control of weeds, insect pests and crop diseases has become increasingly important. Restrictions on chemical products and usage, as well as developing resistance to some weedicides and insecticides has meant that rotating crops and using other management practices have increased the complexity of crop management. Integrated pest, weed and resistance management strategies are becoming increasingly important, as is the concept of area-wide management in irrigated cotton production.

Winter-summer crop rotations are subject to a number of constraints. For example, there is often overlap between the harvesting time of winter crops and the sowing time of summer crops. If dryland cotton is sown in October and wheat harvesting begins in November then it is not possible to grow a cotton crop immediately following wheat (cotton has specific temperature and day-length requirements). It is possible though to grow a wheat crop following a cotton crop, since cotton harvesting occurs in April/May and wheat is sown from late May until July. In dryland situations, soil moisture may limit this practice. Other constraints include machinery and labour availability to conduct 'continuous cropping', and managerial complexity which may be incompatible with farmer objectives. Risk attitudes associated with fluctuating cropping income caused by climatic variation can also be important.

Hamblin and Kyneur (1993) observed that the rotation of cereal crops with pastures (particularly lucerne) has been perceived for decades as less exploitive and more sustainable, but according to Martin *et al.* (1988), only twenty-three percent of those surveyed grew pastures. Hamblin and Kyneur (1993) suggested that for many farmers, who have a mix of soil types and crop and stock enterprises, the management requirements of cereal crop, pulse crop and pasture rotations were too complex to be practical. In addition, low wool and cattle prices in the early 1990s were likely to have been a disincentive to increasing improved pasture areas or introducing pasture into a rotation system. In the western areas landholders tend to keep their crop and livestock areas separate so that wheat/chickpea rotations are on one part of the property, and if there is a livestock enterprise it is carried out independently on other areas.

Norman and Collinson (1986) discussed one function of the descriptive or diagnostic stage of farming systems research (discussed below) as classifying farming families into homogeneous groups or recommendation domains. 'Farmers within each specific group should have the same problems and development alternatives and should react in the same way to policy changes. Target groups should replace conventional frameworks as a basis for research and development planning' (Norman and Collinson 1986, p. 20).

Within the northern cropping region there are constraints imposed by soil type, rainfall patterns, frost incidence and temperatures that have implications for crop production in sub-regional areas. Figure 3.3 shows a classification of the region into six sub-regions that can be distinguished as relatively homogeneous areas.

The six representative sub-regions can be described briefly as follows (John Kneipp, NSW Agriculture, personal communication):

- The Western Clay sub-region has moderate soil fertility; with initially high fertile soils that have been run down over up to 30 years of cropping. Graingrowers are now adding nitrogen fertiliser or including chickpeas in the rotation to improve fertility. There is less rainfall and temperatures are higher in summer, so that management strategies to make the most of available moisture are followed, including earlier sowing;
- The Western Red sub-region contains mixed red soils which were some of the earliest areas cropped. Soil fertility is moderate to low, and is suitable for rehabilitation with legumes, especially lucerne as a ley pasture in the rotation;

- The Inner West sub-region has moderate soil fertility on the heavy clay soils with good water storage capacity. These soils are responsive to added nitrogen, and chickpea crops included in the rotations are working well;
- The Inner East sub-region has a range of soil types, with moderately fertile black and grey cracking clays being the predominant type used for cropping. There are more crop rotations with lucerne pastures and a superior summer cropping environment due to higher rainfall;
- The Liverpool Plains sub-region has similar soil and rainfall characteristics to the Inner East, with moderately fertile black and grey cracking clays being the predominant type used for cropping. Because temperatures are not so high the crop yields are better than in other sub-regions. Some pastures are in the mixed cropping rotations;
- The Northeast Slopes sub-region has large areas under lucerne for grazing, which is often rotated with grain crops such as wheat, barley and sorghum. Livestock enterprises are more common in this sub-region and forage oats is often the only crop grown by many producers.

There are also areas within two regions in Figure 3.3 which have been excluded because cropping is not dominant due to soil type and topographical constraints.

These sub-regions can be called 'representative farm areas' because it is considered that within them the farming activities are homogeneous enough for a representative farm model or analysis to be valuable in analysing management alternatives. The analyses conducted later in this thesis are for particular activity types within one of these areas.

3.4 Issues arising from agricultural activities within the region

3.4.1 Farm level issues

There are a number of natural resource management issues that have needed, or still require, consideration in cropping systems development. The first of these to become apparent was erosion, when bare soil during fallow was exposed to wind and water forces associated with extreme rainfall events. The installation of contour banks and the use of contour ploughing and strip cropping were initially used to combat erosion. More recently the retention of crop stubble on the soil surface (allied with chemical control of weeds during fallow) and a reduction in tillage operations have been used to mitigate erosion.

Soil fertility decline, associated with continuous cropping over several decades, has been observed for some time in northern Australian cropping regions (Dalal and Mayer, 1986a, Whitbread *et al.* 1998). Originally the soil fertility status (especially of cracking clay soils) was relatively high so that crops were grown without the need for application of fertiliser to replace nutrients lost with grain removal at harvest. Other soil quality attributes have also been affected by continuous cropping. The question of what to do about soil status, both in terms of fertiliser management practices and the use of other management is addressed in this thesis.

A more recent issue is the salinity risk associated with replacement of perennial ground cover by annual cropping systems and the related increase in deep drainage of surface water through the soil profile. This has led in many areas to rising ground water levels which bring existing salts in the soil profile closer to the surface. The salinity risk and current impact varies with soil type, slope and hydrogeological configuration. Salinity impacts may be on spatially removed land and watercourses, and they may be experienced some time in the future. Groundwater and river water quality can be affected, with impacts on other farmers, towns and infrastructure.

Another area of emerging concern in the region is soils that are sodic (high exchangeable sodium content leading to dispersal of clays and instability, especially when wet) and sometimes saline in the lower part of the root zone (Oster and Shainberg 2001, Rengasamy 2002, Surapaneni *et al.* 2002). High soil strength, high electrical conductivity values (salinity) and low hydraulic conductivity may accompany sodicity. Grain production potential on these soils is governed by root zone plant available water. Rooting depth, and hence plant available water, can be limited by either one or a combination of these sub-soil constraints. The distribution of cracking clays with high sodicity in the region is not clear, as many cracking clays are not sodic.

Other issues have also arisen associated with the use of pesticides and their residues permeating into groundwater and river systems. Fertiliser runoff and other causes have also contributed to blue-green algae problems in water ways.

Increased resistance to pesticides has become a major issue in the region (Fitt 2000). Cotton production is restricted by the behaviour of insects, particularly *Heliothis* species. There is evidence of increased resistance by these insects to a number of classes of chemicals used for control. Integrated pest management and integrated resistance management strategies are used with the aim of maintaining susceptibility to insecticides within the Heliothis populations. Resistance to weedicides among weed populations is also being discovered, with implications for agricultural production.

These are farm-level issues, although the impact of some problems can be felt between farms, or completely off farms. In the next section larger-scale catchment issues are reviewed.

3.4.2 Summary of issues

In Chapter 1 the topic for this thesis was derived from a general discussion of the crop industry in northern NSW and important issues arising as the industry has developed. Because the topic is concerned with natural resource management over time, the sustainability literature was reviewed in Chapter 2 to see if it added to the problem as described.

In this chapter the region of interest has been defined and described. The regional characteristics of climate, soil types and topography have determined the farming systems and farming practices developed to overcome particular observed issues of concern to farmers and industries. Changes in cropping technologies have been developed to address soil problems – particularly erosion and fertility decline. The region was divided into sub-regions based on a detailed classification of soil and climate, and the two case study locations are described.

3.5 General analytical approach of this study

At the farm activity or enterprise level there are a number of budgeting approaches available (see Makeham and Malcolm 1993, Malcolm and Makeham 1987). Partial budgets are used to assess potential changes within an activity or enterprise due to a new technology. These budgets include only the estimated variation in costs and returns that occur when a new technology or change in plan is considered for an existing activity. Enterprise gross margin budgets can be developed to compare activities for enterprise choice. Crop sequence budgets can also be developed when carryover effects are important or to compare crop sequences with different time spans. Cash flow budgets investigate the likely intervening cash flow patterns when moving from one situation (or steady state) to another. In all these cases the financial analysis relies on estimates of the biological changes that are likely to occur between the 'with technology' and 'without technology' cases. These estimates may derive from experimental results, considered expert opinion or simulation models.

An alternative way of looking at the question of deciding an optimal level of input to a production process is to use estimated production functions (from biological or other simulation models) and economic response theory. These bio-economic methods might be static or dynamic, or deterministic or stochastic. The theory and methods underlying some of these approaches are outlined in the next chapter. Vere *et al.* (1997) outlined the major production systems models, including budgeting methods, optimisation models and simulation models. The methods used in this thesis to evaluate questions of soil quality and soil fertility involve stochastic dynamic bio-economic models used in a normative analysis of optimal crop input decisions.

A sequential approach to analysis of soil fertility under wheat production is adopted. N is the most important limiting nutrient for wheat production in the region and the N application option requires information on how much to apply. The first stage of the analysis considers this question assuming that no other nutrients are limiting.

The optimal N decision rule is then used in an analysis of fertilizer, tillage and stubble management to develop an optimal level of SOC. Of concern with such an approach is whether some aspects of the optimal SOC level might influence the optimal N rule. The analysis was conducted in such a way that this risk is minimised. Further discussion of this issue is presented in Chapter 9.

4. Soil fertility decline: a stocks and flows problem

The literature reviewed in Chapter 2 showed that there is no generally-agreed definition or measure of sustainability, but that many authors supported the need to maintain the natural resource base for agriculture. In Chapter 3 a review of the northern cropping region of NSW showed that there were a number of issues of concern at the farm and catchment level.

One particular issue has been identified for analysis in this thesis - soil fertility decline within the northern cropping region of NSW. This was chosen because it is a distinct and tractable problem for analysis, while being an important issue for graingrowers.

The value of soil is considered to derive from its use for the purposes of agricultural production. Soil scientists have discussed concepts of soil quality (the ability to support crop growth without degradation or pollution) and soil health (the balance and availability of plant nutrients and freedom from plant diseases and pests). Soil fertility is considered to encompass elements of both these concepts. The discussion of soil fertility in this thesis focuses on the organic matter content of soil, its major constituent parts (SOC and N), and other soil structural properties that relate to the organic matter content.

In the analysis a private benefit approach is used which concentrates on managing soil fertility levels in profitable ways. The issue of soil fertility decline can also be considered in the larger context of potentially counteracting greenhouse gas emissions from fossil fuel burning (Lal 1997). If changed crop management practices can lead to carbon sequestration in soils, then soil could become a carbon sink and increased carbon sequestration may lead to mitigation of the greenhouse effect. The wider positive effects are acknowledged but not further evaluated.

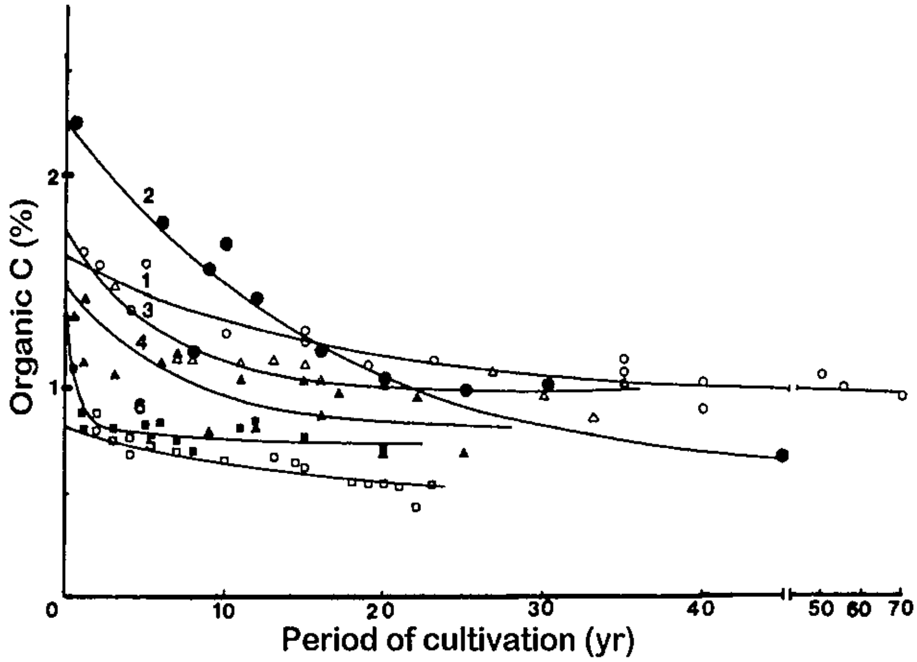
The chapter proceeds by first presenting evidence of soil fertility decline in northern cropping soils. SOM is a vital component of soil fertility, and an integral part of the C and N cycles. These cycles are discussed in relation to the fertility declines. Then a brief discussion of soil fertility in relation to soil quality and soil health is presented. Soil fertility is described in terms of stocks and flows that may change from year to year. The soil management questions to be investigated are then presented and justified. Finally a brief discussion of fertiliser replacement strategies is presented to provide context to subsequent analyses. Relevant economic theory and methods are discussed in the next chapter.

4.1 Evidence of soil fertility decline

Some vertosol soils of northwest NSW and southwest Queensland have been cropped for 50 years or longer. Much of that activity has involved 'conventional' cropping practices of physical cultivation for seedbed preparation and weed control, stubble burning for crop disease control, and little or no application of fertiliser to replace nutrients lost through product removal at harvest. Recently many growers have changed to zero or no tillage methods, but there is still a substantial proportion that continues with conventional methods.

Dalal and Mayer (1986a, b, and c) measured long-term trends in the fertility of soils under continuous cultivation and cereal cropping in southern Queensland. They attributed the declines in soil fertility as being due to cropping with traditional cultivation methods. The declines were measured in terms of SOM and its constituents, including soil SOC, total and mineralisable N, and other soil properties such as bulk density. Their results, showing declining levels of total SOC and total N levels related to period of cultivation, are shown in Figures 4.1 and 4.2.

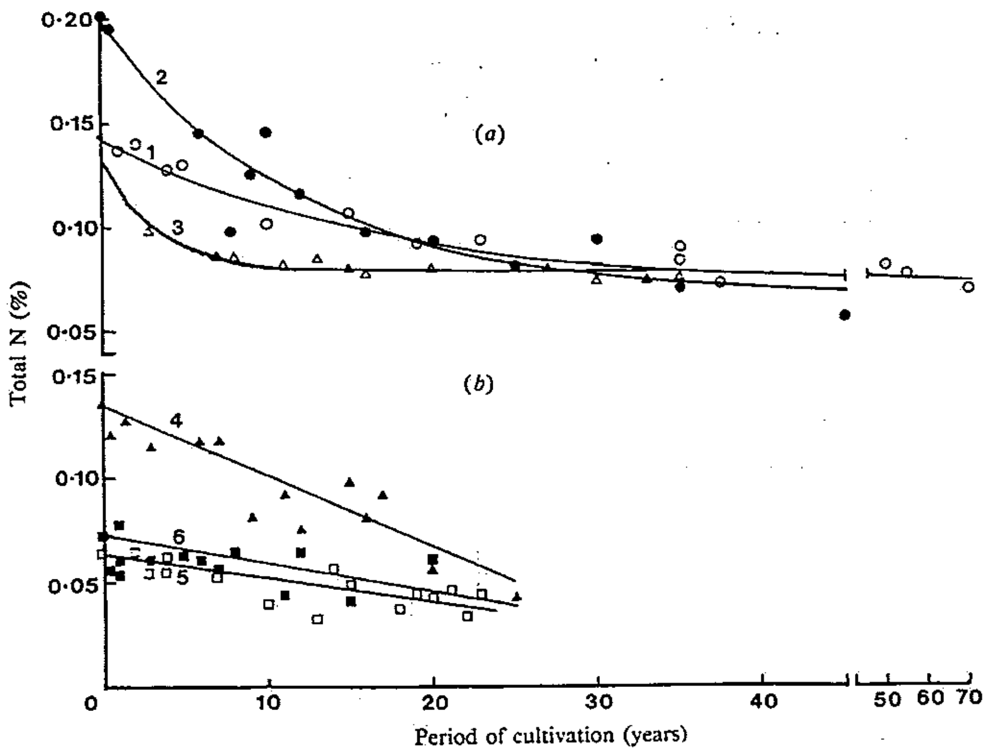
Daniells *et al.* (1996) surveyed a representative set of dryland farming soils in north west NSW to obtain benchmark values for soil total organic C, total N and a biological index of mineralisable N. Half of all the values for total SOC fell in the range 1.2 to 2.2%, with higher values (up to 7.5%) associated with the surface 2.5 cm of pasture sites. Kirchof *et al.* (2001) investigated the effect of tillage on the structure of dryland cropping soils in north west NSW to collect baseline data. They concluded that farmers would experience soil and financial benefits from conservation tillage



Soil types: 1, Waco; 2, Langlands-Logie; 3, Cecilvale; 4, Billa Billa; 5, Thallon; 6, Riverview.

Source: Dalal and Mayer (1986b)

Figure 4.1. Decrease in soil organic carbon in the top soil layer (0-0.1 m) with period of cultivation



Soil types: 1, Waco; 2, Langlands-Logie; 3, Cecilvale; 4, Billa Billa; 5, Thallon; 6, Riverview. Equation (a) exponential, equation (b) linear.

Source: Dalal and Mayer (1986c)

Figure 4.2. Total N concentrations in relation to the period of cultivation

practices, but not necessarily immediately. Whitbread *et al.* (1998) surveyed soils in north-west NSW to investigate the impact of cropping on soil chemical and physical fertility. They found substantial declines in hydraulic conductivity, aggregation and C content. They also found that a large proportion of soil C was lost soon after the commencement of cropping. Similarly, Connolly *et al.* (2001) investigated the effects of rundown in soil hydraulic conditions on crop productivity in south-eastern Queensland. They used simulation to determine how important infiltration and soil hydraulic condition have been to the water balance, crop growth and yield in the past, and might be in the future if management was not changed.

Chan *et al.* (2003) reviewed trends in the sequestration of C and changes in soil quality under conservation tillage on light-textured soils in Australia. They reported a general lack of positive response to conservation tillage; higher SOC levels compared to conventional tillage were found only in the wetter areas. Their expectations, based on overseas experience, were that SOC levels (and therefore soil quality parameters) should improve under conservation tillage compared to conventional tillage. But their results are likely to have been also affected by fertilisation practices, where lower levels of N application than those evaluated later were probably used. However, their stress on the importance of organic matter and SOC in lighter soils points to the need for additional analysis of these lighter-soil situations.

SOM consists of living (micro-organisms, worms etc.) and non-living (humus, partially broken down plant and animal matter, roots) components. Chemically, SOM comprises the organic forms of C, N, and other nutrient elements (eg P, sulphur). These organic forms of nutrients are not directly available to plants, but can be transformed into inorganic forms which are available for uptake.

SOM is vital in most cultivated soils, having important biological, chemical, physical and environmental roles. It is necessary to maintain soil structure, which has implications for properties such as water infiltration and erosion potential. As well as being a natural source of the nutrient elements mentioned above, SOM has a role in retaining cations and is also important in making available micronutrient elements (eg copper, zinc, and manganese).

SOM is the centre of much activity relating to plant and animal residues, micro-organisms and nutrients. The process of building soil fertility for agricultural production involves management practices that are both direct (eg application of fertilisers providing nutrients which are directly available to plants), and indirect (eg use of tillage, stubble and crop fertiliser practices which facilitate SOM build-up and promote the availability of nutrients and moisture to plants). The place of management in rebuilding soil fertility can be shown by an examination of how C and N cycle through the atmosphere, soils, plants and animals. These cycles are discussed in the next section.

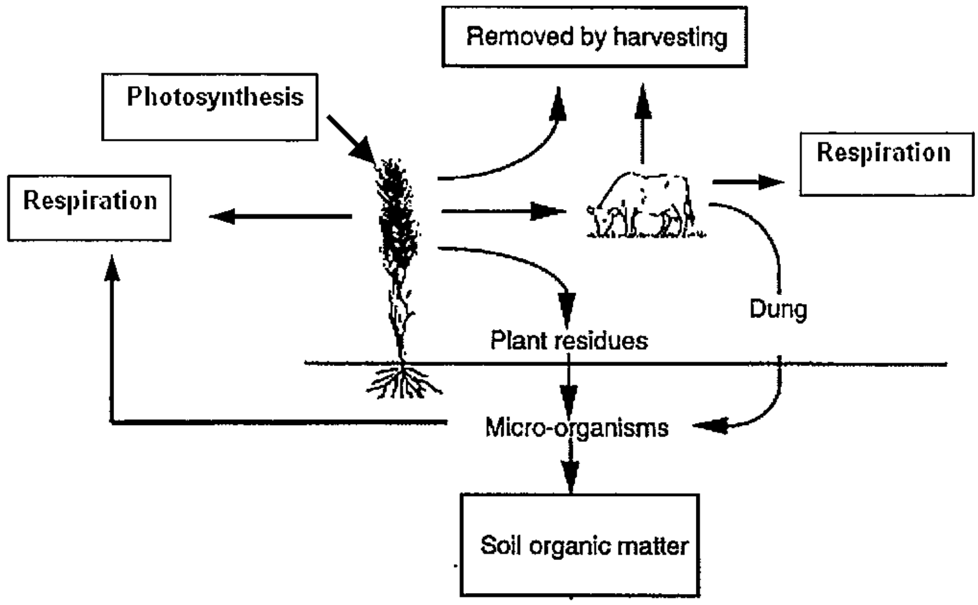
4.2 The carbon and nitrogen cycles

Soil fertility components, such as C and N, are transmitted (or cycle) through the atmosphere, plants, animals and the soil. There are organic and inorganic pools of C and N within the soil. It is valuable to understand these nutrient cycling processes for two reasons. First, an understanding of the processes provides knowledge of the timing and rate at which the nutrients become available to plants. Second, the nutrient pool concept implies that the components of soil fertility can be considered as stocks which can be influenced by management.

4.2.1 The carbon cycle

SOM is between 2 and 5% by weight of dry soil, and SOC comprises about 58% of SOM. Further, the C: N ratio for SOM in cropped vertosol soils is relatively stable at 10: 1. Therefore the process of building up SOM can be described in terms of the C cycle, as shown in Figure 4.3.

Photosynthesis occurs in plant cells containing chlorophyll, and involves conversion of carbon dioxide (from the atmosphere) and water into organic compounds (primarily carbohydrates) with the simultaneous liberation of oxygen. Plant residues are converted into microbial biomass and thence into humus (stable SOM). Animal dung also contributes C to the process.



Source: adapted from Stevenson (1979)

Figure 4.3. The Carbon Cycle

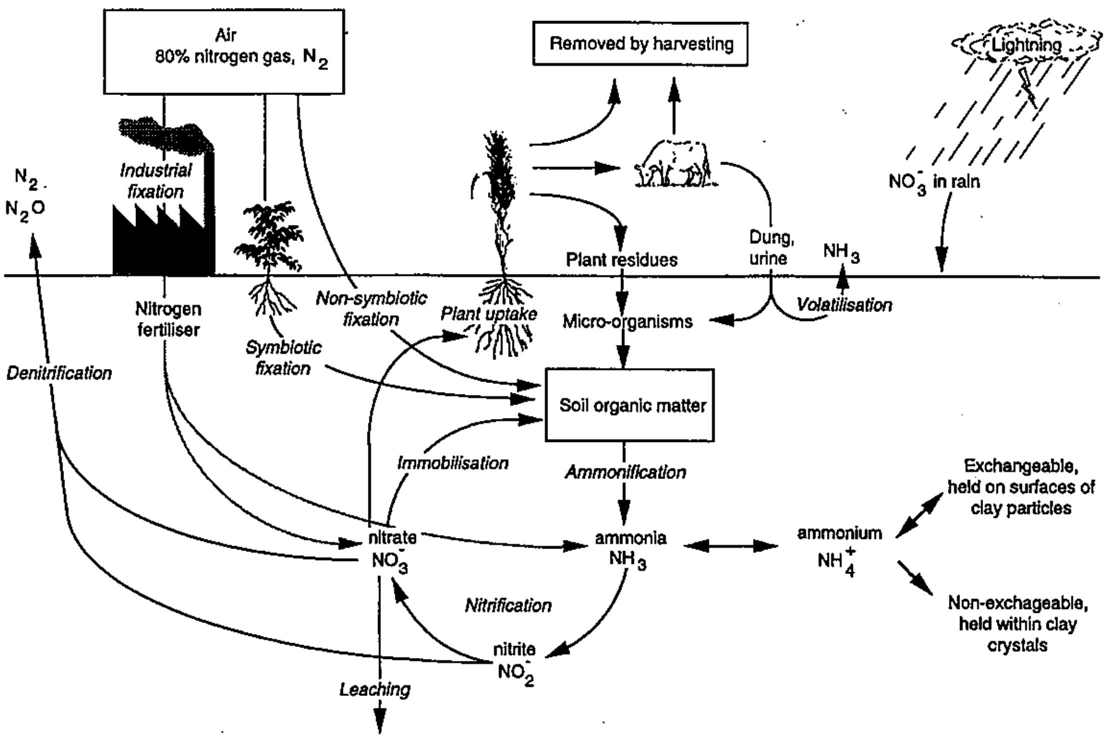
Loss of C (through respiration of carbon dioxide) occurs at several stages of the process. Carbon is also lost through physical removal of both plant and animal products. Due to respiration losses, the C component (and the C: N ratio) is much lower in SOM than in plants. The percentages of C and N in plant material are 40% and 0.5 - 3%, respectively.

The supply of plant residues is substantially influenced by crop production (frequency, time of year and amount) and crop management practices. These practices influence the size of the crop (amount of stubble and root material present), the retention and incorporation of stubble, and the disturbance of soil through cultivation for weed control. In general, the level of SOC in the soil is important as it affects nutrient supply and availability to crops and for other reasons such as water infiltration and water holding capacity. SOC levels can be influenced by soil and crop management practices.

4.2.2 The nitrogen cycle

Protein is vital to human and animal health, and N is essential not only for plant growth but also for the protein content of plants. N for crop growth is sourced from the atmosphere and the soil, and is also available from by-products of the petroleum industry (as synthetic fertilisers). The process of supplying soil N in forms available for plant growth is briefly explained in this section. The SOM and SOC contents of soils can be used as indicators of soil health or potential soil fertility, but they are not directly used by plants.

The N cycle (Figure 4.4) is an expansion of the C cycle to include processes by which the organic N within SOM is transformed into inorganic forms that are available to plants. Total soil N includes both the organic and inorganic forms. The N cycle also includes the fate of various forms of N and the supply of N fertiliser from external sources.



Source: adapted from Stevenson (1979)
Figure 4.4. The Nitrogen Cycle

Minerals in the organic form need to be transformed into inorganic forms (as cations which attach to clay particles, or as anions or water soluble amino acids) to be taken up by plants. Mineralisation is the general process whereby organic matter is converted into inorganic compounds. First ammonium (NH_4^+) and ammonia (NH_3), then nitrite (NO_2^-) and nitrate (NO_3^-) are generated by micro-organisms during mineralisation processes in the soil. Nitrate N is available for plant uptake, but it can also be lost through leaching down the soil profile and immobilisation back into SOM. The nitrates and nitrites can also be lost through denitrification back into the atmosphere.

The nitrate and ammonia compounds are also the basis for synthetic fertilisers derived from the petro-chemical industry. These are products such as anhydrous ammonia, urea, and ammonium nitrate. Another important source of N to crops is by N_2 fixation by legumes.

In Figure 4.4, the major input to SOM (from plant residues) can be reduced through growing smaller crops, cropping less often, stubble destruction and cultivation. This interruption to the N cycle appears to be a major factor in the total N percent decline in Figure 4.2.

4.3 Soil quality and soil health

Concepts of soil use have been discussed in terms of the value of soil for a specific function or purpose (Carter *et al.* 1997). In an agricultural context, soil quality is usually defined in terms of soil productivity (eg for crop growth). Therefore soil fertility is a part of soil quality. Gregorich and Acton (1995) defined soil quality as 'the soil's capacity or fitness to support crop growth without resulting in soil degradation or otherwise harming the environment'. More broadly the Soil Science Society of America (1995) defined soil quality as 'the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation'.

According to Carter *et al.* (1997), 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 (i.e. good quality soils can be degraded by poor soil management). They stated that the health of a soil very closely parallels soil quality. Soil health is mainly concerned with the balance and availability of plant nutrients, and freedom from plant diseases and pests. Thus, soil fertility is also a component of soil health. There appears to be no single measurement that can be used to quantify soil health (Sojka and Upchurch 1999). The soil fertility declines measured by Dalal and Mayer (1986a) relate to both soil quality and soil health according to these definitions.

4.4 Stocks of soil fertility

The declining trends in SOC and total N in Figures 4.1 and 4.2 occurred over a 'long' period of time. Dalal and Mayer (1986b) fitted trends lines to their data according to an exponential equation:

$$C_t = C_e + (C_0 - C_e)\exp(-kt),$$

where C_0, C_e and C_t are SOC concentrations initially ($t = 0$), at equilibrium (as $t \to \infty$), and after a cultivation period of t (years), respectively, and k is the annual rate of nutrient loss. They presented estimates of the equilibrium level of soil carbon C_e for each soil type. However, this calculation did not include any economic input, and was essentially a prediction of consequences if then-current management practices were continued.

The level of SOC or N in cropping soils is a stock that is used up or depleted by crop growth and harvest, and which can be replenished by management (section 4.2). The stock of soil fertility changes over time due to flows (both positive and negative) associated with management decisions and other external events. These flows occur during both the crop and subsequent fallow. One way of representing this is that the stock of SOC at time *t+1* depends on the level at time *t*, plus negative and positive flows resulting from management decisions and other factors (eg climate) in year *t*.

Uncertainties associated with the outcomes can be included. This 'stocks and flows' characterisation of soil fertility management is the basis for analysis in this thesis.

4.5 Soil management questions

Schwenke *et al.* (2001) studied grey Vertosol soils in northern NSW with different ages of cultivation, and considered how best to manage their varying soil fertility. They found that most of the differences in crop productivity between soils with different cultivation ages could be overcome by adding sufficient fertiliser N. Paddock age (as a proxy for soil productivity) was not a reliable indicator of potential productivity. Rather, yields were strongly related to N supply.

The question arises of 'how much' N to add and there have been attempts to develop an answer for wheat growers. N budgeting approaches (Lawrence *et al.* 1996, Martin *et al.* 1996) have been developed based on specifying a target yield and protein and then calculating protein lost with grain removal as a basis for N requirements. These approaches do not include any financial (price) considerations. Hayman (2001b) included prices and developed N recommendations based on expected biological and profit responses. Both these approaches are primarily concerned with the issues of crop inputs and outputs within a single crop and did not consider what happens in the intervening fallow.

In terms of soil fertility, Whitbread *et al.* (1998) stated that the SOM concentrations measured in their reference soils (representing the original soil status) were not necessarily considered as the optimum level. 'SOM concentrations at which favourable soil physical properties are maintained, nutrient supply capacity is optimised, and crop yields are stable and sustainable need to be identified' (p. 679).

In considering the fertility decline curves in Figures 4.1 and 4.2, a relevant question for soil fertility is whether and by how much would SOC and total N in cropping soils rise under optimal crop management. Dalal and Mayer (1986b) estimated equilibrium

SOC concentrations without including any consideration of better management practices. Farquharson *et al.* (2003) showed theoretically that it is possible to change the direction of SOC trends by adopting better management practices, but did not investigate how to achieve the best outcome.

There are two soil management questions to be investigated in this thesis, and they include agronomic, economic and soil considerations. Based on the discussion in this chapter, the first question will be of how much N to add for wheat production using an analysis that characterises soil available N as a stock to be managed from year to year. This will be an extension of Hayman's (2001b) analysis by considering fallow processes and a longer time frame, and provides a measure of an optimal stock of soil N for short-fallow wheat production. This will allow strategic and tactical management recommendations to be derived for N use for this crop, soil type and location. Such an analysis assumes that no other factors are limiting for crop growth.

This information will then be used in a second analysis of other management options (including stubble and tillage management) in crop production. The changes in SOC level are assumed to provide additional benefits via improved soil structure. An outcome of the analysis will be an optimal level of SOC for wheat production on particular soils. This sequential approach to analysing soil fertility management has not been attempted before.

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)). And there are other reasons why crop management that impacts SOM or SOC are desirable (eg control of pests, weeds and diseases). The specification of soil moisture properties in respect of SOM is discussed briefly in the next section and detailed in Chapter 8. The soil-agronomic simulation model used in this thesis accounts for the hypothesised benefits of improved soil water holding capacity (see next section).

In the analysis of N application the output from the bio-economic analysis (discussed in the next chapter) allows development of shadow prices or opportunity values of an extra unit of the stock of N in the soil. The shadow values provide interesting information for decision makers when evaluating the benefits and costs of investing in fertiliser for crop production.

4.6 Soil organic matter and soil properties

The organic matter content of soil is a vital attribute of soil quality that impacts soil aggregation and water infiltration (Franzluebbers 2002). SOM sustains many key soil functions by providing energy, substrates and biological diversity to support biological activity, which affects soil aggregation and water infiltration. Aggregation is important in: (i) facilitating water infiltration; (ii) providing adequate habitat space for soil organisms; (iii) providing adequate oxygen supply to roots and soil organisms; and (iv) preventing soil erosion. Infiltration is an important soil feature that controls leaching, runoff and crop water availability.

For the analysis of crop management strategies presented in Chapters 8 and 9 the impact of higher SOC levels was simulated using variations in soil water holding capacity. In this analysis, 'bucket size' varies directly with SOC content, and this has implications for crop growth. There is no published research on the likely size of such variations, so a set of figures was developed based on the judgement of soil and crop scientists.

4.7 Fertiliser replacement strategies

There is a debate in the soil science fraternity regarding the interpretation of soil tests and derivation of fertiliser recommendations for crop growth (Olsen *et al.* 1987). Historically, the sufficiency concept has been used, which involves 'fertilising the crop' according to likely crop response and associated nutrient removal. The alternative is a build-up and maintenance concept of 'fertilising the soil'; developed from the 'basic cation saturation ratio' (BCSR) which assumes that maximum yields can be achieved by creating an ideal ratio of calcium, magnesium and potassium in the soil (Eckert 1987). When fertilising the soil using BCSR, even with a high soil test additional nutrients are recommended to replace the amount likely to be removed from the crop to be grown (Olsen *et al.* 1987). There is evidence in the United States that public soil testing agencies (the universities) have generally used the sufficiency concept as a basis for making fertiliser recommendations, whereas the BCSR has been used by some private soil testing laboratories (Eckert 1987).

The approach developed in this thesis is akin to fertilising the soil. With respect to soil available N, the strategic approach involves development of an optimal stock together with tactical applications to maximise profits in any year. This is more than sufficiency (fertilising the crop), because there is an optimal stock of soil N to be achieved prior to the crop application. But it is not build-up and maintenance (fertilising the soil), since BCSR ratios are not the basis for developing the recommendations. For SOC, alternative tillage, stubble management and fertiliser strategies are evaluated and the optimal stock of SOC from an economic perspective is an additional output.

An objector to this approach might ask:" Why not just measure soil N each year and use decision analysis to find the optimum input level?" The advantage of setting the problem in a dynamic economic framework is that the trade-offs between fertiliser application and crop responses in the present, and possible carryover effects into the future are accounted for. These carryover effects may or may not be important for the best decision strategy; this will be tested in the analysis. But the development of an optimal stock of soil nutrient is a natural outcome from the fertilisation problem being considered in a stock and flow context. The optimising solution also provides extra economic information which may be useful in considering crop and soil fertility management strategies.

5. Economic methodology

Many problems of natural resource management involve biological and other stocks that can be built up and depleted through usage over time. This characteristic has implications for economic analysis of resource management strategies, since some of the benefits and costs of current actions can be felt in future periods. When there is no relationship between decisions in the present and impacts in the future (i.e. decision periods are separable), static production economic theory is applicable. When decisions in the present have impacts in the future, dynamic economic theory can be used to determine optimal decisions. Dynamic models incorporate feedback, i.e., they include information flows between decision variables and outcomes over time. In this chapter the economic theory and methodologies for considering these issues and conducting appropriate analysis are reviewed.

5.1 Static production theory

To determine the use of an input u in producing output y, a concave, continuous and differentiable production relationship *y(u)* is assumed (see Figure 5.1), with input and output prices of p_u and p_y respectively. Diminishing returns are considered to apply, so that $dy/du > 0$ and $d^2y/du^2 < 0$. France and Thornley (1984) have noted that many biological relationships are of this form. This production relationship is a biological or biophysical constraint, which specifies the production potential of the firm. The optimal static input level to maximise profits, π is derived from:

$$p_y dy/du = p_u. \qquad (5.1)$$

In Figure 5.1, the optimal input level associated with (5.1) is u^*, where marginal revenue equals marginal cost of the input along the production function. The production-maximising level ($u_{\max}$) is also shown.

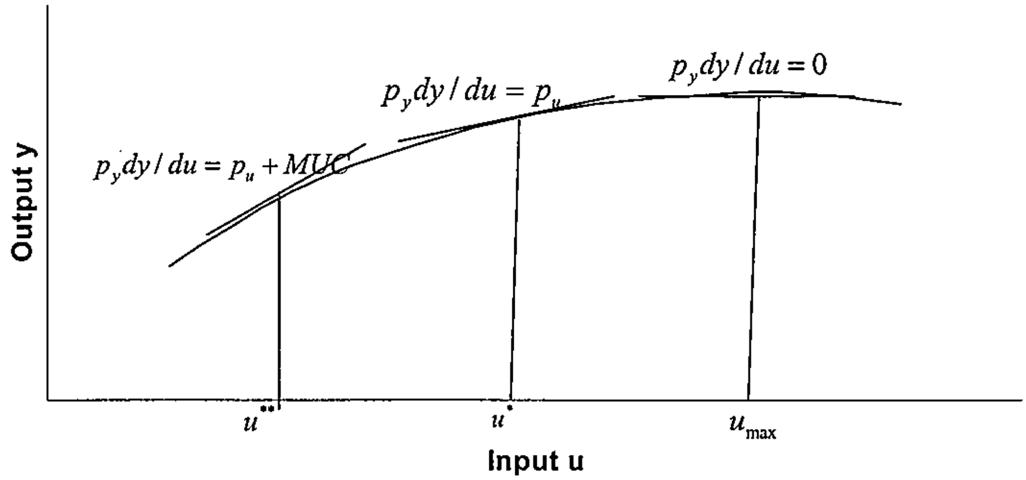


Figure 5.1. Optimum production economic input levels

5.2 Optimal control theory

Dynamic production theory focuses on a system which a decision maker wishes to optimise over a period of time (t). The manner in which the system changes through time can be described by specifying the time behaviour of a variable x_t, which is defined as a state or stock level variable.

Also, there exists a control variable, u_t which determines the path of the state variable through time. In economic problems, a control variable is usually represented as a rate variable, such as an investment rate, consumption rate of a good, or the harvest rate of a resource. The control variable may govern the rate of change of the state variable, rather than its level. The dependence of the state variable on the control variable is described by a first order differential equation, called the state equation or equation of motion:

$$\dot{x} = x_{t+1} - x_t = g(t, x_t, u_t), \tag{5.2}$$

where $\dot{x} = dx_t / dt$ is the continuous-time, and $x_{t+1} - x_t$ the discrete-time, expression for the change in stock level. The relationship *g(.)* assumes that no stochastic events influence the rate of change in the stock. The rate of change in stock level from year *t* to year *t+1* is determined by current stock levels and control decisions.

The typical optimal control problem involves the maximisation of a functional *J[.]* which is determined by x_t and u_t. *J[.]* is a functional, because it depends on a path x_t, rather than individual values of *x* (Chiang 1992). Annual profits are now represented by a function $f(t, x_t, u_t)$. The problem is to maximise, by choice of u_t, the sum of annual profits over the period *0* to *T*. With the time subscripts dropped from *J[.]*, *f(.)* and *g(.)* the problem is:

$$\underset{u}{Max}\, J[x, u] = \int_0^T f(t, x, u)dt, \qquad (5.3)$$

subject to $\dot{x} = g(t, x, u)$,

and $x_0 = \bar{x}$, $x_T = \bar{x}_T$ with $\bar{x}$, $\bar{x}_T$ known constants.

This optimisation problem is solved by writing a Hamiltonian function *H*:

$$H(t, x, u, \lambda) = f(t, x, u) + \lambda\, g(t, x, u), \qquad (5.4)$$

where λ, the adjoint or costate variable, is an unknown (to be determined) function of time.

Pontryagin *et al.* (1962) showed that the necessary conditions for solution of this function are found by differentiating the Hamiltonian with respect to the control, state and costate variables as shown:

$$\partial H / \partial u = \partial f / \partial u + \lambda \partial g / \partial u = 0 \text{ or } H_u = 0 \qquad (5.5a)$$

$$\lambda_{t+1} - \lambda_t = -\partial H / \partial x = -[\partial f / \partial x + \lambda \partial g / \partial x] \text{ or } \dot{\lambda} = -H_x \qquad (5.5b)$$

$$x_{t+1} - x_t = \partial H / \partial \lambda, \text{ or } \dot{x} = H_\lambda \text{ with} \qquad (5.5c)$$

$x_0 = \bar{x}$ also required.

If there is optimal control of u (optimal time path) for (5.3), and a corresponding response in the stock, the Pontryagin Maximum Principle asserts the existence of a costate variable, λ, such that the equations in (5.5) are satisfied identically for all t in the interval $[0,T]$. The state variable must also satisfy any initial and terminal conditions.

Equation (5.5a) is referred to as the Maximum Principle, equation (5.5b) is known as the costate or adjoint equation, and the state equation is restated in (5.5c).

The optimal dynamic input level, equivalent to (5.1), is derived from (5.5a):

$$p_y dy / du = p_u - \lambda \partial g / \partial u, \qquad (5.6)$$

where λ is the current value to the profit objective of an extra unit of the stock.

5.2.1 The Marginal User Cost

Condition (5.6) requires that the input be used where marginal revenue equals marginal cost, which now includes the value of the change in stock at the start of the next decision period. This has been termed the marginal user cost (MUC) (McInerney 1978).

In considering the MUC, the expectation is that $\partial g / \partial u < 0$ since using a unit of the stock as an input to production in the current period means that there is one less unit in the next period. The costate variable λ is the shadow or implicit price of a marginal unit of the stock, and $\lambda \geq 0$ is assumed since the decision maker would never lose from having an extra unit of a beneficial stock. If $\partial g / \partial u < 0$ and $\lambda > 0$ then $-\lambda \partial g / \partial u > 0$ and the marginal user cost is positive. Therefore marginal costs in the dynamic case are greater than the static case and the dynamic optimum u^{**} will be less than u^{*} (Figure 5.1). However, the stock may be a 'bad', such as weed seeds or insecticide resistance, in which cases the relativity between optimal input levels may be reversed.

This standard result is from optimal control theory (Chiang 1992, Conrad and Clark 1987, Lambert 1985, Pontryagin *et al.* 1962). Associated with (5.6) is an optimal path of the stock from an initial level $x_0 = \bar{x}$ according to decisions u^{**}. One of the necessary conditions for solution of the optimal control problem (5.5b) asserts that along the optimal path the change in marginal value of a unit of the stock at any point in time is the sum of the stock's marginal contribution to profit and its marginal contribution to the enhancement of the future value of the stock.

Control theory gives optimality conditions that are valuable for interpretation, but the continuity and differentiability assumptions are often violated when considering specific agricultural and natural resource problems. Methods of solving dynamic optimisation problems are discussed next, and one allows solving problems when these assumptions are violated.

5.3 Solving dynamic optimisation problems

Kamien and Schwartz (1991) detailed three methods of solving dynamic optimisation problems - calculus of variations, optimal control and dynamic programming (DP). Calculus of variations is analogous to classical calculus in its area of applicability. It can be most easily applied when all the functions described are smooth, continuous and differentiable, and when the optimum is strictly interior to the feasible region. Optimal control is the modern extension of the classical theory of calculus of variations that allows for inequalities in the constraints (Kamien and Schwartz 1991, Chiang 1992). It is applicable to those instances when all the functions are smooth, continuous and differentiable, but the technique can also accommodate boundary or corner solutions. Kamien and Schwartz also note that DP is a generalization of both methods.

Generally a model expressed in terms of a system of differential equations may not have an analytical solution and must be solved numerically (Cacho 1997). This process involves: (i) assigning initial values to all state variables; (ii) determining the rate of change of the state variables by solving each differential equation; (iii) estimating the value of the state variables for the next time period, and; (iv) repeating steps (ii) and (iii) for the desired time horizon. Optimal control models may be solved numerically, but difficulties may arise due to the nature of specific models. The solution to DP models involves breaking the problem into a series of smaller sub-problems and repeating solution of the recursive equation (Cacho 1998). Optimal control models may also be solved by redefining them as non-linear programming models with state and control variables in each time period defined as activities and specifying the equations of motion as non-linear constraints linking variables across time periods. The solution method chosen in this thesis was DP.

5.4 Dynamic Programming

DP is a more general approach than optimal control because it does not rely on relationships being concave, continuous, smooth and differentiable, and it can accommodate stochastic events. Kennedy (1986, 1988) has illustrated the principles of dynamic optimisation applied to the management of agricultural and natural resource problems in Australia. He also discussed the types of problems that require dynamic versus static methods of solution. The dynamic programming methodologies outlined here are the deterministic finite-stage and the stochastic infinite-stage formulations.

5.4.1 Deterministic dynamic programming

Kennedy (1988) explained the resource problem in terms of harvesting a fish resource. In more general terms, the problem is to determine the control decision over time periods denoted by $t = 1, \ldots, T$. Given decisions (u_t) and output $y(u_t)$, the problem is to choose the decision in each period to maximise the net present value of returns.

The net return in each period is $f_t(x_t, u_t)$, and after the final period there may be a value of the terminal stock, $F(x_{T+1})$. The net period or stage return is:

$$f_t(x_t, u_t) = p_y y(u_t) - c_t(x_t, u_t), \tag{5.7}$$

where $c_t(x_t, u_t)$ is the cost of deriving the output, which may depend on both the decision made and the level of the stock. The change in stock of the resource from one period to the next (the transformation function) is given by:

$$x_{t+1} = x_t + g_t(x_t, u_t), \tag{5.8}$$

where $g_t(x_t, u_t)$ includes net autonomous growth in the stock as a result of natural processes and any reduction due to management actions.

The Markov property (Howard 1971) is assumed to hold, so that the decision system is fully described at any stage t by the state in the previous stage, hence x_{t+1} and f_t depend only on x_t, u_t and any exogenous variables in stage t (Kennedy 1986).

The optimal control problem is expressed as:

$$\max_{u_1,\ldots,u_T} \sum_{t=1}^{T} \rho^{t-1} f_t(x_t, u_t) + \rho^T F(x_{T+1}), \tag{5.9}$$

where $\rho = 1/(1+r)$ is the discount factor and r the discount rate, and also subject to (5.8) and any initial state information ($x_1 = \bar{x}$).

The corresponding DP recursive equation is:

$$V_t(x_t) = \max_{u_t}[f_t(x_t,u_t) + \rho V_{t+1}(x_t + g_t(x_t,u_t))] \quad (5.10)$$

with $V_{T+1}(x_{T+1}) = F(x_{T+1})$ and $x_1 = \bar{x}$. (5.11)

Equation (5.10) is recursive because determining $V_{t+1}(x_{t+1})$ enables $V_t(x_t)$ to be determined. This also reflects Bellman's Principle of Optimality; that whatever the initial state and initial decision the remaining decisions must constitute an optimal policy for the state resulting from the first decision (Kennedy 1986, Chiang 1992).

The problem is subject to the transformation function (5.8). In the two applications presented later the function g(.) is represented by output from a simulation model.

Kennedy (1988) showed that if (5.8), (5.9) and (5.10) in the deterministic dynamic programming formulation are differentiable, then optimality conditions analogous to the optimal control necessary conditions can be derived.

5.4.2 Infinite-stage dynamic programming with discounting

If the stage return (5.7) and transformation function (5.8) are the same at all stages, then the problem is stationary. Kennedy (1986) noted that for many stationary problems there is a decision horizon of n'' decision stages which exhibits a state-decision profile which is the same as for any stage beyond n''. If the state-decision profile remains the same as n'' increases to infinity, then it is known as an infinite-stage decision vector. The decision process in this case will lead to a constant stream of finite returns. This is because the present value of the infinite stream of finite stage returns converges to a finite sum for any positive discount rate (Kennedy 1986).

5.4.3 Stochastic dynamic programming

Following Kennedy (1986), varying the basic model in (5.9), (5.10) and (5.11) to a stochastic dynamic programming (SDP) formulation results in a more realistic case, where outcomes are subject to random fluctuations.

Often the decision problem is characterised by the state transformation and the return function being dependent on unpredictable factors. When the only unpredictable events affecting the state transformation and stage return at t are those occurring at stage t, the problem can be formulated as a stochastic dynamic programming problem without additional state variables. The objective in this case is changed to one of maximising the present value of expected stage returns, although this involves an assumption that the decision-maker is risk neutral.

Denoting the stage return and state transformation functions as $f_t(x_t, u_t, k_t)$ and $g_t(x_t, u_t, k_t)$ respectively, and $p_t(k_t)$ as the probability that the random variable in stage t takes on the *k-th* discrete value, the recursive equation for the SDP model is:

$$V_t(x_t) = \max_{u_t}[\sum_{k=1}^{m} p_t(k_t)(f_t(x_t, u_t, k_t) + \rho V_{t+1}(g_t(x_t, u_t, k_t)))], \qquad (5.12)$$

subject to:

$$x_{t+1} = x_t + g_t(x_t, u_t, \varepsilon_t)$$

$\sum_{k=1}^{m} p_t(k_t) = 1$, and (5.11).

A stochastic element ε_t is now added to (5.8). The recursive solution of (5.12) yields $V_t(x_t)$ and the optimal decision vector $u_t*(x_t)$ for $t = n, \ldots, 1$.

This SDP approach will be used to solve the numerical models specified in the next chapters. This approach is required when uncertainty is introduced into biological processes by climatic patterns and events. Uncertainty may affect both the stage return and the state transformation function.

The use of SDP to assess natural resource management issues (such as soil fertility decline) 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 ((5.7) and (5.8)) are stationary. Given these assumptions, the representation of the state transformation function in the stochastic case is by a state transmission matrix, which is discussed in the next section.

5.4.4 The state transmission matrix

At each stage of the decision process there are a certain number m ($j = 1, \ldots, m$) of possible states for the resource stock (Kennedy 1986). For each state there may be d possible decisions. Given the stationarity and Markov process assumptions, for each d there will be an $m \times m$ transformed-state matrix which will apply in all stages. Each row of this matrix shows for a stock level m_j in stage t, the probabilities of the stock being in any other state m in stage $t+1$. These probabilities $p_t(j_t)$ sum to unity across each row. Biological simulation models which generate results over extended time frames using weather data as inputs can provide the information required to specify such transformation matrices, which are also called transition probability matrices.

5.5 Implications for resource use decisions

Given the characteristics of natural resource use noted in earlier chapters, and the requirements of microeconomic analysis, the use of dynamic optimisation methods (with bio-economic representations) is suitable for investigating optimal long-term resource use in 'sustainable' production systems. The use of such approaches should provide a basis for analysing and promoting more long-term-efficient agricultural production systems.

6. The Nitrogen Model

6.1 Introduction

Soil fertility decline for wheat growers using fertile northern NSW soils has been identified as important, and a two-stage analysis was identified in Chapter 4 to address this issue. The first response is simply to add synthetic N to improve crop growth, since N is the most important nutrient deficiency on these soils. This analysis will determine how much N to optimally add, if no other soil factors are limiting. The second approach is to broaden the management scope to include tillage and stubble management which encompasses other issues of concern to crop farm managers. These include reduced tillage in mitigating erosion, fallow weed control for soil moisture conservation, and stubble retention to improve soil structure. There is evidence that wheat growers are now adding more N to crops, and one economic question for management is 'how much' N to add. A second question is whether stubble and tillage management (in addition to fertilisation) further improve soil and crop outcomes. Both these questions will be evaluated in this thesis.

In this chapter and the next, the question of how much N is optimal will be addressed to develop strategies and tactics for crop fertiliser management. This information will then be used as input to the C analysis in Chapters 8 and 9, where stubble and tillage management are assessed with the optimal fertilisation strategy to assess crop production in terms of sustaining soil fertility. In this chapter the model to be used for the N question is developed. This has both biological and economic components and accounts for the particular nature of wheat crop outputs and the crop-fallow sequence.

Another possible response to soil fertility decline is to change the crop, in particular to grow legumes which have the ability to fix N from the atmosphere into the soil. This option has not been analysed here for two reasons. First, although legumes are relatively profitable they have not yet been widely adopted due to potential disease problems impacting on crop yields. Wheat is still the major crop grown in the region. Second, the investigation is undertaken to illustrate the method and show the types of output from a dynamic bio-economic analysis for farm management. Once the method has been established for wheat it can be applied to other crops.

An overview of the modelling approach used for the N analysis is presented in Figure 6.1. Specifics of this approach are further developed in this chapter.

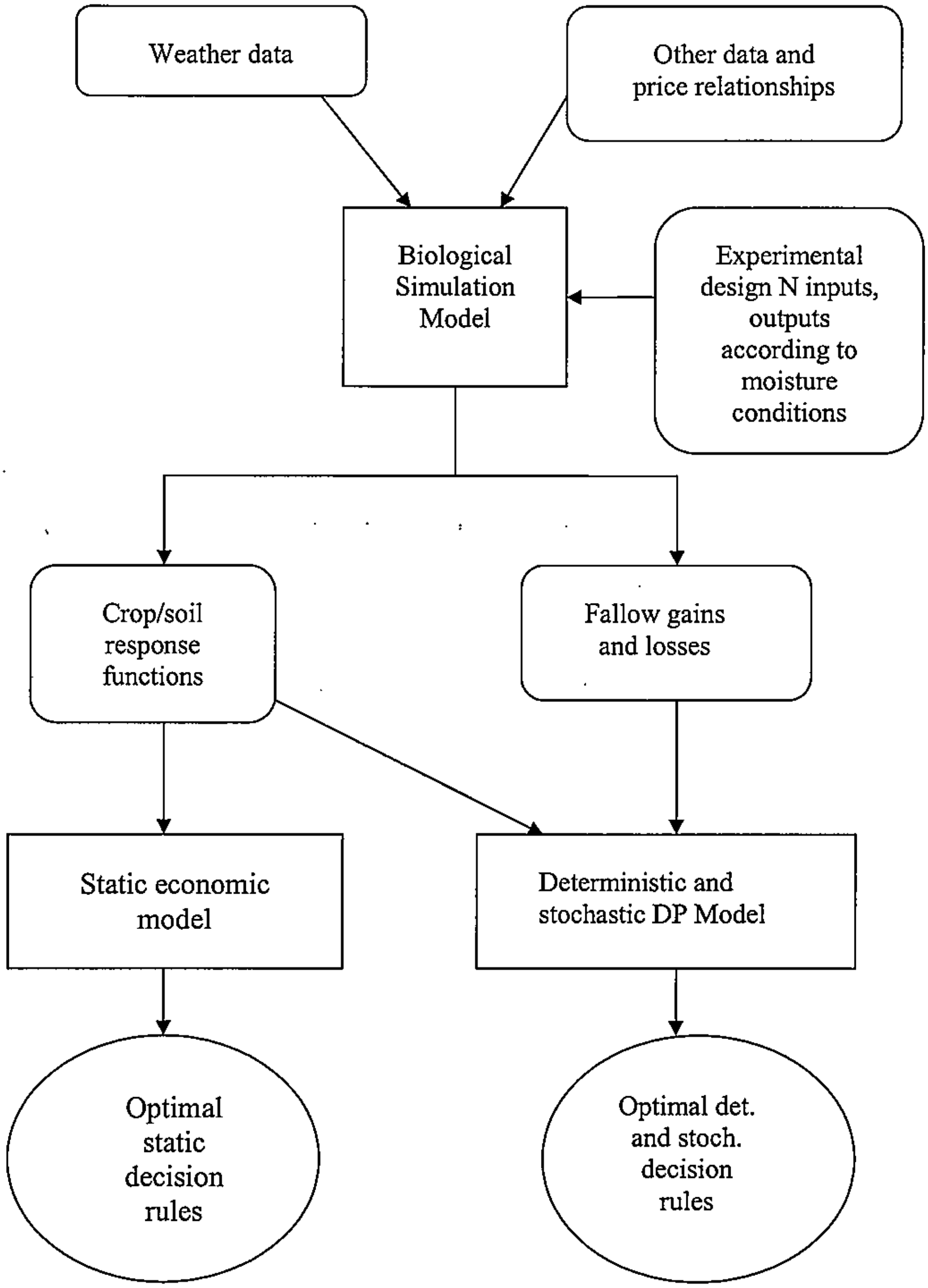


Figure 6.1. Interaction between biophysical and economic models for N analysis

6.2 Production economics considerations

The response of wheat to added N presents some departures from the standard theoretical economic case. In this section and the next, a review of the literature is used to show how these departures can be represented in developing an analytical model for estimation purposes.

6.2.1 Functional forms

Responses of the diminishing-returns type are common in biology and elsewhere (France and Thornley 1984). Economic theory generally posits production functions that are concave, smooth, continuous and differentiable (eg Mas-Colell *et al.* 1995), allowing algebraic derivations of optimality conditions. However, an alternative representation of yield responses to incremental nutrients based on soil and plant science theory was proposed by Lanzer and Paris (1981). For the case of one variable nutrient, they characterised yield response in terms of a maximum attainable yield parameter and a relative yield response function. The resulting function exhibited a yield plateau whose position depended on soil and weather characteristics. For more than one nutrient, the lack of substitutability between nutrients (based on von Liebig's 'law of the minimum') led to the development of a linear response and plateau (LRP) function (Perrin 1976).

There has been debate about crop response functional forms between the agronomic (LRP) and economic (smooth concave functions) points of view (eg Ackello-Ogutu *et al.* 1985). There are implications from this choice for the shape of the response function and the degree of substitutability between two or more nutrients. Berck and Helfand (1990) resolved the issue by illustrating that the effects of spatial variability in soil conditions (across a field) and temporal variability in crop planting and flowering dates resulted in an LRP form for individual plants and a concave response in the more general case.

In their estimation of wheat responses to nitrogen in Brazil, Lanzer and Paris (1981) used an algebraic (Mitscherlich) function. Paris (1992) compared the Mitscherlich-

Baule specification with the quadratic, linear von Liebig, square root and the nonlinear von Liebig (which allows for the possibility of factor substitution, eg between a nutrient and water). He found that the nonlinear von Liebig model outperformed other specifications using a dryland corn production dataset. However, when Llewellyn and Featherstone (1997) compared crop production functions using simulated data for irrigated corn in western Kansas, they found that the Mitscherlich-Baule function was favoured over other specifications (including the linear and nonlinear von Liebig forms). The costs of incorrectly using this functional form were relatively low. An interesting insight from their analysis was that optimal N levels derived from simulated crop responses were generally higher than levels found using experimental yield data.

Some recent investigations of representing yield responses have considered both functional forms and estimation methods. Berck et al. (2000) tested a generalized von Liebig production function on corn and wheat data, and found that it did not fit the data better than an unrestricted regression. A second problem with this form was that the dominant likelihood estimate did not exhibit square isoquants. Ananda *et al.* (2001) tested a Mitscherlich-Spillman type of function to investigate yield damage functions in considering erosion damage under tea production in Sri Lanka. Holloway and Paris (2002) also tested the von Liebig hypothesis against five samples of experimental data and applied recent advances in Bayesian techniques. This indicated a promising way to tackle a difficult estimation problem as that represented by a von Liebig model.

6.2.2 The importance of fallows

In general crop production does not involve continuous use of the soil all year round; rather a fallow or rest period is involved. Even in the northern cropping regions of Australia where rainfall and temperature conditions potentially allow both winter and summer cropping, a fallow is generally required to replenish soil moisture for dryland (rainfed) crops. The other major activity in northern fallows is nutrient mineralisation and other processes which allow build-up of soil N prior to the next crop. As stated in Chapter 4, the soil fertility question can be expressed as a stocks and flows problem.

6.2.3 Implications of theory

In terms of economic theory, the main question considered in this N analysisr is whether, and if so, by how much, the static and dynamic optimum input levels differ for the management alternatives discussed. In an applied management context, the question is whether optimal strategies and tactics for N applications differ between static and dynamic analyses, in other words whether the difference is enough to be concerned about. The answers are likely to depend on the shape of the response and carryover functions, on how they move with climatic conditions, and on the nature of output and input price relativities. In the past, questions of the 'flatness of economic response' issue have related to the magnitude of the difference between the production-maximising and the static profit-maximising input levels (Anderson (1975), Perrin (1976), Pannell *et al.* (2000) and Hayman (2001a)).

6.2.4 Practical outcomes for management recommendations

There is an important advantage when considering the N-fertility question as a stocks-and-flows problem and then using dynamic methods to obtain a solution. The result of such an analysis is development of an optimal stock of soil N over time. If the actual level of soil N can be determined at sowing (for instance by soil tests and/or N budgeting), then the N decision becomes one of simply applying the difference between what is measured in the soil and the optimal stock. The N strategy would be to aim for the optimal stock at each planting/fertilising decision, and the tactic is to measure soil N fertility in any year and apply enough fertiliser to make up the difference. This approach is not currently used and the information from such analysis could be beneficial when developing improved practical management recommendations.

6.3 Previous analyses of input levels when carryover is important

An early example of this type of analysis was presented by Kennedy *et al.* (1973), who considered optimal fertiliser application for a tropical grain crop by using deterministic dynamic programming to develop optimal management strategies. Following this theme, Stauber *et a*l. (1975) developed an economic model to determine optimal nitrogen fertiliser policies for seeded grasses in regions where nitrogen carryover was significant, and they used a stochastic dynamic programming framework. In Australia, the question of determining optimum fertiliser input levels was debated by Helyar and Godden (1977), Battese (1978) and Helyar and Godden (1978). The issues related to biological response functions, residual fertiliser effects in future decision periods, and incorporation of stochastic effects. The suitability and correct use of dynamic programming for this issue was set out by Kennedy (1981), who noted that, in the dynamic optimisation context, the optimal level did not depend on parameters relating to periods beyond the next period.

More generally, Lanzer and Paris (1981) developed a model to analyse fertility recommendations based on Liebig's Law of the Minimum, Mitscherlich's relative yield theory, and the notions of yield plateau and soil fertility carryover. They noted the necessity of making fertiliser recommendations based on a dynamic framework, because of the carryover effects.

The optimality conditions were derived algebraically by Taylor (1983) under two assumptions: that fertiliser carryover is agronomically equivalent to applied fertiliser; and that some addition of fertiliser is optimal in every decision period. He demonstrated that stochastic problems involving optimal fertiliser application rates can be simplified to static certainty equivalent problems. Kennedy (1988) derived the dynamic optimality rules by backward induction.

Other analyses of fertiliser applications have involved the environmental side effects of N use in agriculture. An example of extending the determination of optimal fertiliser use to include impacts on groundwater contamination was given by Yadav (1997). Zhu et al. (1993) used a multi-objective dynamic programming model to evaluate agricultural management strategies as they impacted on N loading in Chesapeake Bay. Another example is the study by Blomback *et al.* (2003) of the use of catch crops (normally a grass species) during fallow to take up N during the most leach-prone periods. The introduction of this technology has been driven by Swedish and European legislation concerning N leaching.

In this chapter a stochastic dynamic programming approach similar to that of Stauber *et al.* (1975) was used. The crop response exhibits a yield asymptote, but no eventual decline that might be associated with 'haying off' of the wheat crop. The agronomic issue of haying off occurs when a crop is planted but then runs out of water in spring as crop water demand rises with air temperature. If there is a large amount of N in the soil this may promote early crop growth, but when water becomes limiting the crop may die (or hay off). The climatic requirements mean that this will happen more often in the western (hotter) part of the region. On the Liverpool Plains (Gunnedah) and with high water-holding soils (Vertosols) this is very unlikely to occur because of the longer cooler season for growing wheat.

The particular characteristics of production and price responses imply that Taylor's (1983) certainty equivalence representation does not apply. Wheat production has two outputs – yield and protein content, with the latter being the major quality measure for price received by farmers. There is also evidence that the quality responses to added N may not be concave. Yield and protein content also interact with climate. Therefore the response of wheat to added N in Australia can be represented by a multi-output production function with important stochastic influences during the growing season, and for which the price rises with quality. These characteristics give the analysis a distinct flavour.

6.4 Utility maximization

Figure 5.1 showed that, theoretically, there may be different optimal input levels when the objective is to maximise: (a) production; (b) profits in the short term (without carryover); and (c) net present value or wealth in the longer term (with carryover). Another question is whether a further adjustment should be made to account for risk aversion by the decision-maker.

Inclusion of risk aversion into stochastic dynamic programming models was debated by Krautkraemer *et al.* (1992) and Kennedy *et al.* (1994). More generally, Pannell *et* *al.* (2000) queried the incorporation of risk and uncertainty into analyses by agricultural economists.

Anderson (1989) and Hardaker *et al.* (1997) discussed the issue of 'when does risk aversion matter?' and concluded that for many 'small' decisions, in a whole-farm context, the utility function might be approximately linear. To help assess this question, Hardaker *et al.* (1997, p. 233) extended Anderson's (1989) quantitative assessment for whether risk aversion matters. A formula was developed for a proportional risk deduction for a 'new' source of risk in a whole-farm plan with an existing background level of risk. This deduction depended on a number of factors, including:

(a) the coefficient of relative risk aversion of the decision-maker;
(b) the coefficient of variation of the returns from existing and new enterprise;
(c) the relative size (in expected value terms) of the new management practice relative to existing activities; and
(d) the correlation coefficient between existing and new enterprises.

The question of nitrogen application to wheat is not a new question for a new enterprise, and so the impact of these factors is lessened. Hayman and Alston (1999) found that grain growers had substantially increased their nitrogen application rates in the period 1992-1997, so the idea of changing fertilisation rates is not new to these growers. A change in N application rates for wheat is likely to vary the mean wheat returns (see Chapter 7). Information on comparative variability of wheat returns was not included in the biological simulation model results. The question of possible increased variance in returns is difficult to determine because the optimal N decision rules developed in Chapter 7 are sensitive to levels of soil moisture at sowing. In view of these factors no analysis incorporating risk aversion into decision-making preferences was conducted for this evaluation.

6.5 Production relationships

The most important nutrient input for growing wheat on Vertosol soils in northern (summer rainfall dominant) Australia is N (Angus *et al.* 1993). The basis of the analysis is that wheat output will have an expected or predicted response as N, or any other input, is added incrementally and all other factors held constant. The response to added input can be written (after Lanzer and Paris 1981) as:

$$y = f(W, S, X \mid G, O). \tag{6.1}$$

Here y is output, W is a vector of weather variables, S a vector of soil types, X a vector of total supply of macronutrients, G a vector of genetic load and O a vector of other factors (eg plant density). In this chapter, the analysis is of one particular soil type, while incorporating W according to rainfall and temperature patterns at planting and during crop growth and subsequent fallow. The amount of a particular nutrient available to the crop is denoted by x, assuming that other macro- and micro-nutrients are non-limiting. As did Taylor (1983) and Stauber *et al.* (1975), the assumption is made that nutrients applied are the same as those already in the soil, so that:

$$x \equiv B + u, \tag{6.2}$$

where B is the supply of N already in the soil and u is the level of N fertiliser application. The level of B is influenced by the inherent fertility of the soil, but, on a year-to-year basis, it is also determined by carryover from one period to the next. This carryover is incorporated explicitly in the analysis as explained in the next section.

An added complexity in the case of wheat is that there are at least 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, that is they cannot be expressed as the sum of separate functions of input variables (Anderson *et al.* 1977). Nor are they priced and sold separately. Smith *et al.* (2003) analysed N input use when inputs affect wheat price and yield. They used econometric estimation of production responses to determine optimal input levels but did not account for carryover effects. Therefore equation (6.1) must be expressed as a multi-output production function:

$$(y_1, y_2(y_1)) = f(.). \tag{6.3}$$

The level of screenings (per cent of small grain) has recently become more important because the Australian Wheat Board (AWB) has included it, as well as protein, in the price-selling grid. The impact of this change has been to reduce the large price falls (the so-called 'cliff faces') under the previous pricing policy when screenings rose above 5%. Large price differences between grades based on protein content have also been eliminated. The issue of incorporating screenings has not been addressed here because the simulation model used does not predict it, but the new price schedule (based on protein content for a given level of screenings) is used. Although a drier finish to the crop year would be associated with higher protein levels, which are also likely to be associated with higher screenings percentages, the graduated screenings grid and the size of the price discounts are unlikely to have a large impact on these results.

Given the dynamic characteristics of the problem, the focus here is on assessing the optimal level (or optimal stock) of total plant available N (x^*) in the soil in a wheat-fallow sequence. The management decision (how much fertiliser to apply for a wheat crop) is denoted by u^* and it, in conjunction with prior carryover B, determines this optimal stock level x^*.

6.6 Soil nitrogen dynamics and carryover

To represent carryover of soil N fertility from one crop season to the next the crop year is defined to consist of a crop period, of about 6 months, followed by a fallow of 6 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 prior to the biological simulations at 63 mm, 97 mm, 124 mm, 180 mm and 222 mm, which were considered to represent very dry, dry, medium, wet and very wet soil conditions after fallow (Dr. J Turpin, Agricultural Production Systems Research Unit, personal communication). 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 soil N outcome after harvest, at the end of the in-crop period, (x_H) depends on the level of total soil fertility at the start of the crop year (x_t), on the fertiliser input used u_t, on crop outputs, and on *ICR*. Therefore:

$$x_H = g(x_t, u_t, ICR_t, y_{1t}, y_{2t}) . \qquad (6.4)$$

The crop outputs (y_1, y_2) from equation (6.3) also depend on *SM*, which is included within *W* in equation (6.1). The simulation results were generated for different levels of both SM_t and ICR_t. Rather than introduce a separate state variable of FR_{t-1} to represent planting soil moisture in equation (6.4), the model was specified for different levels of *SM*, as explained above.

There are a number of underlying physical and biological processes that make up the relationship *g(.)* in equation (6.4) during the crop period. These are treated in detail within the simulation model, but are not discussed here. Estimates of x_H from the simulation model were used in the analysis.

Changes in mineral N over the subsequent fallow period were also estimated (Dr. J Turpin, personal communication). Fallow losses were assumed to be 10% of x_H, based on the opinion of the soil scientist. Fallow gains or net mineralisation (FM_t) were calculated from the simulation model results. They were estimated to be 17, 27, 30, 33 and 40 units of mineral N depending on the *FR* conditions after crop harvest, and these amounts relate to the 10^{th}, 30^{th}, 50^{th}, 70^{th} and 90^{th} percentile fallow climate *FR* outcomes, respectively. These outcomes are termed very poor, poor, average, good and very good fallow scenarios, similar to *ICR*. The FM_t numbers are soil specific, but averaged over the crop-stubble residue loads. The relationship between soil available nitrogen at consecutive sowing periods depends on both in-crop and fallow climate patterns during the crop year, and is of the general form:

$$x_{t+1} = 0.9x_H + FM_t(FR_t). \tag{6.5}$$

There are potentially a very large number of outputs from the simulation model. For each of the five *SM* categories at sowing, there are five yield, protein and nitrogen-after-harvest response functions, according to *ICR* categories. Each response function is specified over ten levels of total soil N availability. In addition the changes in stock of soil N in the subsequent fallow vary according to *FR* category. A total of 125 different response surfaces for each of the three variables of interest were generated to represent variability in the cropping system.

6.7 Price relationships

The analysis in this thesis uses price schedules that attract premiums for protein content (see Figure 6.2). The wheat varieties grown in the case study location (generally Australian Hard or Australian Premium White) are grown for their premium characteristics; hence the use of these price schedules is appropriate.

A further complication in this model is that the price of wheat (p) depends on its protein content. The wheat price (expressed in \$/tonne) is applied to the wheat yield, but it is based on quality attributes (predominantly protein content, but also screenings level). This price schedule is related positively to protein content. In the past, this relationship was a stepped function but now it is smoother. Figure 6.2 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 23-Oct 2002 schedule was observed in a period of reduced wheat supply and drought when the premiums for both Prime Hard wheat and incremental protein content were larger.

The price schedule can be written as:

$$p = h(y_2(y_1)). \tag{6.6}$$

The impact of equation (6.6) on the N decision is to encourage fertiliser application because wheat protein content is greater when fertility is higher. The price of N, p_u, used in the analysis was \$1.00 per unit (kg of N), and this was assumed to remain constant over the decision period.

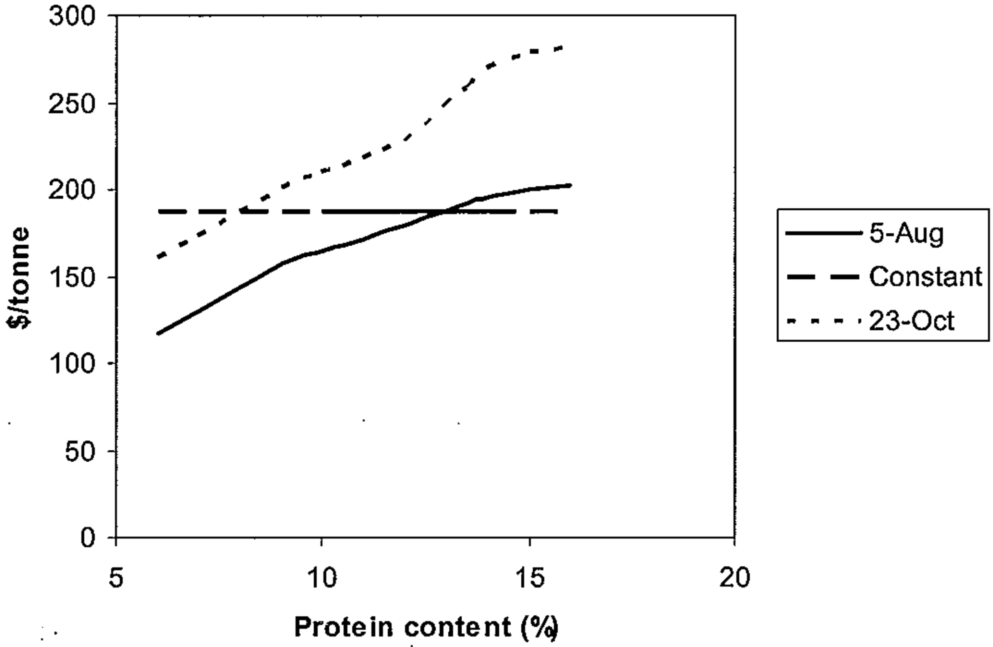


Figure 6.2. Wheat price schedule according to protein level

6.8 Decision model

The mathematical statement of the model is derived from a stochastic version of the multi-output production function represented in equations (6.1) and (6.3), the carryover function (6.5) and the total available nitrogen identity (6.2). These relationships have been specified as:

$$(y_{1t}, y_{2t}(y_{1t})) = f(ICR_t, x_t, u_t, \varepsilon_t \mid S_v, G_t, O_t) \tag{6.7}$$

$$x_{t+1} = 0.9x_H(x_t, u_t) + FM_t(FR_t) + \xi_t \tag{6.8}$$

$$x_t \equiv B_t + u_t \tag{6.9}$$

where the variables containing t subscripts denote conditions, inputs, outputs or outcomes in period t, and ε_t and ξ_t are random variables assumed to be distributed normally. S_v is the Vertosol soil type studied in this analysis.

Given the assumption that decision makers are efficient, maximisation of the expected present value of profit was assumed, given a discount factor ρ. The recursive equation for the (risk-neutral) SDP problem is:

$$V(x_t, p, p_u) = \underset{u_t}{MaxE}[\,p(y_{2t})f(x_t, u_t, ICR_t) - p_u u_t + \rho V_{t+1}(x_{t+1}, p(y_{2t+1}), p_u)]\,. \tag{6.10}$$

The stock modelled is the plant available N in the soil, which can be augmented by applying N fertiliser at crop sowing and carryover between crops. In practice wheat growers can split the application with some applied later based on plant tissue tests. The thesis did not consider split applications, but this could be considered for future analyses. The error involved in this assumption is not likely to be large (J. Kneipp, personal communication).

Another major issue involved in the wheat decision is soil moisture. As noted above, rather than including moisture as a stock to be managed, the impacts of climatic uncertainty are included via stochastic outcomes for yield, protein and carryover. Stauber *et al.* (1975) excluded soil moisture as a state variable without creating any specification chain errors in terms of the Markov structure. The present formulation allows the soil moisture stock to be accounted for as a factor in the decision-making process while not burdening the computational load of the solution program. The results from this analysis are decision rules or strategies for the possible range of climatic outcomes, assuming that the climatic trends of the past are a reasonable guide to future patterns. The solution code was written in MATLAB® (The MathWorks 2000).

Meteorological records for Gunnedah over the past 90 years indicate that the last 40 to 50 years have experienced higher average annual rainfall than previously (Bureau of Meteorology records and J. Gordon, NSW Agriculture Agroclimatology Unit, personal communication). The modelling results were for the whole 90 years and include the earlier (drier) period, which would make them more relevant if a climate change scenario towards drier sequences is observed (CSIRO 2001).

6.9 Experimental design and data generation

6.9.1 The need for prediction

An important issue in an applied study such as this is the derivation of likely wheat responses as nitrogen is added, for the geographic area of interest. On fertile soils in northern NSW, the response of wheat to N fertiliser has been extensively studied (Holford 1981, Holford *et al.* 1985, Holford and Doyle 1992, Doyle and Holford 1993). Experiments at 58 sites in the north-western slopes and plains of NSW were summarised by Holford *et al.* (1992), who derived yield and protein responses to added nitrogen. They found differences in protein response to N according to the level of soil fertility. Such experiments are vital in developing and validating crop growth simulation models and one such model (described next) was used in this analysis.

A simulation modelling approach allows control over factors that can confound a field experiment designed for a specific purpose. For instance, when investigating the impact of adding N incrementally to determine crop responses, use of a simulation model allows control over factors such as soil type, location (the 'tyranny of site'), and soil history. As well, simulation with comprehensive records of seasonal data overcomes the 'tyranny of season' effects that reduce the value of short-term field trials. However, simulation models do not always account for other agronomic management issues, and in this case the responses did not account for possible impacts of pests, weeds and diseases.

A generalised response of wheat yield and protein content to added N is shown in Figure 6.3. Holford *et al.* (1992) found that wheat yield responses were well fitted by the Mitscherlich equation, but that most wheat protein response curves were linear or slightly convex to the horizontal axis. This pattern is observed in the simulation results presented below. The potentially non-concave response is unexpected in economic theory, but can be incorporated into the DP framework.

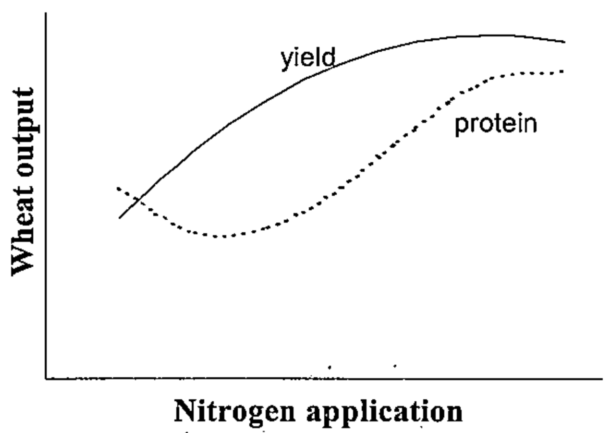


Figure 6.3. Generalised responses of wheat yield and protein to added N

6.9.2 Simulating response data

Angus *et al.* (1993) reviewed the use of models of the yield response of crops to applied nutrients. Their strength is in integrating nutrient information with information on other factors which affect yield and its response to added nutrients.

The APSIM model (McCown *et al.* 1996, Probert *et al.* 1998) was used to generate biological outcomes as a basis for estimation and discussion of results. APSIM is a cropping systems simulation model developed for use as an analytical tool for both research workers and grain growers in the grain cropping regions of north-eastern Australia. The major factors affecting production addressed by this model are climate variability, soil water characteristics, soil nitrogen fertility, variety 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 and under crop rotations with either fixed length fallows or opportunistic sowing rules. The model uses historical climate data to simulate growth according to user-defined sowing and management rules. For this analysis, APSIM was configured to simulate continuous wheat with summer fallow, where soil fertility and soil moisture were reset each planting at predetermined levels to obtain state-transition probabilities.

The key concept conceptually in APSIM is the central position of the soil rather than the crop, despite the fact that the output generally of greatest interest is crop yield (McCown *et al.* 1996). Changes in the status of soil state variables are simulated continuously in response to weather and management. Crops proceed, each finding the soil in a particular state and leaving it in an altered state. All crops share the same aerial space in which various processes take place, eg soil water and nitrogen transfers and transformations, surface residue decomposition, and radiation interception. This structure allows ready simulation of the effects of one crop on another via its effects on the soil, in both sequences and mixtures of crops.

6.9.3 Experimental design

The model was run over a 90-year historical period for Gunnedah, NSW, according to an experimental design as shown in Figure 6.1 and Table 6.1. The five *SM* levels were generated within APSIM for the same sowing date each year. For each factor specified to capture the effects of climatic variability (*ICR* and *FR*), the range of model results was captured through recording 5 percentiles of the particular 90-year distribution of results. The percentiles used are detailed in Table 6.1. The particular APSIM results of interest were crop outcomes (yield, y_1, and protein content, y_2, of wheat), and soil available N at harvest (x_H). Estimates of changes in soil N fertility levels in the subsequent fallow were also obtained. These changes also depended on rainfall patterns (*FR*), and consisted of gains (mineralisation) and losses (due to denitrification or leaching) as explained in the Table.

The model was run at 10 levels of total soil fertility (i.e. soil nitrate N levels at sowing) to generate results for each crop output and soil outcome in each of the climatic categories. These soil fertility levels were obtained by increasing soil nitrate at 25-kg increments from 25 kg to 250 kg, in addition to a base soil level of 25 units (kg/ha). This process was conducted to generate response functions, which were used as a basis for the economic analysis of alternative fertiliser management strategies.

Table 6.1. Experimental design used to simulate crop outputs and fallow outcomes with APSIM model, N analysis

Climatic factors for classifying outputs/outcomes	Number of categories	Predicted outputs/outcomes	Details of categories
		At sowing	
Soil moisture *SM*	5		63, 97, 124, 180, 222mm (a)
		During the crop	
In-crop rain *ICR* percentiles	5	Crop yield y_1	10^{th}, 30^{th}, 50^{th}, 70^{th} 90^{th} (b)
		Protein content y_2	10^{th}, 30^{th}, 50^{th}, 70^{th} 90^{th} (b)
		Soil fertility at harvest x_H	10^{th}, 30^{th}, 50^{th}, 70^{th} 90^{th} (c)
		During the fallow	
Fallow rain *FR*	5	Mineralisation gains	17, 27, 30, 33, 40 kg/ha of nitrogen (d)
		Demineralisation and leaching losses	10% of x_H (e)
Total soil nitrogen levels: 25 kg increments from 25 to 250 kg added to an initial 25 units in the soil, the basis for response functions for crop outputs and soil outcomes			

(a) Soil moisture levels (mm of plant available moisture per metre depth of soil) at sowing based on previous simulations of fallows, called very dry, dry, medium, wet and very wet *SM*. These were generated at a particular sowing date.
(b) Percentiles of crop outputs from 90-year APSIM distributions, called very poor, poor, average, good and very good *ICR*.
(c) Percentiles of soil N fertility outcomes from 90-year APSIM distributions, called very poor, poor, average, good and very good *ICR*.
(d) Estimates of gains in soil fertility following crop harvest and during fallow, related to the 10^{th}, 30^{th}, 50^{th}, 70^{th}, and 90^{th} percentiles of *FR*.
(e) Estimates of losses in soil fertility following crop harvest and during fallow, 10% of soil fertility at harvest x_H .

The five *ICR* outcomes were selected to have an equal likelihood of occurrence. Similarly, each of the five *FR* outcomes was allocated the same probability. However, the fallow and in-crop climate conditions between and within crops are uncorrelated.

The soil type chosen was a black Vertosol (i.e. deep cracking clay, Isbell (1996)) and soil nitrate (or mineral) N was reset at planting each year according to the 10 levels of soil fertility as described. 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. Similarly, the impacts of frost and disease were assumed to be non-limiting. However, an appropriate planting date was chosen so that the risk of frost damage would be low.

These assumptions (soil type, wheat variety, common sowing date, crop location) can all be changed within APSIM to test the impact of varying these factors. The analysis has been conducted to illustrate the approach using one case, but sensitivity of these factors would need to be conducted to test the robustness of the results prior to dissemination to farmers.

6.9.4 Simulated data

Subsets of the actual simulation model responses are shown in Figure 6.4. The three columns of graphs represent cases of very dry, medium and very wet *SM*. The yield, protein and soil N left after harvest responses are shown as the total soil N (initial fertility plus applied N) in the system increases. Within each graph there are three responses, according to whether the *ICR* was very poor, average or very good.

The yield responses were generally concave, but they plateau at some level of total N, depending on climatic conditions. This is due to the crop reaching a moisture limit, and the start of this plateau is positively related to both *SM* and *ICR*. The yield response schedules move both up and across as *SM* and *ICR* improve. The protein responses generally increase and then level off; there are some linear increases but there is not evidence of substantial convexity. Protein response schedules move inversely with both *SM* and *ICR*. This is expected because drier conditions are associated with higher protein content. Levels of soil nitrogen after harvest are generally related linearly with nitrogen above some initial fertility level. In general the initial level of carryover depends on *SM* and *ICR*. These schedules are also related inversely to both *SM* and *ICR*, and this is expected because there is less nitrogen removed in dry fallow seasons. Although protein content in wheat is higher, the effect of lower yields in drier crop years means that relatively less fertility is removed.

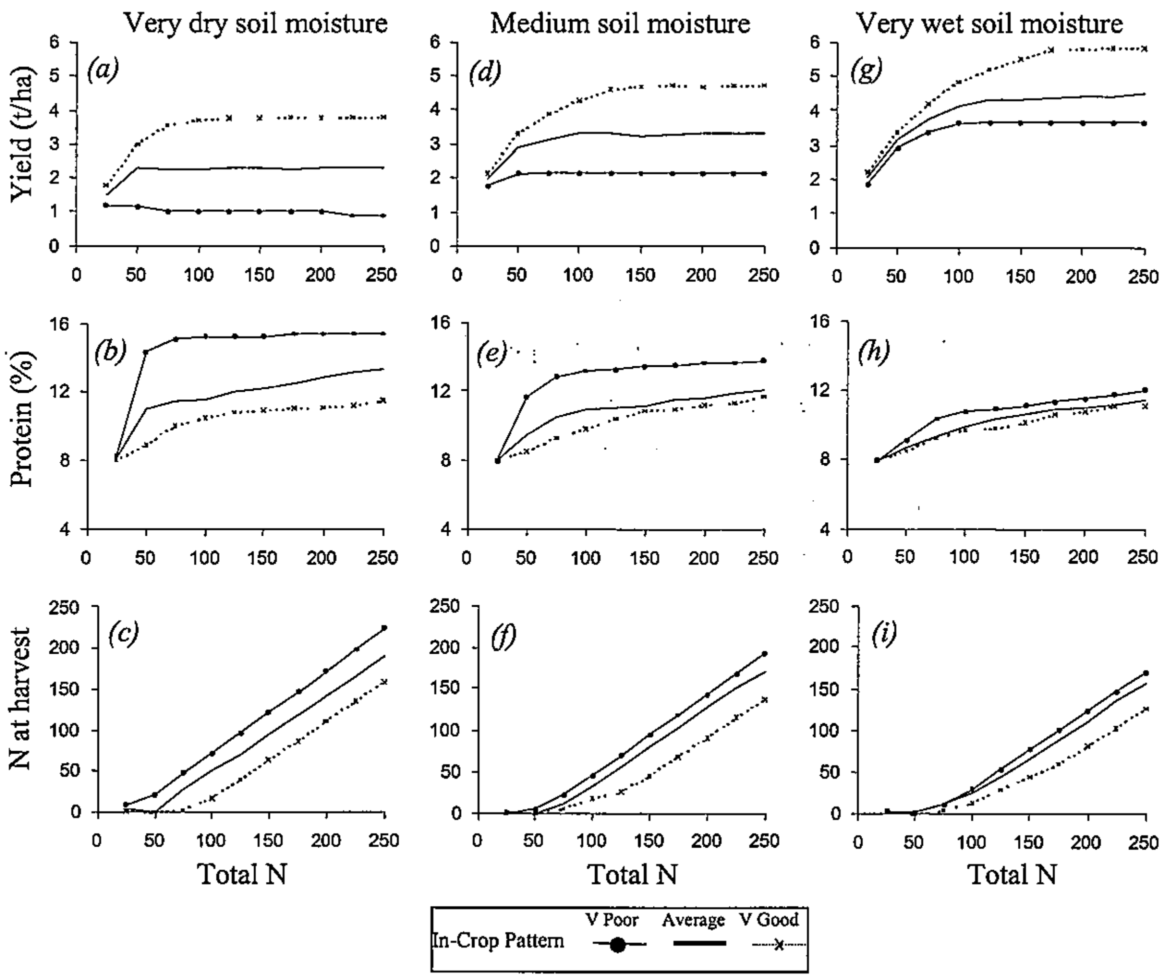


Figure 6.4. Selected responses generated by APSIM for yield, protein and soil available N after harvest

6.9.5 Estimating smoothed responses

Because there was some variation in individual simulated responses, regression equations were estimated and tested for each response case. This allowed the economic analysis to capture the essence of the response without being distracted by occasional outliers. Although the protein responses to added N have been hypothesised to show concavity over some input ranges, the simulated protein responses in Figure 6.2 are generally concave. Therefore for both yield and protein a modified Mitscherlich form was found suitable in most cases; although in some low rainfall situations the response was essentially flat. The form of Mitscherlich used was:

$$Y = \alpha + (\beta - \alpha)[(1 - k\exp((N-1)(TotalN - 100)/100)/(1 - k\exp(N-1)))]. \qquad (6.11)$$

The implications of use of the Mitscherlich form need to be stated. The Mitscherlich, Cobb-Douglas and translog all impose convex marginal products and bias findings towards decreasing skewness; and yet a risk-neutral farmer is not skewness-neutral. In fact a risk-neutral farmer tends to use more N where the yield function has a convex marginal product.

The parameters of the estimated yield and protein equations are shown in Appendix 1. The particular functional form in equation (6.11) was found to be suitable for this type of data (S. Harden, personal communication). The linear response parameters for N after harvest responses are also shown in Appendix 1. There is little difference in the slopes of the lines but the initiation points (on the total N axis) vary. The smoothed response equations were the basis of the datasets that were generated for the optimising analysis. Results of this analysis are presented in the following chapter.

7. The Nitrogen Model: Results and Discussion

7.1 Introduction

This chapter contains results of the analyses conducted with the model specified in Chapter 6. These results are used to address questions of how much N to apply to a wheat crop under various circumstances.

Normally, the decision maker can observe or estimate soil moisture content at sowing, but does not know what type of in-crop or fallow rainfall is likely for the year. The first group of results relates to the case where perfect knowledge is assumed for both types of climatic patterns, i.e. *ICR* and *FR* are assumed known. Subsequently, uncertainty is introduced via probabilities of *ICR* and *FR* outcomes and stochastic results are presented in an expected-value framework. Detailed simulation results are presented in Appendix 2; summaries are presented in the main text.

7.2 Deterministic results

7.2.1 The static case

The first analysis conducted was for the static case, i.e. without any N carryover from one crop to the next. The results are essentially those outputs observed at harvest – yield and protein content which depend on total available N, *SM* and *ICR*.

The static results are presented in full in Appendix Table 2.1, with summaries in Tables 7.1 and 7.2. The optimal static N application is shown as a surface according to *SM* and *ICR* in Figure 7.1. As expected, the optimum N-application rate increases as both *SM* and *ICR* improve. There is some variation in this surface, caused by the underlying simulated response rules. For medium *SM*, the optimal N application ranges from 95 to 115 and 205 units in the cases of very poor, average and very good *ICR* conditions, respectively, and average *FR* conditions. The wheat enterprise profit (gross margin) results in Table 7.2 for optimal input follow the same trend of increasing with both *SM* and *ICR*.

Table 7.1. Comparison of static and deterministic dynamic results, selected *ICR* cases for average *FR*: N analysis

Soil moisture at sowing *SM*	In-crop conditions *ICR*	Static N application kg/ha	Dynamic N application at sowing kg/ha	Dynamic N stock x_{LT} (a) kg/ha	Dynamic total N at sowing (b) kg/ha
	Very poor	0	27	63	90
Very dry	Average	105	57	108	165
	Very good	135	87	93	180
	Very poor	0	37	48	85
Dry	Average	105	65	100	165
	Very good	185	99	96	195
	Very poor	95	52	58	110
Medium	Average	115	75	110	185
	Very good	165	106	99	205
	Very poor	125	70	80	150
Wet	Average	155	90	115	205
	Very good	195	130	115	245
	Very poor	125	83	142	225
Very wet	Average	155	90	115	205
	Very good	195	129	121	250

(a) Optimal soil N stock at sowing

(b) Total crop requirements from soil and added N, sum of application and optimal soil N stock

Table 7.2. Comparison of static and deterministic dynamic financial results, selected *ICR* cases for average *FR*: N analysis

Soil moisture at sowing *SM*	In-crop conditions *ICR*	Annual gross margin - static N application $/ha	NPV of optimal static decision $/ha (a)	NPV of optimal dynamic decision $/ha (b)
	Very poor	-15	-30	165
Very dry	Average	114	224	1427
	Very good	320	629	2947
	Very poor	41	81	655
Dry	Average	200	393	2114
	Very good	370	728	3463
	Very poor	129	254	1401
Medium	Average	256	504	2474
	Very good	436	858	3986
	Very poor	276	543	2661
Wet	Average	360	708	3390
	Very good	545	1072	4925
	Very poor	317	624	3004
Very wet	Average	394	775	3708
	Very good	579	1139	5288

(a) Results for optimal static strategy, discounted at 7% p.a. over 10 years

(b) Results for an initial soil N level of 100 units, discounted at 7% p.a. over 10 years

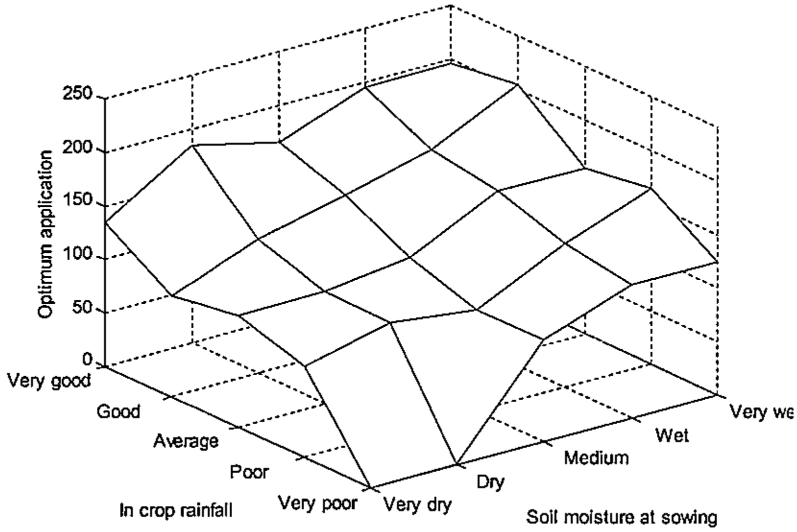


Figure 7.1. Static optimum N application levels

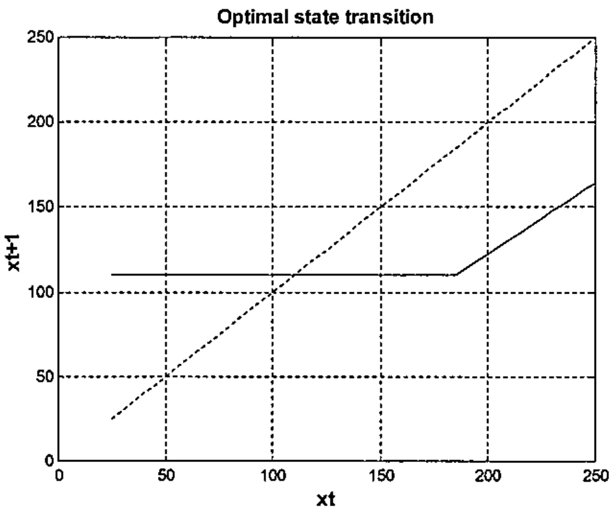
7.2.2 The dynamic case

When carryover effects are included the results are presented differently to the static case. Because the level of soil N is influenced by what happens in the fallow between consecutive wheat crops, the concept changes to a stock of soil N which is being managed by decisions at different points in time. Therefore the dynamic decision includes two components – an optimal input application decision and an associated optimal 'target' stock of soil N fertility.

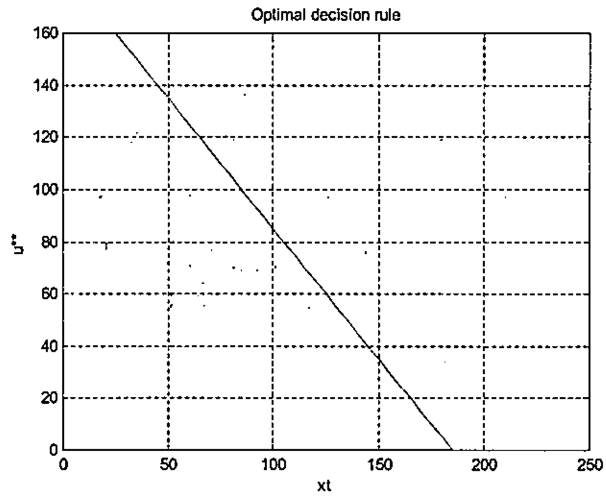
The dynamic results are fully shown in Appendix Table 2.2, with summaries in Tables 7.1 and 7.2. These results consist of: (a) an optimal dynamic N application; (b) an optimal dynamic soil N stock x_{LT}; (c) an optimal total nitrate N level required for the crop at sowing (the sum of (a) and (b)); and (d) the net present value (NPV) of the dynamic decision strategy if followed for 10 years from an initial soil N level of 100 units. Table 7.2 also contains the NPV of optimal static decision over 10 years.

In Table 7.1 the dynamic optimal total N available to the crop at sowing (eg 185 units for medium *SM* and average *ICR* and *FR*) is the crop requirement from both sources (soil available N and applied fertiliser). Ideally the economic results show that this should be made up of 110 units in the soil (Figure 7.2 (a)) and 75 units added by the grower, as shown by reading from the graph in Figure 7.2 (b).

(a)



(b)



(c)

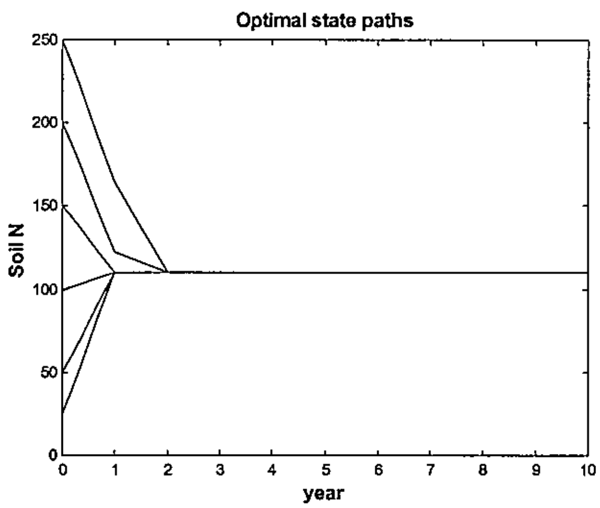


Figure 7.2. Deterministic dynamic results, medium SM, average ICR and FR

The optimal state transition from one year (x_t) to the next (x_{t+1}) is shown as the solid line in Figure 7.2(a). The dotted line at 45^0 to the axes represents the set of steady states (where $x_{t+1} = x_t$). Where this line intersects the optimal state transition is the long term optimum stock level x_{LT}. In this case the level is 110 units, derived after considering the expected crop outputs (i.e. amount of protein removed from the system at harvest) and fallow outcomes. The optimal decision rule is shown by the line in Figure 7.2 (b) for any measured level of N stock. At soil fertility levels lower than x_{LT} (110 units) the higher fertilisation decisions (u^{**}) from Figure 7.2(b) will increase soil fertility towards x_{LT}. At higher soil fertility levels the optimum decision is to apply lower or zero rates of fertiliser so that the soil N fertility stock will subsequently be reduced towards x_{LT}.

The relationships in Figure 7.2(c) show the optimal state path for some initial levels of soil fertility. That is, they show how the optimal decisions change any initial soil fertility level to achieve the longer term optimum x_{LT} of 110 units. At high initial levels of soil N fertility it is optimal to exploit the system by running down the available soil fertility. This result is due to the direct substitutability between synthetic and soil available N, the cost associated with replacing soil N and the presence of the discount rate in the objective function.

The graph of all optimal dynamic decisions (Figure 7.3) shows a similar pattern to the static result (i.e. increasing with both *SM* and *ICR*), but at a lower level. This is expected from theory (Figure 5.1). It also shows the potential value of better information about future weather patterns (Marshall *et al.* 1996), and explains why grain growers have developed crop planting rules based on soil moisture at sowing.

The optimal stock level also varies according to climatic conditions, as demonstrated in Figure 7.4. On reflection, this varying optimal stock level should not come as a surprise, but it may not be recognised by everyone in the industry. There is a trade-off between the optimal application rate and the optimal stock from Figures 7.3 and 7.4.

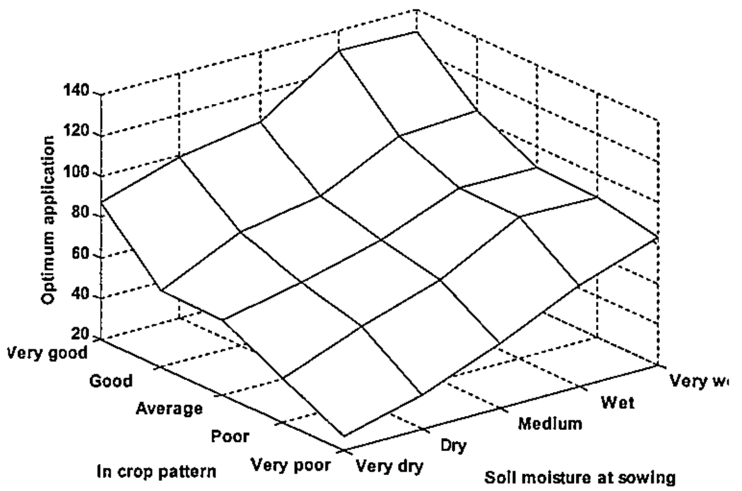


Figure 7.3. Dynamic optimum N application levels, average *FR*

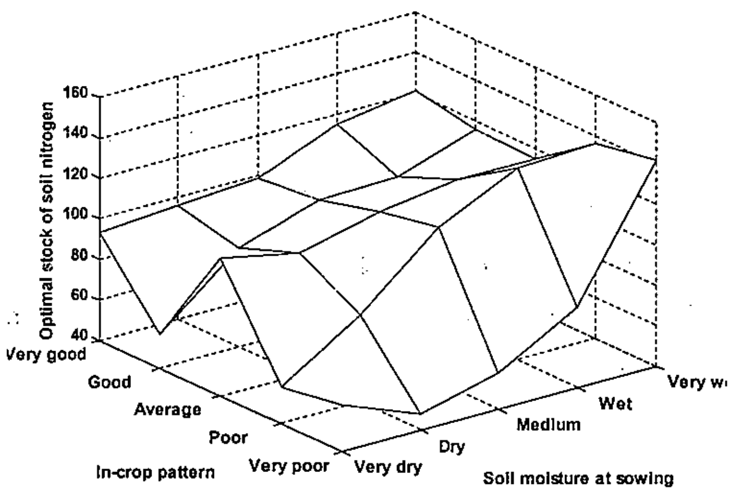


Figure 7.4. Dynamic optimum soil N stock levels, average *FR*

An examination of Appendix Table 2.2 shows that for each *SM* and *ICR* category the optimal total soil N at sowing (optimal stock plus optimal application) is constant. For each crop moisture case, as fallow moisture increases it is more worthwhile having extra N stored in the soil, with less purchased and applied at sowing.

An example of financial results for the dynamic case is given in Table 7.2. These NPV figures are from an initial soil N level of 100 units, other NPVs apply if the initial soil N fertility differs. They increase with both *SM* and *ICR*. These represent future earning capacity of the land, but not land values because the future income flows are not into perpetuity and they exclude overhead costs.

In considering the results in Table 7.1, we expect from theory that the optimal application rate will be greater for the static than the dynamic case because applied N carried over to the next crop is not considered in the former. When comparing the optimal static and dynamic decisions, apart from two of the very driest scenarios the latter is always less than the former by amounts ranging from 40 to 86 units of N for the cases in Table 7.1. These applications rates are less than the static optima by between 33% and 55%.

A financial comparison of the static and dynamic optima is shown in Table 7.2. For each soil moisture and rainfall case, the NPV of the annual gross margin associated with the static optima (discounted at 7% over 10 years) is shown. In all cases the NPV of the optimal static decision is less than for the optimal dynamic decision. These are very substantial financial improvement over each static case.

The deterministic results are an over-simplification, in that perfect foresight is assumed, but they provide some useful insights. First, as expected, the optimal input levels (both static and dynamic) vary directly with climatic and soil moisture conditions. Second, the optimal soil N stock levels are shown for soil moisture and in-crop conditions, and there appears to be a trade-off between N application and stocks. Third, the impact of N carryover effects is to reduce the dynamic optima below the static optima, by substantial amounts in some cases. Finally, there is a substantial financial improvement from the dynamic over the static decisions in each case.

7.3 Stochastic results

When the probabilities associated with *ICR* and *FR* conditions are included, the results are presented in an expected value framework that accounts for possible variations in crop output due to climatic patterns. The APSIM results were generated by resetting *SM* and soil nitrate N levels at the start of each year over a 90-year simulation. Hence, these stochastic results are presented for each possible *SM* case over the expected range of crop outcomes. The results are shown in Table 7.3.

Table 7.3. 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

Results are presented in the same format as for the dynamic deterministic case – the optimal N application, the optimal longer-term soil N stock, and the total nitrate N required given the crop expectations for each N input level at sowing.

Optimal total N required at sowing ranges from 135 units (very dry *SM*) up to 245 units (wet *SM*). These are on the high side of the ranges of the deterministic results in Table 7.1. The optimal soil stock ranges from 81 to 142 units. The optimal N application varied from 54 units to 105 units, and these figures are generally consistent with those in Table 7.1, and appear to be reasonable in terms of magnitude and trend as *SM* changes. For medium SM, the optimal N strategy involves applying 81 units of N to a soil nitrate N level of 124 units. If the soil nitrate N level is lower, then the tactic is to apply higher levels until the total N at sowing reaches 205 units.

The results in Table 7.3 are broadly in line with accepted practice and thinking, that is, apply more N as levels of *SM* and expectations of subsequent moisture improve. They are not completely realistic because different *SM* levels are associated with the same expected *ICR* and *FR* outcomes. What they do add to accepted knowledge is an estimate of the level of soil fertility that should be maintained prior to sowing a wheat crop. The results also give an indication of the difference in strategy as seasonal conditions vary for a common soil type.

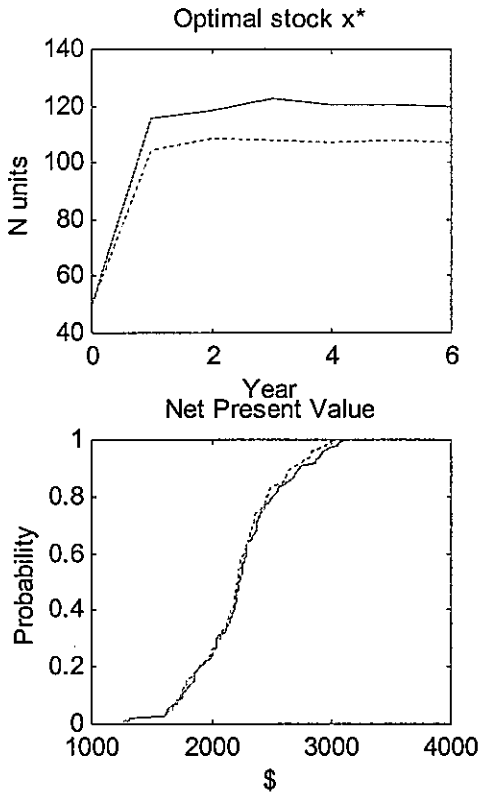
7.3.1 Comparison of deterministic and stochastic results

There is a difference between the dynamic deterministic and stochastic results. For medium *SM* and average *ICR* and *FR,* the optimal N stock and application in the deterministic case (110 and 75 units respectively from Table 7.1) was lower than the medium *SM* results in the stochastic case (124 and 82 units respectively from Table 7.3). To investigate this further, both sets of results were subjected to a Monte Carlo sampling procedure whereby random sampling of *ICR* and *FR* occurrences was used to generate an optimal average state path, optimal average N input path and a cumulative distribution function for NPV. The results, starting from an initially low level of soil N, are shown in Figure 7.5.

The optimal paths of the N stock and the N input decision are both higher in the stochastic than the deterministic case in Figure 7.5. This result is not expected for risk-averse decision makers (see Anderson *et al.* 1977, Chapter 6). However, Babcock (1992) found that optimal N fertiliser rates for risk-neutral producers may increase if uncertainty about the weather or about soil N levels exists. He considered that the motivation for increasing N rates is that producers might not want to be 'caught short' of fertiliser in good years. The likelihood that some unused N after a crop would be carried over into the next season, and not lost, may also contribute to this type of decision. This result is also consistent with the findings of de Koeijer *et al.* (2003) who found that variation in weather resulted in a higher economic optimum N level. Comparison of the cumulative distribution functions of NPV confirmed the financial benefits of this strategy.

7.4 Sensitivity analysis

Some of the parameters in the bio-economic model were varied to determine the robustness of the results. Economic parameters tested were the discount rate, wheat price schedule and the price of N. Biological parameters tested were the amount of net change in soil N during fallow was varied.



Deterministic result – dotted line, stochastic result – unbroken line

Figure 7.5. Optimal decisions, state paths and NPV for one set of deterministic and stochastic results over 6 years

From the base model, sensitivity analysis was conducted as follows:

- the discount rate was varied from 7% to 8%;
- the price of elemental N was varied from \$1.00/kg to \$1.20/kg;
- two alternative wheat price schedules were tested (as shown in Figure 6.1), first a single (farm-gate) price of \$187.73 for all wheat (i.e. no premium for protein content), and second a higher price schedule; and
- the carryover of available N during fallow was varied by increasing the losses of soil N after harvest (x_H) from 10% to 30%, 50%, 70%, 90% and 100%. This tested the effects of lowering the linkage between the fertiliser decision in one year and the next.

The results are shown in Tables 7.4 and 7.5, and must be compared to Table 7.3. The effect of raising the discount rate from 7% to 8% was only observed in the net present value results, the optimal N decisions were unchanged. The effects of increasing the

N price by 20% were small, with the optimal N stock and application decision being slightly reduced for the cases of medium and wet *SM*.

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 8 and 30 kg/ha and the optimal application rate 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 there seemed to be only limited response, in terms of N decisions, to changes in these economic parameters.

Table 7.4. Sensitivity analysis of economic variables, N analysis

Soil moisture at sowing *SM*	Optimal N application kg/ha	Optimal N stock x_{LT} kg/ha	Total N at sowing kg/ha	Net present value $/ha
		Discount rate of 8%		
Very dry	54	81	135	2559
Dry	71	114	185	2639
Medium	81	124	205	2715
Wet	105	140	245	2862
Very Wet	103	142	245	2907
		Nitrogen price of $1.20/kg		
Very dry	54	81	135	2568
Dry	71	114	135	2647
Medium	78	107	185	2721
Wet	100	125	225	2864
Very Wet	103	142	245	2910
		Wheat price constant (no protein premium)		
Very dry	52	73	125	2980
Dry	68	97	165	3069
Medium	72	83	155	3159
Wet	102	103	205	3327
Very Wet	106	119	225	3376
		Wheat price higher		
Very dry	60	120	180	3890
Dry	71	114	185	3994
Medium	81	124	205	4090
Wet	105	140	245	4273
Very Wet	103	142	245	4331

The ranges over which prices have been varied for the sensitivity analysis are well within possible historical fluctuations. Table 7.5 contains prices for wheat (AWB export quality) and urea from 1995 to 2002. There have been some relatively large year-to-year changes in prices, and the sensitivity analysis would indicate larger variations in results if such changes had been used.

Table 7.5. Historical price variation – wheat and urea

Year	AWB export quote (A$/t)	Year	Urea ($/t)
1995/96	304.56	1995	455.90
1996/97	264.92	1996	479.60
1997/98	246.22	1997	434.80
1998/99	234.65	1998	380.60
1999/2000	220.72	1999	333.80
2000/01	217.53	2000	371.60
2001/02	312.31	2001	443.60
2002/03	317.99	2002	387.40

Source: ABARE Commodity Statistics 2003

The results of changes in biological parameters in Table 7.6 are 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. The optimal amount applied rose. These results are reasonable, in that as there is less N in the soil-plant system the optimal stock must be lower and the amount required to be added must be higher.

7.5 Marginal value of a unit of soil N

When a response function as shown in Figure 5.1 is used as the basis of agricultural production decisions, the shape and degree of curvature of the function are important in determining the value of extra units of the input.

For a static production response, the input demand functions associated with equation (5.1) for very dry, medium and very wet *SM* (for average expected *ICR* in each case) are shown in Figure 7.6. These functions are calculated as the change in wheat income ($/ha) associated with a change in total soil available N (kg/ha). They confirm the results in Table 7.1, of optimal N inputs of 105, 115 and 155 units for the very dry, medium and very wet cases respectively, given that the marginal cost of N is $1/unit.

Table 7.6. Sensitivity analysis of biological variables, N analysis

Soil moisture at sowing *SM*	Optimal N application kg/ha	Optimal N stock x_{LT} kg/ha	Total N at sowing kg/ha	Net present value $/ha
		30% fallow losses		
Very dry	65	70	135	2527
Dry	83	82	165	2609
Medium	95	90	185	2687
Wet	121	104	225	2837
Very Wet	120	105	225	2882
		50% fallow losses		
Very dry	61	44	105	2415
Dry	87	58	145	2500
Medium	92	53	145	2579
Wet	130	75	205	2732
Very Wet	130	75	205	2777
		70% fallow losses		
Very dry	67	38	105	2322
Dry	98	47	145	2409
Medium	96	44	140	2490
Wet	118	47	165	2646
Very Wet	148	57	205	2691
		90% fallow losses		
Very dry	72	33	105	2237
Dry	96	34	130	2327
Medium	105	35	140	2410
Wet	129	36	165	2569
Very Wet	129	36	165	2614
		100% fallow losses		
Very dry	75	30	105	2197
Dry	100	30	130	2288
Medium	110	30	140	2372
Wet	135	30	165	2533
Very Wet	135	30	165	2577

Wheat growers with Vertosol soils at Gunnedah would expect to earn at least $12 per extra unit of N applied when soil N is 40 units/ha, with the marginal value declining as soil N increases.

In the dynamic case, the co-state, or implicit, value of the stock (λ_t from equation (5.6)) helps determine the marginal user cost associated with Figure 5.1. Optimal management of a renewable stock over the planning horizon implies that there is no value to the resource user from an extra unit of the stock in any time period.

Following Kennedy (1986, p. 15), differentiating both sides of equation (5.10) with respect to x_t gives:

$$dV_t / dx_t = \partial f_t / \partial x_t + \rho(dV_{t+1} / dx_t)(\partial g_t / \partial x_t)$$

or

$$\lambda_t = \partial f_t / \partial x_t + \rho\lambda_{t+1}(\partial x_{t+1} / \partial x_t)$$

This means that the increase in the optimal value of the resource stock at the beginning of any period consists of two parts, the additional period gain and the increase in the optimal value of the next period, discounted one time period.

The stochastic N results were used to derive values of dV_t / dx_t, or λ_t. These are shown in Figure 7.7, for SDP results with medium SM. These shadow values are from the final stage of the solution after convergence had occurred. The shadow price in Figure 7.7 is much lower than the marginal values in Figure 7.6. This is expected because the V matrix (optimal value function) is a result of the optimal decision in each state and stage of the DP solution, i.e. the function should be relatively flat. The shadow value of N drops below \$1 close to the optimal N stock of 124 units from Table 7.3.

In summary, wheat growers with low levels of soil available N will derive relatively large returns in the immediate year from adding N fertiliser. In the longer term, the shadow value of N will be much lower if optimal N strategies are followed.

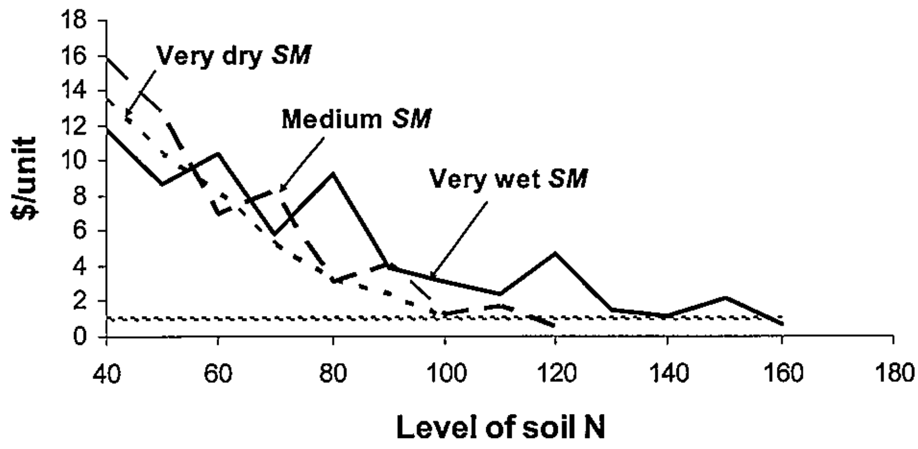


Figure 7.6. Marginal value of a unit of soil available N (static case)

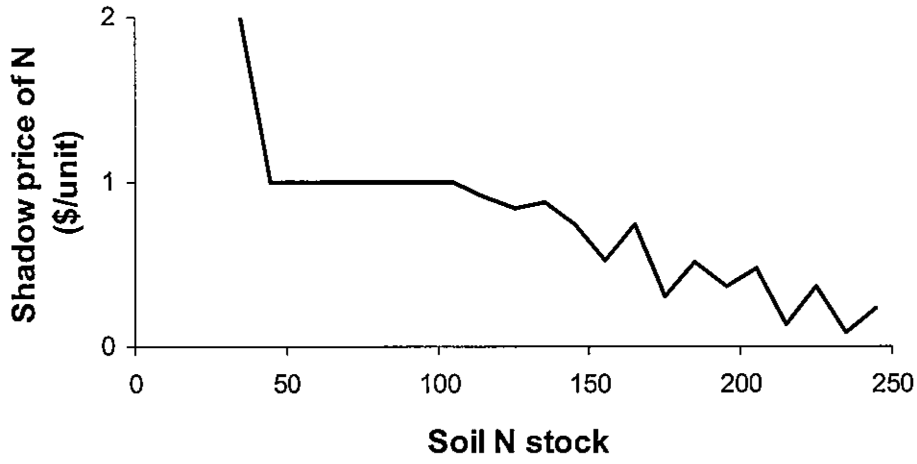


Figure 7.7. Shadow value of a unit of soil available N (dynamic case)

7.6 Interpretation of the results as strategies and tactics

The results in Tables 7.1 to 7.5 can be interpreted in terms of management strategies and tactics for wheat growers with soils and climates similar to those studied.

The results in Tables 7.1 to 7.3 imply that the best N fertilisation strategy at wheat sowing is to aim for the optimal total soil N at sowing (205 units of nitrogen in the medium *SM* case). If this amount is not there, then the tactics would involve:

1. Measuring the amount of soil moisture and soil available N at sowing (this can be done relatively precisely and cheaply); and
2. Adding synthetic N to each crop according to the schedule in Figure 7.2(b) for each soil moisture case.

This process incorporates optimal N to maximise profits, and expected gains and losses of soil N through crop growth, grain removal and fallow processes. These tactics are similar to the N budgeting approach of Martin *et al.* (1996) but with two important differences. First, this approach provides an optimal stock of soil N for a given soil type and climate. The best strategy now is to apply fertiliser to achieve a soil fertility level as well as replacing N lost in the crop and fallow. Second, it has been derived through a process using profits as the objective and according to expected crop responses to incremental additions of N.

With respect to the second point, sensitivity analysis indicated that under a higher price schedule for wheat (according to protein content) the optimal application rates were identical except for the very dry *SM* case, where 60 units were applied and the optimal soil N level was higher (120 units). The total N recommended for the crop was higher. Raising the price of N by 20% did not affect the results beyond the levels already discussed. In general, the results did not appear to be very sensitive to changes in input or output prices.

7.7 Discussion

The primary question in this chapter concerns the development of fertiliser management strategies for wheat growers under declining soil fertility. Site-specific characteristics of climate, soil-crop system, and wheat prices, make this a novel analysis of a particular question. The particular focus was on the carryover of soil N from one period to the next, in conjunction with substantial output variability and wheat prices based on quality characteristics.

The testing and development of alternative management strategies under these conditions was presented in terms of economic theory. More practically, wheat growers and advisors are interested in management strategies and tactics that they can apply in actual situations. The results of the analysis have been presented as strategies and tactics for the case considered.

In some respects, it is difficult to compare the static and dynamic results. First, the estimated optimal fertiliser input levels (u^* and u^{**} in Figure 5.1) are associated with different amounts of N in each crop-soil system. Without carryover effects, the static case, soil fertility build-up or decline during the fallow is excluded, so that the total amount of N in the system is less than the dynamic case. Second, a comparison of the two cases is also complicated by the fact that in the dynamic case there is a stock, x_{LT}, of N in the soil, for which a fertiliser application decision is made, based on expected crop output and soil fertility outcomes during fallow. However, the optimal N input levels were lower in the dynamic than the static cases, and this result is as expected from theory. In economic terms, the NPVs are substantially greater for the dynamic, compared to the static cases. After accounting for the different amounts of N in the system, and differing input strategies, the NPVs were substantially greater for dynamic N strategies.

The interpretation of the optimal strategy for the dynamic case is as follows: bring the stock of soil nitrate N to the optimal long-term level through appropriate fertiliser application. This level will relate to the inherent fertility of the soil, the wheat crops capable of being grown under different fertilisation rates, and prices of inputs and outputs. Then apply the net amount that is considered necessary to replace nutrients removed through crop growth and harvest, as well as changes occurring in the subsequent fallow. The optimal static strategy involves knowing the soil N level at sowing and adding fertiliser to earn the most expected profit for that crop. However, this is an overestimate of fertiliser needs if there is other N not accounted for in the system (this also applies to the static case).

From the dynamic results, optimal soil fertility stock levels generally increase as *SM* changes from dry through to very wet. The interpretation of these figures is straightforward. As moisture conditions improve, the crop yield responds to extra N and the optimal stock increases. For very dry soil planting conditions, the crop response will be a relatively higher protein content (at the expense of yield), and since wheat payments are based on protein (quality) there is incentive to maintain a higher N stock level.

Sensitivity analysis of the optimal input and stock levels of N over a range of prices suggested that the results are relatively insensitive to these price changes. Variation of the discount rate only affected the net present value figures. The insensitivity to the range of wheat prices can be explained by the type of relationship between fertiliser N and expected wheat yield and protein content as moisture patterns vary, combined with the influence of grain protein content on wheat prices. For example, in a wet year expected yield is higher and extra N contributes to the yield response, so that crop revenue is expected to be greater. In a drier year, protein content is higher (at the expense of yield) and extra N contributes to greater protein, which receives a price premium. If the wheat price schedule moves up or down, there is unlikely to be a substantial change in incentive with respect to fertiliser application rates.

However, the results show that the best fertilisation level does vary according to climatic conditions. Examination of Figure 6.3 shows that as SM and ICR vary, the yield and protein responses move both vertically and horizontally. These interactions are the basis for existing wheat grower practices of soil moisture monitoring and the interest in climate forecasting to improve crop management practices.

The pattern of NPV results is unsurprising. These figures vary directly with initial soil fertility levels, and also as soil moisture at sowing becomes wetter. The Vertosol soils are inherently fertile, although sometimes in a run-down condition. The reason for these results is that as the soil fertility level increases, improved productivity allows better crops and greater returns to the grower.

There are implications for the underlying theory from this analysis. The simulated biological results in Figure 6.4 show evidence of a yield plateau; but there is substantial variability in the level and onset of that plateau. This reinforces the basis for Berck and Helfand's finding that sufficient variability in an LRP response can lead to a concave response. This analysis of wheat responses has also shown that multiple-output production and quality-dependent prices need to be considered as more commonplace characteristics of production systems.

The flatness of economic response to added inputs near the optimum has been discussed and accepted (Anderson 1975). That discussion related to the difference between u_{max} and u^* in Figure 5.1. This analysis has considered whether there is an important difference between u^{**} and u^*, through inclusion of fertiliser carryover effects. The economic comparison of NPVs showed a substantial advantage from following N strategies for wheat production based on a dynamic conceptualisation of the soil-plant system, and appropriate analysis. Maintaining an acceptable stock of soil nitrogen over time allows a lower level of fertiliser to be used at each crop sowing decision, with improved economic outcomes. A rejection of the economic flatness of response for this analysis seems possible for the fertiliser carryover question.

A wider interpretation of these results is also possible. These results could be used for wheat when it is grown in rotation with other crops. That is, it should not need to be interpreted solely in a wheat-only rotation. It seems reasonable to use these decision rules for the wheat component of any rotation.

The level of x_{LT} can also be considered as an optimal longer-term level of plant available N fertility. Dalal and Mayer (1986b, 1986c) (Figures 4.1 and 4.2) presented historical curves of soil fertility decline for similar soil types. Their total N % figure included both inorganic (plant available or mineral N) and organic N (which is not directly available to plants), and therefore the optimal (inorganic) N stocks derived here are not directly comparable. However, the analysis of organic C in the next two chapters will provide a valid comparison.

Two final comments can be made about the size of the recommended levels of N fertiliser from this analysis compared with current recommendations. The first relates to results from simulated versus experimental yield data. Llewellyn and Featherstone (1997) found that optimal N levels developed from simulated crop responses were generally higher than levels found using experimental yield data. This analysis has used only simulated responses. However, Babcock (1992) found that optimal N fertiliser rates for risk-neutral producers may increase if uncertainty about the weather or about soil N levels exists. This result contrasts with the standard prescription that producers should reduce fertiliser applications because N fertilisation typically increases yield variance. Smith *et al.* (2003) found that the N rate increases the variance of yield but reduces the variance of price. Babcock (1992) considered that the motivation for increasing N rates is self-protection, it may be profitable to reduce the probability that they will be 'caught short' of fertiliser. The results in the foregoing analysis are consistent with the findings of de Koeijer *et al.* (2003) who found, for N used in sugar beet production, that variation in weather results in a higher economic optimal N level and in the agronomic efficiency decreasing by 10%.

The second comment is that the N levels seem relatively large compared to some current recommendations. For northern NSW, an example calculation from Hayman

(2001b) shows that for an initial 30 kg soil N/ha, recommended fertiliser applications are 24, 67 and 105 kg N/ha in poor, average and good seasons respectively. In contrast, the figures in Table 7.3 recommend that total N at sowing be 185, 205 and 245 units of N for dry, medium and wet SM, respectively, which would correspond to 155, 175 and 215 kg N/ha applied to a soil with 30 kg N/ha. These latter levels are substantially higher. However, preliminary results from a survey of cropping practices in the Gunnedah district (Schwenke and Young 2004) indicate that some wheat growers are now applying 100 to 150 units of N, and that they consider the optimal total available N rate (applied fertiliser plus NO_3N soil test) to be 200 units. This is close to the recommendations from Table 7.3.

In section 2.12 the working hypothesis was that the value of accounting for dynamic effects would outweigh the cost and effort of dealing with the extra complexity. The basis for judging whether the outcomes were different enough to be important was to be discussed separately in each case. It seems from this discussion that the recommendations from the dynamic analysis are substantially different from the static case, and that there are substantial economic advantages for the wheat grower. These findings support acceptance of a conclusion that inclusion of dynamic effects is worthwhile.

One further comment on higher levels of N in the soil-plant system is that the implications of N accumulation in groundwater have not been addressed here. This is a very important issue in Europe and the US, because of higher fertiliser application rates, the use of manures and the relative permeability of the soils. This issue does not appear to be as important in Australia at present, but further work could be done on this issue.

7.8 Conclusion

Using dynamic economic production theory and methodology, the analysis presented here has developed management strategies and tactics for determining optimum soil N fertility levels, and N fertiliser amounts to apply for wheat production on fertile soils in one region of northern NSW. The strategy of aiming at an optimal soil N fertility level and adding synthetic N according to expected crop outcomes is a new idea for providing fertiliser advice to farmers. Setting the problem in a dynamic stochastic context has offered wheat growers strategies and tactics according to measurable soil moisture and available N at sowing. This offers flexible and desirable management advantages to wheat growers.

The levels of N input recommended are lower for the dynamic than the static case, as expected from theory but the comparison is qualified because there is also a stock of N present in the dynamic situation. However, the recommended N application levels may be higher than some other extension recommendations. There is some evidence that wheat growers in the region of Gunnedah are now applying N at rates consistent with results of this analysis. This may give support to acceptance of the notion that inclusion of carryover effects is worthwhile.

8. The Carbon Model

The measured declines in soil fertility presented in Chapter 4 were expressed in terms of SOM and its constituents (including SOC and total N percentage). Schwenke *et al.* (1997a) proposed the addition of N fertiliser to overcome soil fertility decline, since N is the most important nutrient deficiency in northern Vertosol soils. But there are other management options available to graingrowers which can help in build-up of SOM and provide crop and soil benefits (including the supply of other nutrients and soil structure enhancements). These other options include strategies for tillage and stubble management and they, together with fertilisation, are considered in this and the next chapter to show their impact on crop growth and profits.

In this chapter the model used for analysis is presented. Because the soil focus is broader than just mineralisable N, the soil fertility measure monitored is SOC. The model developed here involves evaluation of tillage, stubble management and fertiliser strategies for crop growth and profits. As in the N analysis, wheat crop sowing according to soil moisture is treated separately through decision rules in the crop simulation manager program. The focus here is on the subsequent question of soil fertility management, and we assume that moisture retention strategies have been adequately implemented.

Farquharson *et al.* (2003) used crop simulations and budgeting to show that it is possible to reverse the decline in SOC using contemporary best management practices, but did not determine the 'best' combination of practices. This analysis extends their work by using a dynamic optimising analysis.

In the first section of the chapter the economic model is set out. This includes the management options evaluated, the profit function specification, and the dynamic programming formulations of the problem. The latter parts derive from the material in Chapter 5. SOC is the measure of soil fertility of interest here: it is assumed to respond to soil and crop management and to improve soil water holding capacity. The rest of the chapter outlines how the SOC responses to management are predicted, and provides the basis for improvements in soil water holding capacity associated with higher levels of SOC. The experimental design and simulation strategy are also presented in this chapter. The results of this analysis are given in the next chapter.

8.1 Economic model

Because there are carryover effects on soil fertility of wheat crop tillage and stubble management practices, the underlying question relates to the profitability of crop and soil fertility management strategies in a dynamic economic context. The decision process involves a set of alternative management actions which are taken to produce crops at minimum cost, but which also have implications for levels of soil fertility. These levels are inputs to the production process, but crop outputs also impact soil fertility outcomes.

The analysis is again conducted for wheat, the main dryland crop grown in the region. A short fallow wheat crop sequence was analysed to draw some conclusions about crop management and SOC. Other crop sequences (long fallow wheat, inclusion of summer crops and pulses in fixed rotations, and opportunity cropping) also used by graingrowers are not explored here. The analysis is conducted to determine the soil fertility management necessary for wheat production.

8.1.1 Management options

There are 6 management options considered, denoted by M. Management options involve combinations of soil fertilisation, stubble treatment, and tillage methods for moisture retention and weed control (Table 8.1). Fertilisation options involve applying N at two rates – zero (0N) and the optimal rate for medium *SM* from Chapter 7 (+N).

The M evaluated here involved either cultivating or spraying for weed control and either retaining or burning the stubble during the fallow period. The cultivation options considered were zero tillage (ZT) and a conventional (or full) cultivation (CT). Stubble management involved retaining stubble (ZT or CT) or burn and till

Table 8.1. Crop management options for C analysis

Management option	Description	Strategy
M_1	Zero N, zero tillage	0N, ZT
M_2	Plus N, zero tillage	+N, ZT
M_3	Zero N, conventional till	0N, CT
M_4	Plus N, conventional till	+N, CT
M_5	Zero N, burn and till	0N, BT
M_6	Plus N, burn and till	+N, BT

(BT). ZT 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 again. Soil outcomes under CT are likely to be poorer soil structure (including the chance of severe soil erosion), less soil moisture and lower SOM levels. Burning of stubble under BT reduces replenishment of SOM and uses cultivation for weed control. The same adverse soil outcomes for CT are likely for BT.

The costs associated with the management options (derived from Scott 2002) are presented in Table 8.2. Variable costs of management options are used in the analysis because the focus is at the enterprise rather than the farm level. Different management requires different types of machinery and the costs are 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.

8.1.2 Profit function

As discussed in Chapter 6, wheat production is a multi-output process by which yield (y_1) and protein (y_2) depend on underlying soil fertility (proxied by *SOC*),

Table 8.2. Crop management options and variable costs, C analysis

Name	Fallow(b) $/ha	Wheat costs(a) Variable(c) $/ha	Total $/ha
M_1	43	177	220
M_2	43	177	220
M_3	25	145	170
M_4	25	145	170
M_5	14	145	159
M_6	14	145	159
	Urea N added at a cost of $1.00/kg N		

(a) Wheat costs from Scott (2002).
(b) Summer fallow for wheat.
(c) For +N options, excludes N (urea) fertiliser cost
(d) Fallow cost for CT and BT involves 3 and 2 workings with a chisel plough, respectively.

management inputs (M_i) and a random element (ε). The production function at time t can be written as:

$$(y_{1t}, y_{2t}(y_{1t})) = y\ (SOC_t, M_t, \varepsilon_t)$$

The price of wheat depends on protein content, but crop income is based on yield. The crop profit (π) or stage return function is:

$$\pi_t = p_y(y_2).y(y_{1t}, y_{2t}(y_{1t})) - p_n N - C_t(M_t),$$

where p_y and p_n are the prices of wheat and N respectively, N is the amount of fertiliser applied and $C_t(M_t)$ are the other costs associated with alternative management practices (Table 8.2).

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 optimal N management strategies developed in Chapters 6 and 7 are based on soil moisture at sowing. The crop planting rules used in the simulations for this SOC analysis are based on a minimum level of soil moisture during the planting window. Therefore management of soil moisture has been included in this analysis, even though it is not explicitly included in the economic model.

8.1.3 Dynamic programming formulation

The deterministic optimisation problem can be written as:

$$\max_{M_t} \sum_{t=1}^{T} \rho^{t-1} \pi_t (SOC_t, M_t) + \rho^T F(SOC_{T+1}),$$

subject to

$$SOC_{t+1} = SOC_t + g(SOC_t, M_t),\ M_t \in (M_1, ..., M_6).$$

The DP framework is required because the profit and transformation relationships are not continuous or smooth. In addition, there is uncertainty associated with the stage return and state transformation relationships, so SDP is required.

8.1.4 Stochastic dynamic programming formulation

Stochastic programming is used when the state transformation and the stage return depend not only on the state of the system and the decision taken, but also on unpredictable events outside the control of the decision maker (Kennedy 1986). de Koeijer *et al.* (2003) state that the most important variable production factors are soil fertility, occurrence of pests, weeds and diseases, and weather. The impacts of pests, weeds and diseases have been excluded from this analysis to concentrate on managing soil fertility for crop production under conditions of weather variation. APSIM uses daily temperature and precipitation inputs to simulate crop growth, and this analysis utilises 100 years of such weather data at Breeza to generate distributions of crop outcomes for each M. The effects of daily and annual weather variability are felt in wheat production and wheat profits.

The objective becomes to maximise the expected present value of profit (*EPV*):

$$\max EPV = \max_{M_t} E\left[\sum_{t=0}^{\infty} \rho^t \pi(SOC_t, M_t, e_t)\right], \qquad (8.1)$$

where e_t is the error term associated with the probability distribution for π and *EPV*. This is subject to a set of first order difference equations for the state variable:

$$SOC_{t+1} = SOC_t + g(SOC_t, M_t, \varepsilon_t), \qquad (8.2)$$

where ε is a random variable defining the probability distribution for the state variable.

The recursive equation becomes:

$$V_t(SOC_t) = \max_{M_t}\{E[\pi(SOC_t, M_t, e_t)] + \rho E[V_{t+1}(SOC_{t+1})]\}. \qquad (8.3)$$

A numerical solution procedure (DP) can be used to solve the recursive equation (8.3). The state and decision variables are discrete, with the state space represented as a vector of values covering the range of interest. The recursive equation is solved for all values of M_t for each SOC_t, based on transition probability matrices.

The state transition involves probabilities of events occurring. Jones *et al.* (2003) used *i* and *j* as 'from' and 'to' indexes for states, *k* as an index of decisions, and p_{ij}^k as the (transition) probability of going from state *i* at stage *t* to state *j* at stage *t+1*, given that the *k*-th decision is applied. The state transition probabilities can be derived from the density function for ε_t, or they can be estimated by running the biophysical simulation model for historical weather sequences (100 years of weather were available). If the stage return is random as well, the probability p_{in}^k represents the probability for a stage return *n* corresponding to state *i* and the *k*-th decision. The recursive equation can be written as:

$$V_t(i) = \max_k \left[\sum_n p_{in}^k \pi(i,k) + \rho \sum_j p_{ij}^k V_{t+1}(j) \right]. \tag{8.4}$$

This is the numerical approach adopted in this study for solving the SDP soil fertility problem.

The solution process involves integration of a biological simulation model and the SDP model. The solution process is shown in Figure 8.1.

8.2 Biological model

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 the location for which the N simulations were conducted. Historical average annual rainfall at Breeza has been 600 mm, with slight summer dominance. 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 in the context of the overall northern grains region by Webb *et al.* (1997).

The issue being tested in this chapter and the next is how alternative management strategies for wheat production influence long term profits, in part through impacts on SOC with associated implications for soil water-holding capacity. The analysis required predictions of agronomic and soil biology changes under different management strategies and climatic conditions. The APSIM model (see section 6.9.2) was again used to simulate these responses to management and climate using 100 years of historical climate data. The average agronomic results provided inputs to the production (y_t) and stage return (π) functions. The 99 year-to-year changes for biological (SOC) results (except for the reset years, see below) were used to estimate the transition probabilities p_{ij}^k associated with (8.2) for each management

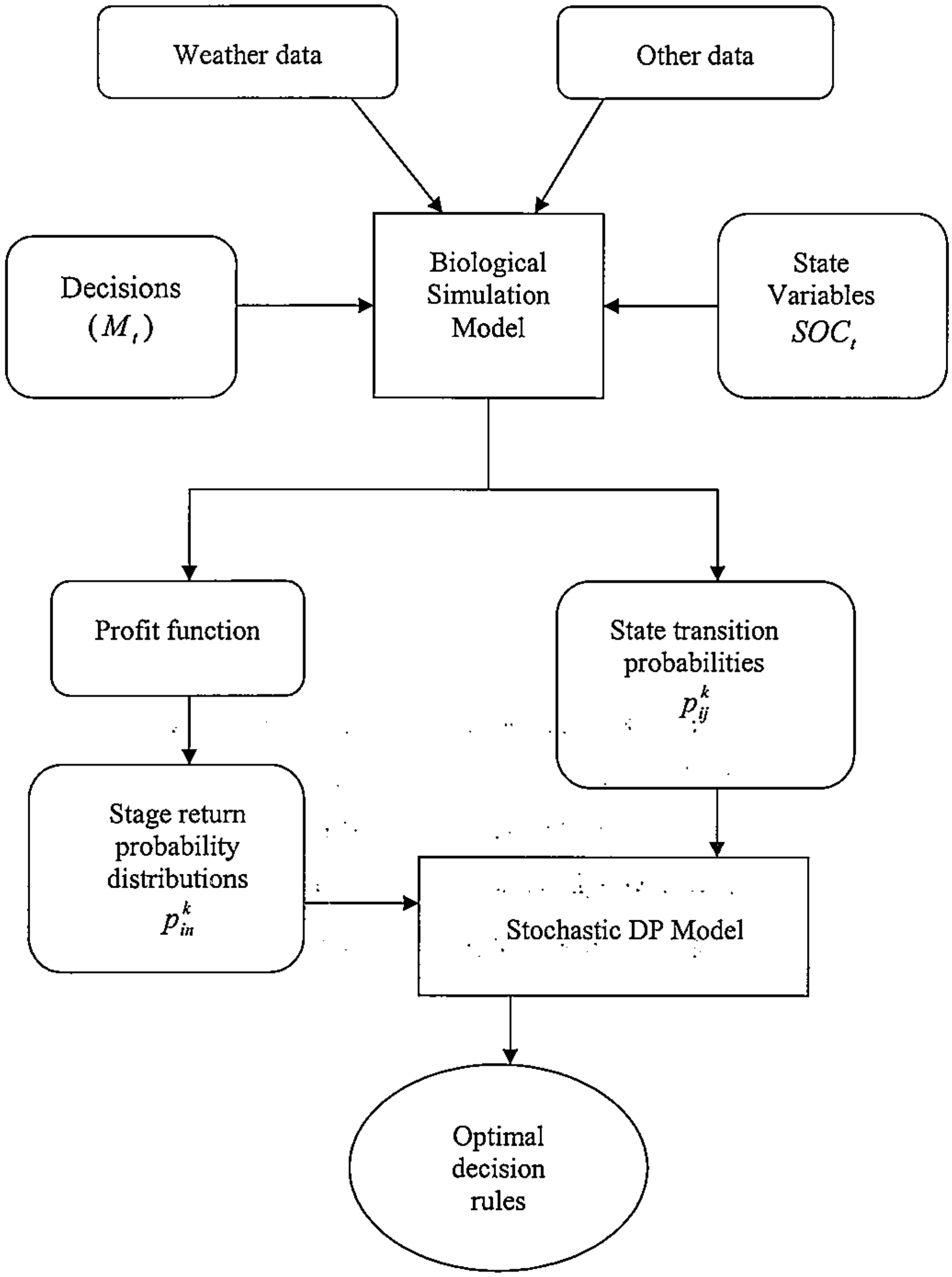


Figure 8.1. Interaction between biophysical and economic models for C analysis

strategy. The stage return probabilities p_{in}^k were also derived from wheat revenue calculated from the simulation results (wheat yield and protein content) in each year.

The simulation model was calibrated to the Breeza site using relevant biological parameters and past trial data. The pattern of, and relationship between, paddock and simulation modelling activities is shown in Figure 8.2.

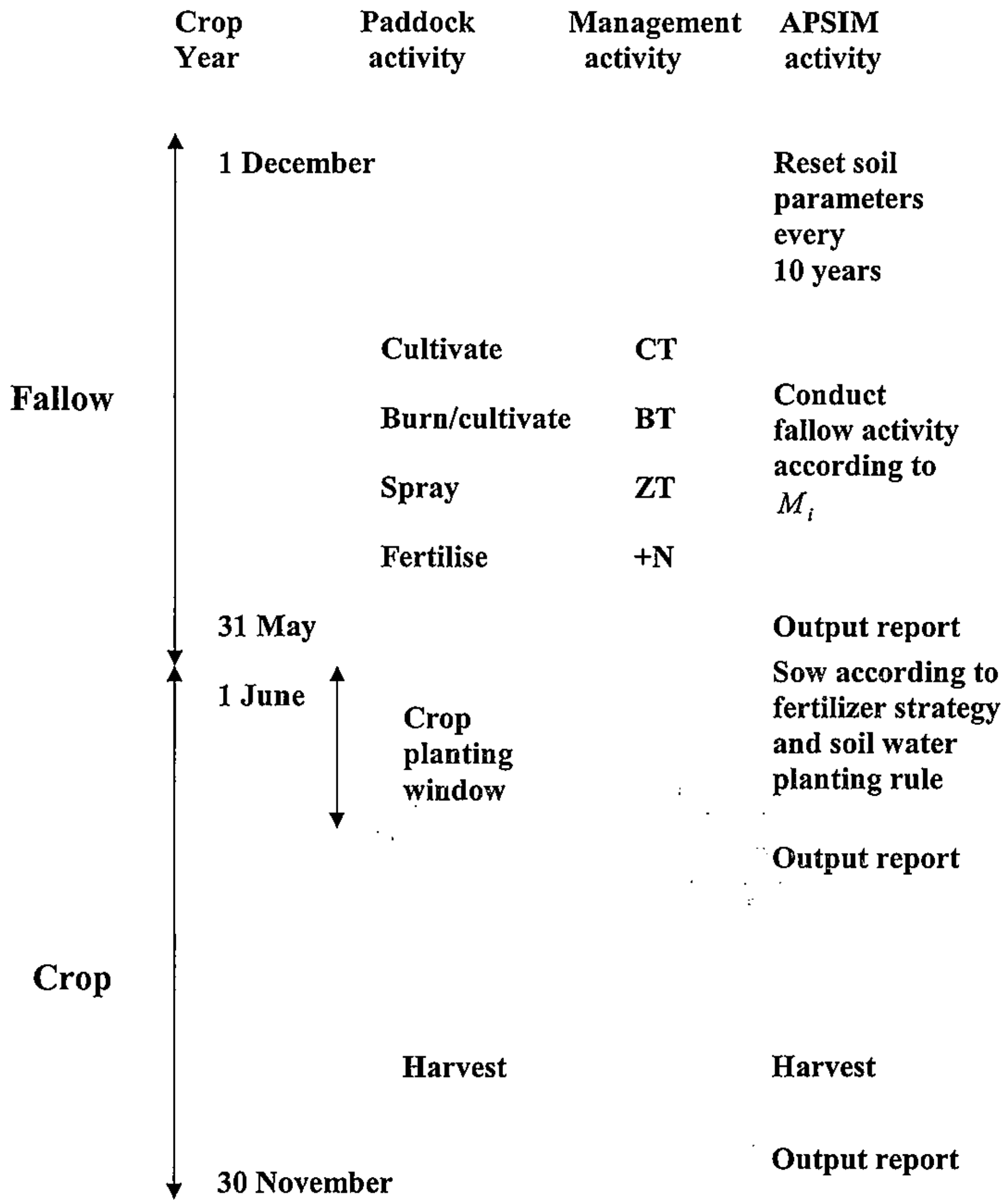


Figure 8.2. Crop year activities

8.2.1 Accounting for soil carbon

In a cropping system, C is found both above (plant residues) and below ground (incorporated plant residues, plant roots and soil organic matter). The representation of C processes within APSIM is shown in Figure 8.3. In that Figure, *FOM* is the fresh organic matter, *BIOM* is the more labile (mobile) soil microbial biomass and products, and *HUM* is the rest of the SOM. Flows of C from plant residue pools to SOM pools (plant decomposition) and from one organic matter pool to the other (organic matter decomposition) all involve loss of C from the soil system to the atmosphere (as CO_2 respired by micro-organisms). Carbon may also be lost from the soil system by burning of plant residues. To maintain organic matter concentrations in the soil, these C losses (outputs) need to be balanced by plant photosynthesis (C inputs).

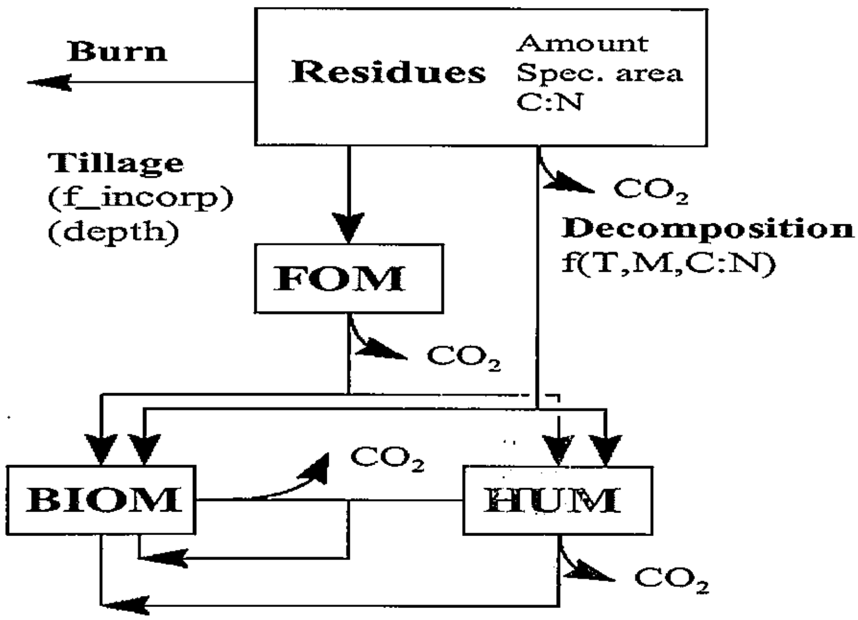


Figure 8.3. Carbon processes in cropping systems. Fresh organic matter (FOM), soil microbial biomass and products (BIOM), and all other soil organic matter (HUM). Adapted from APSIM version 1.6.

Since major management decisions typically are made based on an annual cycle in cropping systems, it is important to evaluate the impact of these decisions over the same time frame, i.e. on a yearly basis. It is relatively straightforward to account for organic matter decomposition over a year; simply compare the level of SOC at the start of the period with the level at the end of the period. However, it is more complex to account for C inputs as a result of the decisions. This is because although all photosynthetic inputs resulting from the decision are generated in the decision-year, much of that C is actually lost as carbon dioxide during decomposition over subsequent years rather than being added to SOM.

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 (10 years) the changing SOC contents are measured by:

$$\Delta Soil\ C = (BIOM + HUM)t_1 - (BIOM + HUM)t_0$$

where the initial and longer term *FOM* and *Residues* impacts within APSIM are included in this measure. The transition probabilities were calculated for a stage of one year.

8.2.2 Impact of soil carbon

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 'bucket size'. In APSIM the amount of soil water capable of being stored in a soil is specified according to three parameters - LL15, DUL and SAT. The parameter LL15 is the 15-bar lower limit of soil water content. It is approximately the driest water content achievable by plant extraction. This defines the 'bottom of the bucket'. DUL is the drained upper limit of soil water content. It is the content of the bucket retained after gravitational flow and is sometimes referred to as 'Field Capacity'. The difference between DUL and LL15 is plant available water content (PAWC). SAT is the saturated water content. This defines the "top of the bucket". These parameters are defined at each soil layer in APSIM. An example of the variation in bucket size with soil depth is shown in Figure 8.4.

There are 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 water-holding capacities at different levels of SOC was derived for testing in this analysis.

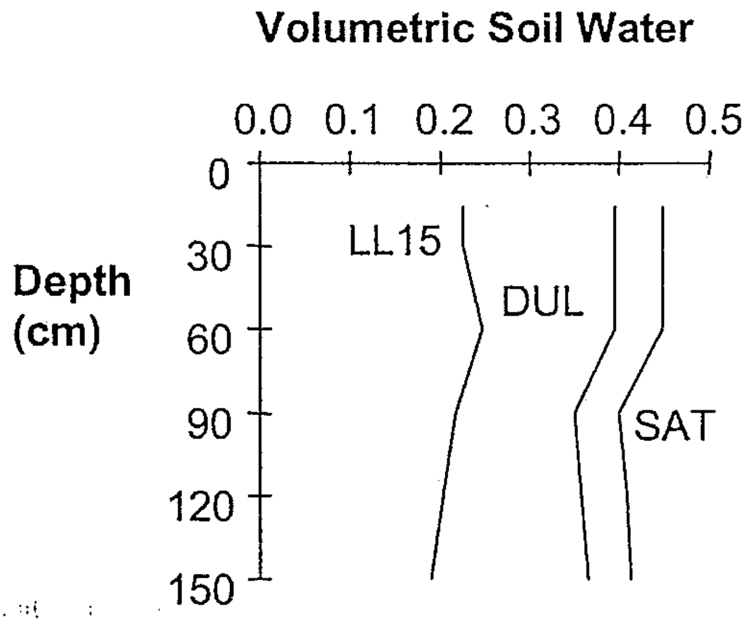


Figure 8.4. Soil water holding capacity and soil depth (APSIM documentation)

The parameter values in Table 8.3 were suggested by Dr Merv Probert (CSIRO, personal communication). Changes in soil water-holding capacity 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.

Table 8.3. 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
LL15	mm/layer	22	22	22	22	22	22
DUL	mm/layer	48	48	48	42	42	42
SAT	mm/layer	53	53	53	47	47	47
PAWC	mm/layer	26	26	26	20	20	20

Source: Dr Merv Probert CSIRO (personal communication)

8.2.3 Experimental design

The experimental design involved selecting a range of SOC contents in soil. Soil measurements were taken at the Breeza site (Dr Graeme Schwenke, personal communication). 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.

Seven concentrations of SOC were simulated so the recursive equation was solved for the following values of the state variable [1.76, 1.66, 1.56, 1.46, 1.36, 1.26, 1.16]. The unit of measurement for SOC within APSIM is tonnes per ha, but it is easy to convert between the SOC percentage and tonnes per ha using the soil bulk density. Changes in SOC measured in the top 10 cm of soil were used in developing the transition probabilities.

8.2.4 Simulation strategy

To generate the results required to estimate the transition probabilities, the model was specified to run in a fallow-crop sequence. Within the model, soil moisture and soil nitrate levels were reset every 10 years to average post-harvest levels, and SOC was reset to the different SOC concentrations as required in the experimental design and Table 8.3.

Sowing decisions were based on sowing window dates and moisture contents in the soil profile and on the soil surface. These parameters were derived from current agronomic recommendations in the district. If soil moisture content was insufficient during the planting window, no crop was planted.

With respect to the +N fertiliser management strategy, testing of the optimal rules from Chapter 7 (Table 7.3) showed that their application needed to be carefully assessed. Those rules from Chapter 7 were developed based on sowing at a specific date. The more usual practice is that farmers use a time window (from 1 June to 15

August at Breeza) to make the sowing decision. Within this period APSIM checks daily for soil moisture conditions as a basis for crop sowing.

When running APSIM with these separate N strategies (from Table 7.3) for the C analysis it became apparent that in some years both the dry and medium *SM* conditions could be met within the same sowing window. This caused complications when simulating N strategies and making comparisons. As a result it was decided that for the C analysis only one +N strategy would be tested. This strategy was for medium *SM* conditions, i.e. to add fertiliser N so that soil available N was 205 units at sowing.

8.3 Practical issues

The results presented in the next chapter are derived from APSIM analysis where predictions of outputs (yield and protein content of wheat) and outcomes (changes in SOC status) are the basis for an economic evaluation of management strategies. These results are synthetic, and need to be considered as such by crop managers and advisors.

A practical issue for the question of SOC management relates to the accuracy with which SOC can be measured in farm paddocks by commercial soil tests. Schwenke *et al.* (1997b) 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 is impossible to distinguish responses of SOC to management from sampling error. Therefore, monitoring SOC to check the results of management is unlikely to be a useful short-term management tool at the farm level.

8.4 Summary

The carbon model is based on production and profit functions in which wheat returns depend on management (including N fertilisation) and also on the stock of SOC, which contributes through a hypothesised link to soil water-holding capacity. Because of soil carryover effects, the dynamic model specification includes, as a constraint, the process of change in SOC from one year to the next. Climatic variability is an inherent part of the system, so the stage returns and state transitions are expressed as probabilities.

A bio-physical simulation model was used to predict yields and changes in SOC. The model, operating on a daily time step, was run using 100 years of weather data. These results were used to develop the stage return and state transition probabilities for the recursive equation (8.4), which was solved numerically using DP techniques.

Only a particular part of the soil-crop system was analysed, which assumes that other management factors are accounted for according to best management practice. This is in line with the discussions in Chapter 3, that it is necessary to analyse sub-components of crop enterprise or system in detail before wider ramifications (eg at the whole farm level) are considered. Because the model and analysis are based on simulation predictions, the results must be considered as synthetic. However, such approaches are a valid part of the R&D process.

9. The Carbon Results

9.1 Introduction

The results of analysis with the C model described in Chapter 8 are presented here. First, the biological results of state transition probabilities and stage return matrices are shown. Then the results of the economic analysis are presented. A sensitivity analysis is included. The economic results include optimal decisions for management of different initial soil fertility levels, the time paths of SOC levels to stable equilibria, and the NPVs at a 7% discount rate.

9.2 Biological results

APSIM results for the management strategies set out in Table 8.1 are first presented. These results consist of 100 years of simulations for each management strategy. Trends in SOC over 10 years for each management strategy from the APSIM simulations are shown in Figure 9.1. These are averages of ten 10-year cycles from initially 'low', 'medium' and 'high' levels of SOC. At each fertility level the +N strategies show increasing SOC, whereas the zero N strategies have flat responses.

The results are also presented as probabilities of falling within SOC and wheat income categories which are given in Table 9.1. The presentation of biological information involves the probabilities that SOC will move from any initial state in year *t* to any other state in year *t+1*. This representation is based on assumptions concerning the Markov property, that such transition probabilities are not affected by decisions or events beyond one year, and that the biological processes are stationary, i.e. that they do not vary over time. The stage return probabilities are, for any initial SOC state in any year, the chance of wheat income being within any income category in that year. Both these probability tables are developed for each management strategy.

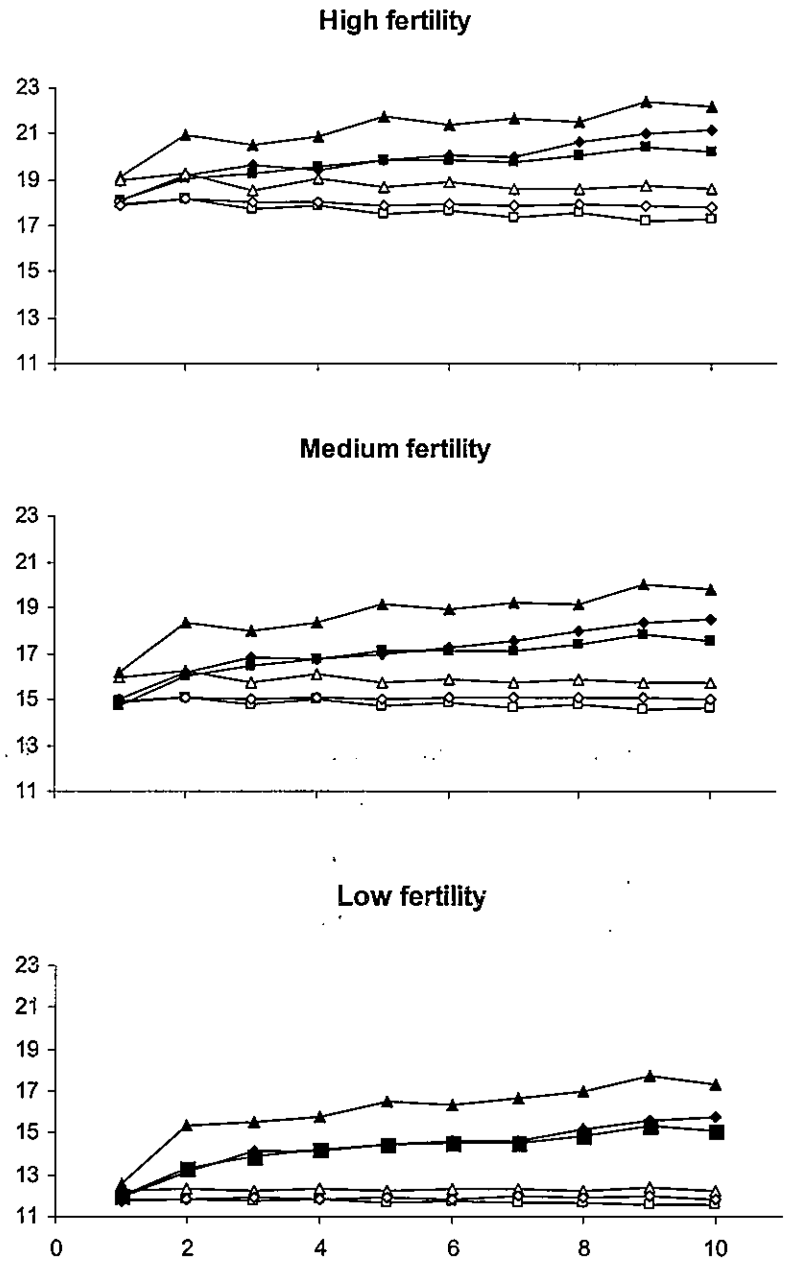


Figure 9.1. Average changes in below-ground carbon (0-10 cm) in wheat crops at Breeza over 10 years under different crop strategies (triangles, wheat cultivated; diamonds, wheat no-till; squares, wheat burn-till; solid shapes, plus N; blank shapes, zero N)

Table 9.1. SOC and wheat income categories, C analysis

SOC level t/ha	Category	Wheat income level $/ha	Category
14-15	1	0-300	1
15-16	2	300-600	2
16-17	3	600-900	3
17-18	4	900-1200	4
18-19	5	1200-1500	5
19-20	6	1500-1800	6
20-21	7	1800-2100	7
21-22	8	>2100	8
22-23	9		
23-24	10		

The state transition matrices for management strategies 1 and 2 (BT) are shown in Tables 9.2 and 9.3. Similar information for other management is presented in Appendix 3. In Table 9.2 with zero N, there is an 11% chance of SOC levels in category 2 (15-16 t/ha from Table 9.1) in any year falling to 14-15 t/ha in the following year, whereas there is a 71% chance that SOC will remain in category 2, and an 18% chance of increasing to 16-17 t/ha. From Table 9.3 the corresponding probabilities for the plus N case are 17%, 3% and 53%, with a 27% chance that SOC will increase to 17-18 t/ha. Thus there is an 80% probability that SOC will increase from state 2 to state 3 or higher when N fertiliser is used with the BT management.

Table 9.2. State transition matrix for SOC: Burn and till with zero N

SOC_t	SOC_{t+1} category									
	1	2	3	4	5	6	7	8	9	10
1	0.88	0.12								
2	0.11	0.71	0.18							
3		0.31	0.47	0.22						
4			0.29	0.56	0.15					
5				0.23	0.64	0.14				
6					0.16	0.67	.017			
7					0.01	0.24	0.58	0.17		
8							0.27	0.62	0.11	
9							0.06	0.48	0.39	0.07
10								1.00		

Table 9.3 State transition matrix for SOC: Burn and till with added N

SOC_t	SOC_{t+1} category									
	1	2	3	4	5	6	7	8	9	10
1	0.20	0.50	0.30							
2	0.17	0.03	0.53	0.27						
3	0.05	0.13	0.23	0.50	0.09					
4		0.10	0.10	0.28	0.42	0.09				
5			0.15	0.09	0.33	0.37	0.06			
6				0.11	0.09	0.40	0.32	0.08		
7					0.06	0.12	0.45	0.30	0.07	
8						0.09	0.10	0.44	0.39	
9							0.11	0.09	0.46	0.35
10								0.14	0.08	0.78

The patterns of state transition probabilities for other management strategies with zero N are presented in Appendix Tables 3.1 and 3.5. The probabilities for all zero N cases generally cluster around the diagonal, where $SOC_t = SOC_{t+1}$, so that these management strategies do not appear to promote the build-up of SOC. The patterns of probabilities for other plus N strategies are shown in Appendix Tables 3.3 and 3.7. In contrast to the zero N case, the patterns of probabilities in each of these cases are that SOC would be likely to build up over time.

Stage return matrices for the BT strategy are shown in Tables 9.4 and 9.5. A comparison of the pattern of probabilities in each case indicates that wheat enterprise income is likely to increase under the N fertilisation strategy. The patterns of probabilities for other strategies are shown in Appendix Tables 3.2 and 3.4 (for CT) and 3.6 and 3.8 (for NT). Similar trends to the BT case are observed for each management strategy

Table 9.4. Stage return matrix for SOC: Burn and till with zero N

SOC_t	Wheat income category							
	1	2	3	4	5	6	7	8
1	0.87	0.10	0.03					
2	0.89	0.03	0.08					
3	0.72	0.21	0.06	0.01				
4	0.73	0.20	0.04	0.04				
5	0.70	0.25	0.02	0.01	0.01			
6	0.65	0.30		0.04	0.01			
7	0.58	0.36		0.05	0.01			
8	0.56	0.38	0.01	0.05				
9	0.65	0.35						
10	1.00							

Table 9.5. Stage return matrix for SOC: Burn and till with added N

SOC_t	Wheat income category							
	1	2	3	4	5	6	7	8
1	0.20	0.05	0.30	0.30	0.15			
2	0.17	0.03	0.40	0.33	0.07			
3	0.23	0.05	0.30	0.36	0.05			
4	0.24	0.08	0.28	0.36	0.04			
5	0.29	0.06	0.22	0.32	0.11			
6	0.24	0.08	0.18	0.38	0.11	0.01		
7	0.21	0.06	0.23	0.32	0.17	0.01		
8	0.24	0.07	0.20	0.31	0.16	0.01		
9	0.22	0.06	0.23	0.33	0.15			
10	0.29	0.10	0.17	0.34	0.10			

9.3 Economic results

9.3.1 Deterministic simulation

The first set of results is derived from solving equation (8.4) using the transition probabilities and stage return probabilities discussed above. 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 9.6, and the optimal state paths are in Figure 9.2.

Table 9.6. 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	CT/+N	CT/+N	CT/+N	CT/+N	CT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N
2	CT/+N	CT/+N	CT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N
3	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N
4	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N
5	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N
6	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N	NT/+N
NPV	5549	5499	5493	5591	5528	5590	5650	5721	5856	5866

(a) Management strategies from Table 8.1
(b) $/ha at 7% discount rate

These results are calculated in an expected value framework, where the stage return probabilities are multiplied by mid-interval incomes (wheat income categories in

Table 9.1) to provide the expected income for each decision in each state in each time period. This is a deterministic simulation based on expected values (Cacho 1997).

From Table 9.6 several points can be made. First, the optimal decision converges by year 3 to a stable strategy for each initial soil fertility level. Second, all optimal management involves applying N, as discussed above. Third, the optimal final management always involves no tillage. Finally, as expected, the NPV figures 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 time leads to a relatively flat economic response, as seen in Figure 7.7 and the associated discussion.

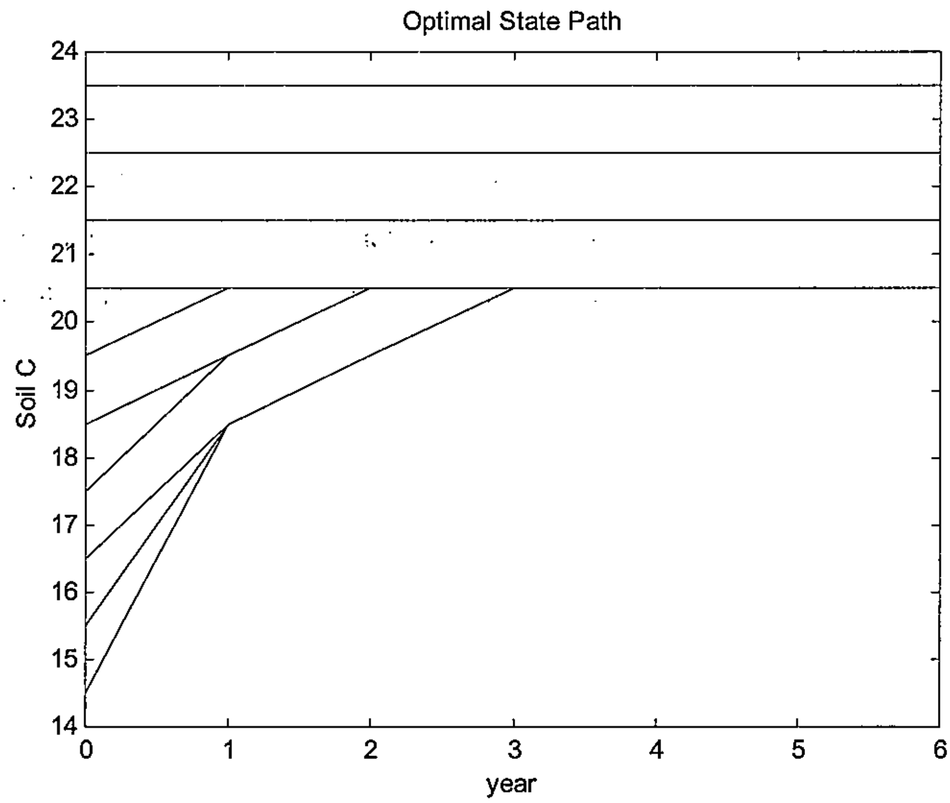


Figure 9.2. Optimal path for SOC from initial values

Examination of Figure 9.2 shows that the optimal level of SOC is a minimum of 20-21 t/ha, this is 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 in this deterministic case it is optimal to maintain the SOC at its original levels rather than let it run down. This counterintuitive result may be due to interactions between management costs (Table 8.2) and the state transition equations (Tables 9.2, 9.3 and Appendix Tables 3.1, 3.3, 3.5, and 3.7).

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.

A sensitivity analysis was conducted for the discount rate used in the analysis. As the discount rate was raised by 1 percentage point the NPVs were reduced slightly, but there was no change in the optimal management pattern. This is the same result as in the N analysis.

9.3.2 Monte Carlo simulation

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 deterministic analysis does not allow representation of 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 (Tables 9.2 and 9.3 and Appendix Tables 3.1, 3.3, 3.5, and 3.7) as a cumulative distribution function, as shown in Figure 9.3. The sampling process 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 (Figure 9.3), 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, as presented in Figure 9.2), the stochastic state transition was simulated over 6 years (twice the time period to achieve convergence in the

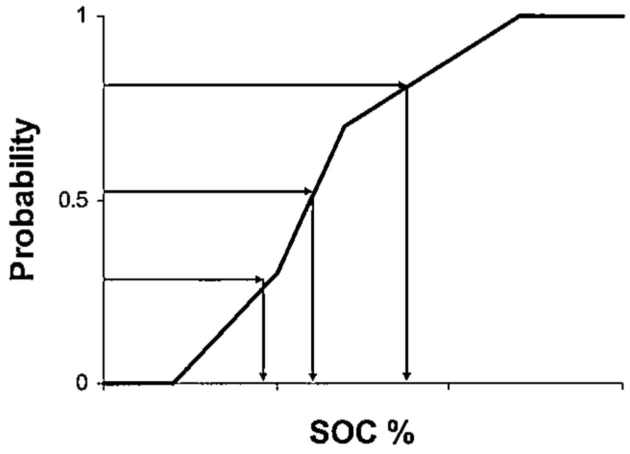


Figure 9.3. Cumulative distribution function for transition probabilities of SOC

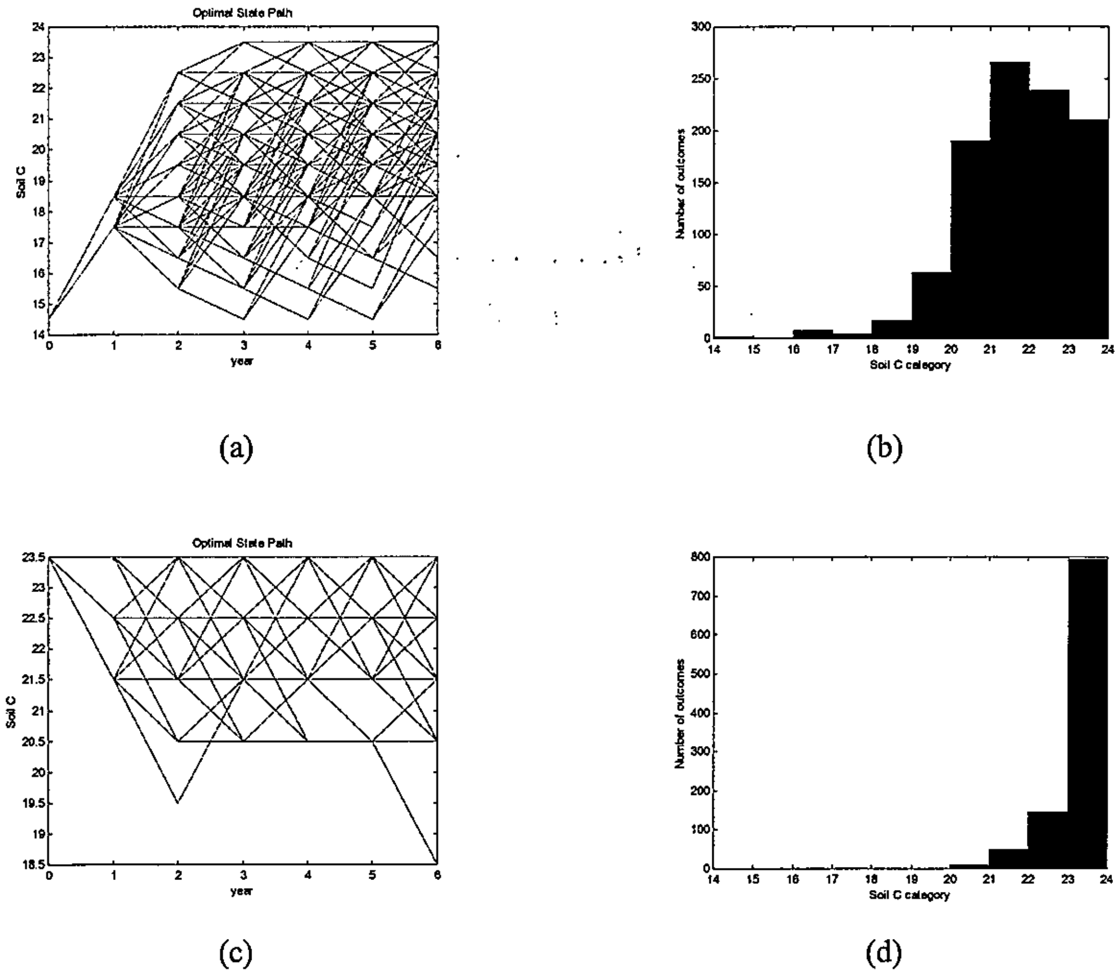


Figure 9.4. Stochastic results for low and high initial SOC levels, temporal pattern of change and histogram of final values after 6 years

deterministic simulation). For each initial SOC level, 1000 random draws were generated and the same series was used by specifying the initial random seed. 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 9.4.

The results in Figure 9.4 show that rather than the precise optimum state paths from the deterministic simulation seen in Figure 9.2; there is a distribution of outcomes after 6 years. With an initially low SOC content (Figure 9.4 (a) and (b)); the target level of SOC is 23.2 t/ha (the mean of the distribution in Figure 9.4 (b) 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 (Figure 9.4(c) and 9.4(d)), the mean level of SOC after 6 years is 21.7 t/ha (2.1%), although some outcomes are as low as 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 promotes lower variability in this attribute.

Optimal management was to always apply N and generally to use no tillage, except at lower SOC levels, where conventional tillage is initially used. The alternation between conventional and no tillage would be due to the differences in variable costs and state transition probabilities for these two strategies.

9.4 Implications for Nitrogen results

The question was raised in Chapter 3 of whether the optimal rules for SOC would have an impact on optimal N management, as developed in Chapters 6 and 7. In further discussions with a soil scientist the following points can be made. First, the changed bucket size will have an impact on soil moisture availability at sowing, and different SM levels were already included in the analysis deriving crop responses to added N. Second, the differences in bucket size for in-season crop growth will not be an issue for most years, because the in-crop rainfall would be insufficient to fill the soil water bucket. And third, the question is whether the different bucket size would affect N mineralisation rates during crop growth. Estimates of monthly N mineralisation at Gunnedah range from 15 to 29 kg/ha over the 6 months June to November, according to age of cultivation. This variation in N mineralisation during crop growth is likely to be within the ranges of simulations used to determine the optimum N levels. Based on these points, the soil scientist was of the opinion that the determination of the optimal SOC rule would not affect the optimal N decision (Dr G. Schwenke, personal communication).

9.5 Discussion

The C analysis is based on a hypothesized improvement in soil water-holding capacity as SOC increases. There appears to be little direct soil or agronomic research on this issue, and it could be that the Vertosol soils with high clay content would have less response of this type than other soils (Chan *et al.* 2003). However, the results presented in this chapter are valuable in illustrating the approach, and demonstrating that an optimal stock of SOC is associated with management. This may lead to further hypotheses being generated for field trials or simulation experiments.

The main result of this C analysis is similar to the N analysis, that an optimal level of soil quality can be achieved based on 'best' management practice for growing wheat in northern NSW. The results from this analysis can be compared with SOC levels measured on site. The recommended management practices (Table 9.4) are unsurprising to innovative farmers, scientists and advisory officers – maintain stubble, spray for weed control in fallows, use no tillage, and fertilise to grow large crops which are also more profitable. However, there are still substantial numbers of wheat growers who do not use such practices.

The new information generated here is an estimate of the optimal level of SOC. A minimum of 2.0% SOC for the black clay Vertosol soils at Breeza when growing short-fallow wheat is relatively high compared to the initial level on site, and to Dalal and Mayer's trends in Figure 4.1. However, if the model represents the soil and crop processes accurately such a level is within the capabilities of standard management practices. Sensitivity analysis of the discount rate showed that no management changes occurred at 8%. A stochastic analysis of the state transition processes showed that the distribution of SOC outcomes was wider for low rather than high initial SOC states.

The change in optimum SOC shown here is interesting in light of Lal's (1997) comments on the potential for C sequestration as a result of better soil and crop management. If widespread adoption of improved soil management practices could be encouraged, then potentially there could be substantial changes in SOC levels. In lighter-textured cropping soils the role of SOC in crop production is potentially more important; however, Chan *et al.* (2003) found evidence of sustained improvement in SOC only in the wetter areas of Australia.

While higher levels of SOC may deliver environmental benefits to the rest of the community, the problem of adoption of a private activity (better crop management) for a public good (improved C sequestration) is unlikely to be successful unless the private benefits are clearly demonstrated. The analysis here has shown that there are benefits from reduced tillage techniques and the use of N, both in terms of profits and the capacity to maintain SOC at reasonable levels, so that these cropping systems are more sustainable and resilient.

10. Conclusion

This thesis has addressed the management of soil fertility in crop production. The study was motivated by concern that soil fertility in northern cropping systems is being degraded by poor management so that even from the private (as opposed to the public) perspective of farmers, such practices may not be profitable or sustainable in the long term. By investigating farm-level options for remediation of soil fertility in a wheat production system, the analysis has attempted to identify 'temporally-sustainable' resource use, using a relatively narrow definition of the sustainability term.

The focus on economics and temporal sustainability of a natural resource utilised for human purposes forms the base for an examination of the issue within a neo-classical economic framework. The maximisation of profit obtained from wheat production over the long term and with a soil fertility constraint has allowed a private-benefit analysis of a renewable resource in an inter-temporal framework.

The resulting sustainability emphasis has been on asset renewal and maintenance over time, addressing the question of 'can we sustain the farming system into the future?' This thesis has avoided potentially harder questions such as 'what to do with a non-renewable resource?', 'what mechanisms are able to manage a public resource used by many agents?', or 'how do we change individual management behaviour which increases private costs while aiming to achieve some less tangible environmental (public) benefit?' Nevertheless, the private inter-temporal management of natural resources, which includes trade-offs between present and future costs and benefits, is a substantial issue for many natural resource managers; especially as the externalities associated with the management of soil fertility are uncertain and may be small relative to the cost of reducing them.

The working hypothesis or question of interest tested in this thesis is whether there are real advantages for management in analysing soil quality questions in a dynamic framework, compared to the simpler and cheaper static economic methodology. An assessment of this hypothesis for the two cases studied in the thesis is given below. In each case a brief review of background material is presented.

10.1 Summary

The literature review and discussion of economics and sustainability suggested that, associated with the ideals of sustainable development (as represented for instance by the definition in the Brundtland Report), there are substantial problems in evaluating sustainability issues at both the micro and macro levels. For 'larger' issues (eg species extinction, storage of nuclear waste) problems arise in discounting over very long time periods and incorporating the impacts of irreversibilities. At the micro level, sustainability analyses face problems in defining system boundaries and incorporating the feedback, or carryover, effects on natural resources caused by crop management decisions. The main sustainability issues for renewable natural resources used in agricultural production came down to the need to manage the resource base, used as an input to agricultural production, in a profitable manner over time.

A review of the history of farming systems development in the northern cropping region of NSW provided a basis for a classification of several distinct sub-regions. Within each of these, the particular soil, climate and topography characteristics have influenced development of farming systems that are relatively homogeneous, and therefore are suitable for representative farm or farm enterprise analysis. The two studies presented were for locations within one of the sub-regions, but were for a soil type that is widely distributed in northern NSW and southern Queensland.

The underlying economic theory (optimal control) and methodology (numerical analysis using DP) are well known for analysing the efficient use of resources through time. A number of authors have discussed the application of such techniques to questions of inter-temporal resource management, including the fertiliser input problem when carryover is present. The novel aspects of the work presented here include that soil fertility is defined more broadly than in studies based on mineral nutrients only. The shadow value of a unit of soil N was calculated from both the static and dynamic formulations. Also, the results have been used to develop management strategies and tactics, which should have relevance for wheat growers in northern NSW. Another aspect of the analysis is that wheat has been treated as a multi-output product, with both yield and quality (protein content) being important issues for managers in a variable climatic pattern. Finally, this study represents the first attempt to model the hypothesized advantages (in soil water holding capacity) from higher SOC levels.

Soil fertility has been discussed in terms of the C and N cycles, and evidence of soil fertility decline has been presented for both elements. A sequential approach was used whereby a *ceteris paribus* analysis of the N input question was first conducted ignoring SOC levels. Then, optimal SOC levels were examined based on the optimal N strategy for a range of fertiliser, tillage and stubble management practices.

The dynamic economic analysis of nitrogen management resulted in an estimate of the optimal total stock of soil-available N at sowing, and an optimal application. The sum of these is the strategic target of total crop available N at sowing. The effect of soil moisture is also considered. For instance, when *SM* is medium the strategic level of total N at sowing was 205 units, which in the ideal world would be met by applying 81 units to a soil N stock of 124 units. However, the tactical response if measured soil N differs from this amount is to just add the difference to make total available N up to 205 units. This differs from current recommendations which prescribe N according to yield and protein targets for the current crop. The level of soil moisture at sowing is readily measurable and understood by many growers. The results provide both a long-term strategy and shorter-term tactics for wheat growers.

The marginal value of a unit of N was calculated for both the static and dynamic cases. The marginal value from a single crop perspective was as high as \$16/unit of N at low levels of soil N and decreased to \$1, the marginal cost of fertiliser, when the level of soil available N was optimal. This sort of information could be used in extension programs to convince growers to change the amount of N fertiliser applied. From the DP results the value of the co-state variable for N was much flatter and closer to the marginal value of the input than in the single-crop case. The value of the co-state was derived from changes in the optimal value function at different levels of N stock, which resulted from the optimal decision in each state and stage of the solution.

The first hypothesis related to whether it was potentially valuable to assess the question of N input for wheat production in a dynamic economic framework (by including carryover), rather than using static methods. There are two aspects to this question: are the results different (or different enough to be worried about), and do the results provide more useful information in a realistic decision-making context? The first question is a 'flatness of response' issue. The results in Tables 7.1 and 7.2 indicate that the impact of N-carryover effects is to reduce the dynamic application optima below the static application optima, by substantial amounts in some cases. The NPV of the dynamic decision was substantially larger in the dynamic case for all levels of soil moisture These results support the view that dynamic analysis is worth the extra effort.

The second question would also seem to have a potentially positive response. The climate (rainfall patterns and frost occurrence) is quite variable in northern NSW for wheat growing, and flexibility has been a key aspect of successful cropping systems. The results from Chapter 7 can be interpreted as strategies and tactics; the former representing the long-term optimal fertility target and the latter being applicable as variations in soil moisture and N mineralisation in prior fallows are observed at crop sowing time.

Some agronomists and soil scientists agree that soil fertility is a 'stocks and flows' question and that N carryover is important. However, it may be another matter to ask farmers and scientists to accept these results of what may be considered to be a 'black box' analysis. The total optimal dynamic N stocks at sowing (eg 205 units for medium soil moisture) appear to be very high, although recent survey evidence suggests that some growers are applying very large amounts of N to their wheat crops. The explicit recognition of N carryover in this analysis, the use of an optimising economic framework which allows optimal stocks of a resource to be developed, and the presentation of results as management strategies and tactics together comprise a step forward in making N recommendations for sustainable wheat production in northern NSW.

The soil carbon analysis represented a broader interpretation of soil fertility than just of a single limiting factor, and was also based on hypothesized production advantages associated with increased SOC from deliberate management. Many authors have talked generally about the benefits of SOC, but fewer have been prescriptive about them. In discussions with soil and plant systems experts it was suggested that improved fertiliser, tillage and stubble management would improve SOC, and that this could have an impact on soil water-holding capacity. A set of parameters was provided by one scientist as a basis for a hypothetical analysis of the potential benefits from improving wheat production through indirectly influencing SOC. The C analysis was based on these hypothetical benefits, the implication is that if there are no such benefits then there is no use monitoring and managing SOC.

On this basis the C analysis resulted in a set of optimal management strategies for different initial levels of SOC. This was in direct response to the long-term declining trends in Figure 4.1. The aim was to determine an optimal level of SOC, which was not necessarily the original soil status.

The deterministic C results in Figure 9.2 showed that it was optimal to build up SOC to about 2.0 percent in the soil, if starting SOC levels were initially lower. For higher SOC levels it was best to use management to maintain fertility at these levels. The optimal fertiliser strategy always involved using high applications of N to grow large crops, and tillage management involved no-till in the longer term. When a stochastic simulation of the transition probabilities was conducted the results showed a distribution of outcomes that was wider for lower than higher initial states.

This analysis has involved a novel application of optimality for soil fertility measured in terms of SOC. It has relied on a set of parameters hypothesising improvements in soil water-holding capacity from higher levels of SOC. Soil scientists and agronomists have recommended stubble retention for erosion control and chemical fallows for soil moisture and N accumulation prior to sowing. The outcome is that declines in SOC (due to continuous cereal cropping with aggressive soil and stubble management over a long period) can potentially be reversed. Moreover, the types of management necessary to achieve such changes and the levels of SOC that are likely to result from such management have been suggested. Rather than managing SOC directly, farmers should be using appropriate fertiliser, stubble and tillage management for a more sustainable crop and soil outcome.

In considering the working hypothesis for the C analysis, it seems that there may be value from dynamic analysis if quantification of the potential benefits from higher SOC leads to further R&D on the technical advantages of SOC. The C analysis was contingent on the assumed improvements in soil water-holding capacity. If such an analysis leads to further work which can identify benefits of both a private and public nature, then the hypothesis of advantageous dynamic analysis may be accepted. Again, a benefit of this approach is that an optimal level of SOC can be estimated for different soil types. A potential problem is the difficulty in practically measuring SOC with acceptable accuracy and at reasonable cost.

10.2 Further research

Whether scientists, advisory officers and wheat growers will accept these results is yet to be seen. When considering the recommendations for fertilisation, tillage and stubble management outlined above it must be remembered that this is a normative analysis based on simulation model results. The study has taken a wider view of soil fertility through considering both the C and N cycles and investigating both direct and indirect management of soil fertility. It has developed management strategies and tactics for wheat growers that have recommended higher levels of N application than previously prescribed. Some farmers are beginning to apply N to wheat in similar quantities.

Further research for N application could include the relaxing of various assumptions underlying the analysis to further test the robustness of the results. In particular the split application of N is increasingly possible as more farmers adopt controlled traffic technology. The splitting of N applications may allow a farmer to use more information about *ICR* (and Southern Oscillation Index data and seasonal forecasts) to adjust rates and generate higher profits (or fewer losses). Another example involves the assumption of a uniform price for wheat and N. This could be relaxed since futures markets are already giving some indication of the wheat price in the current and subsequent year. These prices could be combined with an expected or forecast price for subsequent years.

The analysis could also be extended to other soil types and regions with different crop responses. This would allow identification of decision rules that are widely applicable and the conditions under which the rules would vary. The only real constraint on this sort of analysis is the ability of simulation models to be applied for response prediction in all the desired cases.

The analysis could also be extended to consider different crop sequences with alternative management. This is feasible given the range of crops and soil types that the APSIM model can simulate. If a crop and succeeding fallow are treated separately, then an optimal stock of soil fertility can be generated in each case and the results applied as each crop is considered in a crop sequence. The decision rules would be developed according to measured soil moisture and available N at sowing. Such rules would need to be considered together with weed and disease considerations.

Whether these extensions are conducted will depend on the demand for such analyses from farmers and extension agents. The results of this thesis have provided potentially valuable insights into temporally sustainable natural resource use by crop and farm managers. Thinking in the terms advocated here can be applied to analyses of similar issues, for instance strategies to control insecticide resistance in cotton production.

The sustainability of soil fertility in its application to crop production has not generally been discussed in an economic context. However, questions such as 'what are the optimal levels of C and N for sustainable crop production?' lend themselves to economic analysis because of the optimising framework. This study has demonstrated an approach to answering such questions.

Appendix 1: Fitted response equations for N analysis

The APSIM responses to total nitrogen available were estimated and the parameters of the equations are presented in the Tables below. For the yield and protein responses a modified Mitscherlich equation was used, although in some cases the yield response was essentially flat. The nitrogen left after harvest responses were linear. The Mitscherlich equation below was used for all protein and most yield responses:

$$Y = \alpha + (\beta - \alpha)[(1 - k\exp((N-1)(TotalN - 100)/100))/(1 - k\exp(N-1))] \qquad \text{(A6.1)}$$

Two yield datasets were fitted with the data points for total nitrogen = 75 omitted, and three were fitted with an overall mean only (found in column 2). One yield dataset was fitted with an altered equation:

$$Y = \alpha + (\beta - \alpha)[(1 - k\exp((N-1)(TotalN - 60)/140))/(1 - k\exp(N-1))] \qquad \text{(A6.2)}$$

Clair Alston and Steve Harden (NSW Agriculture) helped with the estimation of these relationships.

Appendix Table 1.1 Estimated parameters of yield response equations

Soil moisture at sowing	In-crop conditions	Alpha	Beta	k	Number of data points
	Very poor	NA	1.01	NA	NA(a)
	Poor	NA	1.72	NA	NA(a)
Very dry	Average	2.20	2.29	0.58	9(b)
	Good	2.78	2.78	0.25	10
	Very good	3.51	3.78	0.64	10
	Very poor	NA	1.47	NA	NA(a)
	Poor	2.28	2.29	0.35	9(b)
Dry	Average	2.78	2.82	0.47	10
	Good	3.25	3.41	0.60	10
	Very good	3.76	4.27	0.72	10
	Very poor	2.00	2.15	0.25	10(c)
	Poor	2.79	2.84	0.52	10
Medium	Average	3.15	3.28	0.60	10
	Good	3.54	3.82	0.66	10
	Very good	3.94	4.68	0.77	10
	Very poor	3.20	3.39	0.64	10
	Poor	3.49	3.84	0.71	10
Wet	Average	3.70	4.15	0.73	10
	Good	3.94	4.68	0.78	10
	Very good	4.26	5.44	0.83	10
	Very poor	3.38	3.67	0.67	10
	Poor	3.59	4.09	0.73	10
Very wet	Average	3.76	4.39	0.76	10
	Good	3.95	4.87	0.80	10
	Very good	4.24	5.65	0.84	10

NA: Not Applicable
(a) Flat response, intercept only
(b) One data point omitted
(c) Functional form (A6.2)

Appendix Table 1.2 Estimated parameters of protein response equations

Soil moisture at sowing	In-crop conditions	Alpha	Beta	k	Number of data points
	Very poor	15.19	15.32	0.42	10
	Poor	13.02	13.43	0.56	10
Very dry	Average	11.35	12.73	0.79	10
	Good	10.74	11.48	0.71	10
	Very good	9.88	11.13	0.84	10
	Very poor	14.26	14.36	0.40	10
	Poor	11.89	12.74	0.69	10
Dry	Average	10.77	11.76	0.76	10
	Good	10.16	11.23	0.80	10
	Very good	9.62	11.16	0.88	10
	Very poor	12.84	13.54	0.63	10
	Poor	10.81	12.09	0.80	10
Medium	Average	10.27	11.59	0.82	10
	Good	9.79	11.11	0.85	10
	Very good	9.31	10.98	0.92	10
	Very poor	10.52	11.92	0.82	10
	Poor	9.92	11.37	0.87	10
Wet	Average	9.61	10.98	0.87	10
	Good	9.37	10.98	0.92	10
	Very good	9.08	10.57	0.94	10
	Very poor	10.52	11.92	0.82	10
	Poor	9.92	11.37	0.87	10
Very wet	Average	9.61	10.98	0.87	10
	Good	9.37	10.98	0.92	10
	Very good	9.08	10.57	0.94	10

Appendix 2: N Simulation model results

Appendix Table 2.1 Static deterministic results for optimal N application decisions and annual wheat gross margin returns

Soil moisture at sowing	In-crop climate patterns	Optimal application of N (a)	Annual gross margin for optimal decision (b)
	Very poor	0	-15
	Poor	85	60
Very dry	Average	105	114
	Good	95	201
	Very good	135	320
	Very poor	0	41
	Poor	105	128
Dry	Average	105	200
	Good	125	257
	Very good	185	370
	Very poor	95	129
	Poor	95	202
Medium	Average	115	256
	Good	145	319
	Very good	165	436
	Very poor	125	276
	Poor	135	323
Wet	Average	155	360
	Good	165	434
	Very good	195	545
	Very poor	125	317
	Poor	165	358
Very wet	Average	155	394
	Good	205	463
	Very good	195	579

(a) Units are kg N /ha
(b) Units are $/ha

Appendix Table 2.2 Dynamic deterministic results for optimum N crop requirements, optimal soil N fertility stock levels, application decisions and net present value of wheat gross margin returns

Soil moisture at sowing	In-crop rainfall	Fallow rainfall	Optimal N applic. u^{**} (a)	Optimal soil N stock x_{LT} (a)	Optimal total N for crop (b)	NPV of optimal decision (c)
Very dry	Very poor	Very poor	40	50	90	80
		Poor	30	60	90	145
		Average	27	63	90	165
		Good	24	66	90	185
		Very good	17	73	90	230
	Poor	Very poor	55	45	100	788
		Poor	45	55	100	854
		Average	42	58	100	873
		Good	39	61	100	893
		Very good	32	68	100	938
	Average	Very poor	70	95	165	1343
		Poor	60	105	165	1408
		Average	57	108	165	1427
		Good	54	111	165	1447
		Very good	47	118	165	1492
	Good	Very poor	71	44	115	1829
		Poor	61	54	115	1894
		Average	58	57	115	1914
		Good	55	60	115	1933
		Very good	48	67	115	1979
	Very good	Very poor	100	80	180	2864
		Poor	90	90	180	2928
		Average	87	93	180	2947
		Good	84	96	180	2967
		Very good	77	103	180	3012
Dry	Very poor	Very poor	50	35	85	571
		Poor	40	45	85	636
		Average	37	48	85	655
		Good	34	51	85	675
		Very good	27	58	85	720
	Poor	Very poor	70	70	140	1386
		Poor	60	80	140	1451
		Average	57	83	140	1470
		Good	54	86	140	1490
		Very good	47	93	140	1535
	Average	Very poor	78	87	165	2029
		Poor	68	97	165	2095
		Average	65	100	165	2114
		Good	62	103	165	2134
		Very good	55	110	165	2179
		Very poor	89	76	165	2460

	Good	Poor	79	86	165	2525
		Average	76	89	165	2549
		Good	73	92	165	2564
		Very good	66	99	165	2610
	Very good	Very poor	112	83	195	3378
		Poor	102	93	195	3443
		Average	99	96	195	3463
		Good	96	99	195	3482
		Very good	89	106	195	3528
Medium	Very poor	Very poor	65	45	110	1317
		Poor	55	55	110	1382
		Average	52	58	110	1401
		Good	49	61	110	1421
		Very good	42	68	110	1467
	Poor	Very poor	82	103	185	1931
		Poor	72	113	185	1996
		Average	69	116	185	2015
		Good	66	119	185	2035
		Very good	59	126	185	2081
	Average	Very poor	88	97	185	2389
		Poor	78	107	185	2459
		Average	75	110	185	2474
		Good	72	113	185	2493
		Very good	65	120	185	2539
	Good	Very poor	96	89	185	2931
		Poor	86	99	185	2996
		Average	83	102	185	3016
		Good	80	105	185	3035
		Very good	73	112	185	3081
	Very good	Very poor	119	86	205	3901
		Poor	109	96	205	3967
		Average	106	99	205	3986
		Good	103	102	205	4006
		Very good	96	109	205	4051
Wet	Very poor	Very poor	83	67	150	2576
		Poor	73	77	150	2641
		Average	70	80	150	2661
		Good	67	83	150	2680
		Very good	60	90	150	2726
	Poor	Very poor	103	122	225	3007
		Poor	93	132	225	3072
		Average	90	135	225	3092
		Good	87	138	225	3111
		Very good	80	145	225	3157
	Average	Very poor	103	102	205	3306
		Poor	93	112	205	3371
		Average	90	115	205	3390
		Good	87	118	205	3410
		Very good	80	125	205	3456
		Very poor	115	90	205	3931

	Good	Poor	105	100	205	3996
		Average	102	103	205	4016
		Good	99	106	205	4035
		Very good	92	113	205	4081
	Very good	Very poor	143	102	245	4840
		Poor	133	112	245	4905
		Average	130	115	245	4925
		Good	127	118	245	4944
		Very good	120	125	245	4990
Very wet	Very poor	Very poor	96	129	225	2919
		Poor	86	139	225	2984
		Average	83	142	225	3004
		Good	80	145	225	3023
		Very good	73	152	225	3069
	Poor	Very poor	102	123	225	3344
		Poor	92	133	225	3409
		Average	89	136	225	3428
		Good	86	139	225	3448
		Very good	79	146	225	3493
	Average	Very poor	103	102	205	3624
		Poor	93	112	205	3689
		Average	90	115	205	3708
		Good	87	118	205	3728
		Very good	80	125	205	3774
	Good	Very poor	117	103	220	4186
		Poor	107	113	220	4251
		Average	104	116	220	4271
		Good	101	119	220	4290
		Very good	94	126	220	4336
	Very good	Very poor	142	108	250	5203
		Poor	132	118	250	5268
		Average	129	121	250	5288
		Good	126	124	250	5307
		Very good	119	131	250	5353

(a) Units are kg N /ha
(b) Total N applied to crop plus optimal soil N level
(d) For an initial soil N level of 100 units, discounted at 7% pa over 10 years, units are $/ha

Appendix 3: SOC Simulation model results

Appendix Table 3.1 State transition matrix for SOC: Conventional till zero N

SOC_t	SOC_{t+1} category									
	1	2	3	4	5	6	7	8	9	10
1	0.17	0.26	0.35	0.22						
2	0.29	0.57	0.03		0.07	0.03				
3		0.23	0.70	0.05		0.01	0.01			
4		0.03	0.14	0.63	0.19	0.01	0.01			
5			0.05	0.41	0.24	0.17	0.07	0.07		
6				0.02	0.21	0.55	0.14	0.02	0.05	
7					0.08	0.16	0.58	0.11	0.01	0.05
8						0.09	0.15	0.55	0.14	0.07
9							0.08	0.22	0.47	0.23
10								0.16	0.51	0.34

Appendix Table 3.2 Stage return matrix for SOC: Conventional till zero N

SOC_t	Wheat income category							
	1	2	3	4	5	6	7	8
1	0.48	0.35	0.17					
2	0.88	0.06	0.06					
3	0.95	0.01	0.02	0.01				
4	0.90	0.08	0.01	0.01				
5	0.73	0.20	0.05	0.02				
6	0.75	0.19	0.01	0.04	0.01			
7	0.80	0.13		0.05	0.01			
8	0.69	0.24		0.07	0.01			
9	0.59	0.40	0.01					
10	0.80	0.20						

Appendix Table 3.3 State transition matrix for SOC: Conventional till added N

SOC_t	SOC_{t+1} category									
	1	2	3	4	5	6	7	8	9	10
1				0.33	0.67					
2	0.14			0.07	0.43	0.21	0.14			
3		0.16			0.16	0.452	0.26			
4		0.06	0.06	0.06	0.03	0.23		0.35	0.13	0.06
5			0.13	0.07	0.11	0.09	0.28	0.26	0.07	
6			0.02	0.15	0.03	0.13	0.20	0.20	0.22	0.05
7				0.11	0.13	0.05	0.18	0.22	0.11	0.17
8				0.02	0.16	0.09	0.07	0.20	0.15	0.31
9					0.01	0.14	0.08	0.06	0.26	0.45
10						0.02	0.12	0.10	0.05	0.71

Appendix Table 3.4 Stage return matrix for SOC: Conventional till added N

SOC_t	Wheat income category							
	1	2	3	4	5	6	7	8
1		0.33		0.67				
2	0.14	0.07	0.43	0.21	0.14			
3	0.16	0.05	0.42	0.32	0.05			
4	0.16	0.03	0.35	0.32	0.13			
5	0.26	0.07	0.24	0.28	0.15			
6	0.23	0.10	0.32	0.23	0.12			
7	0.30	0.10	0.26	0.24	0.10			
8	0.32	0.10	0.22	0.24	0.10	0.02		
9	0.29	0.14	0.21	0.19	0.16	0.01		
10	0.29	0.12	0.20	0.27	0.10	0.02		

Appendix Table 3.5 State transition matrix for SOC: No till zero N

SOC_t	SOC_{t+1} category									
	1	2	3	4	5	6	7	8	9	10
1	0.89	0.11								
2	0.13	0.43	0.44							
3		0.63	0.27	0.10						
4			0.06	0.93	0.01					
5				0.02	0.98					
6						0.89	0.11			
7						0.14	0.63	0.24		
8							0.36	0.47	0.17	
9								0.33	0.66	0.02
10									1.00	

Appendix Table 3.6 Stage return matrix for SOC: No till zero N

SOC_t	Wheat income category							
	1	2	3	4	5	6	7	8
1	0.87	0.12	0.01					
2	0.78	0.18	0.03	0.01				
3	0.90	0.06	0.04					
4	0.77	0.21		0.02				
5	0.78	0.20	0.02					
6	0.66	0.27	0.02	0.03	0.01			
7	0.60	0.34	0.05		0.01			
8	0.56	0.33	0.08	0.03				
9	0.70	0.30						
10	1.00							

Appendix Table 3.7 State transition matrix for SOC: No till added N

SOC_t	SOC_{t+1} category									
	1	2	3	4	5	6	7	8	9	10
1		0.56	0.44							
2			0.47	0.47	0.07					
3		0.06		0.75	0.19					
4			0.09	0.09	0.71	0.11				
5				0.05	0.33	0.56	0.06			
6					0.07	0.43	0.40	0.10		
7					0.02	0.05	0.49	0.38	0.06	
8						0.01	0.06	0.52	0.37	0.03
9							0.01	0.04	0.50	0.44
10								0.02	0.07	0.91

Appendix Table 3.8 Stage return matrix for SOC: No till added N

SOC_t	Wheat income category							
	1	2	3	4	5	6	7	8
1		0.22	0.33	0.33	0.11			
2		0.13	0.40	0.47				
3	0.06	0.19	0.56	0.19				
4	0.06	0.09	0.51	0.34				
5	0.05	0.08	0.30	0.52	0.06			
6	0.06	0.05	0.24	0.61	0.05			
7	0.06	0.05	0.23	0.62	0.05			
8	0.07	0.08	0.16	0.62	0.07			
9	0.04	0.05	0.16	0.59	0.15			
10	0.06	0.05	0.15	0.57	0.17			

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