LAND-USE MODELING FOR EXPLORING ALTERNATIVE AGRICULTURAL FUTURES: LINKING CHOICES AND CONSEQUENCES

by

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Abstract

The Lower Mainland of British Columbia is the province's most concentrated farming region and contributes about 60% of the provincial gross farm receipts. However, agriculture here is faced with significant environmental, social and economic challenges. Rapidly increasing population and urbanization, coupled with intensification of agriculture, are resulting in land-use shifts that are posing a serious threat to its sustainability. Understanding the dynamics of land-use changes and their future evolution, and quantifying their impacts are central to the debate on sustainability.

Land-cover and land-use changes result from complex interactions between environmental and socio-economic factors. Although land-use research commonly has focused on biophysical variables, it is also necessary to understand and incorporate the human factors, particularly the role of human choices and decisions made at individual and institutional levels when predicting land-use changes.

In this thesis I develop a model, AgFutures, which links human decision-making with land-use changes and their consequences. AgFutures is an integrated land-use model that is capable of generating a wide range of possible agricultural futures in response to users' choices related to land-use policy in the region, agricultural management practices, and food consumption preferences. The model forecasts urban and agricultural land-use changes – considering different food production systems comprising extensive cropping, livestock and greenhouse operations – up to 2040, and quantifies their impacts on sustainability, under different user-defined scenarios. It uses a number of social, economic, environmental, agricultural and institutional variables and parameters as input, for projections of land conversions and their impacts.

The key novel aspects of this model include: a) the integration of cellular automata-based dynamic spatial simulation methods and interactive multi-criteria decision-making methods with GIS to explicitly address the spatially-dependent multi-scale linkages between land-use changes and the human decision-making process; and b) its design, which represents a balance between the need for rigour and the need for a tool that can be used by a wide array of users. A suite of indicators that measure the impacts of land-use changes are produced and the multi-dimensional information is presented through an impact matrix, cobwebs and hierarchically
aggregated indices to satisfy the different needs for details by different users. Different indices have been developed, an Outcomes Index, a Relative Sustainability Index, and a Relative Benefits Index, all of which are used for quantitative comparison of different scenarios.

Four different scenarios – 'Baseline', 'Agribusiness', 'Protectionist', and 'Vegebusiness' – were constructed for the Lower Mainland using this model. Each of these scenarios were developed for two policy options related to preservation of agricultural land – preserve and do not preserve agricultural land. By 2040, due to urbanization, around 3600 hectares of agricultural land will be lost under the preservation of the Agricultural Land Reserve (ALR) scenario, while more than 25000 hectares will be lost in the scenario that does not preserve the ALR. Hot-spots of land-use changes have been identified. There is a positive linear relationship between economic agricultural output and its impacts. As expected, the agribusiness scenario results in the highest impacts on the environment, while the protectionist scenario results in the least impacts. However, the relative benefits of increases in agricultural production over its impacts are highest for the vegebusiness scenario. The benefits are, in general, less for those scenarios which do not preserve agricultural land. The overall impacts on sustainability are less for the protectionist and vegebusiness scenarios than for the baseline and agribusiness scenarios. However, these results change when different weights are applied, indicating the critical role of value judgments of people in derivation of sustainability indices.

The model helps understand the complex trade-offs associated with different choices and is a valuable tool for policy planners, stakeholders as well as the general public that assists in making informed land-use decisions for a sustainable future.
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<td>AHP</td>
<td>Analytical Hierarchy Process</td>
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<td>ALR</td>
<td>Agricultural Land Reserve</td>
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<tr>
<td>AML</td>
<td>Arc Macro Language</td>
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<tr>
<td>BC</td>
<td>British Columbia</td>
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<tr>
<td>CA</td>
<td>Cellular Automata</td>
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<tr>
<td>CLUE</td>
<td>Conversion of Land Use and its Effects</td>
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<td>CUF</td>
<td>California Urban Futures</td>
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<td>California Urban and Biodiversity Analysis</td>
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<td>DICE</td>
<td>Dynamic Integrated Climate-Economy model</td>
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<td>FAO</td>
<td>Food and Agriculture Organization</td>
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<td>FASOM</td>
<td>Forest and Agricultural Sector Optimization Model</td>
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<td>GBFP</td>
<td>Georgia Basin Futures Project</td>
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<td>GEM</td>
<td>General Ecosystems Model</td>
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<td>GIS</td>
<td>Geographical Information Systems</td>
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<td>II</td>
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<td>IIASA-LUC</td>
<td>International Institute for Applied Systems Analysis – Land Use Change</td>
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<tr>
<td>IMAGE</td>
<td>Integrated Model to Assess the Greenhouse Effect</td>
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<td>LM</td>
<td>Lower Mainland</td>
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<td>LUCAS</td>
<td>Land-use Change Analysis Systems</td>
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<tr>
<td>MCDM</td>
<td>Multi-Criteria Decision Making</td>
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<td>NELUP</td>
<td>NERC/ESRC Land-use Programme</td>
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<tr>
<td>OECD</td>
<td>Organization for Economic Co-operation and Development</td>
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<td>Patuxent Landscape Model</td>
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<td>SLEUTH</td>
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1 Introduction and Objectives

1.1 Introduction

Land is a multi-functional resource that supports various human activities including settlement, agriculture, forestry and recreation. Some of the most profound changes in land-cover occur due to these human activities. Humans alter the landscape in the practice of agriculture to meet their needs for food, fibre and other products. These changes in land-use and land-cover have different effects on the environment, such as adverse effects on water quality, land degradation and reduction in biodiversity. Through these environmental impacts, land-use and land-cover changes driven by human activity have the potential to significantly affect food security and the sustainability of the world’s agricultural systems. Moreover, there are competing uses of land. Urbanization has often taken place at the cost of agricultural lands and has resulted in the intensification of agriculture affecting the sustainability of production systems. With increasing population and pressure on land there is widespread interest in making a transition to “sustainable agriculture” that meets human needs for food, protects the integrity of natural systems, enhances the quality of life of people and is economically profitable. Consequently, it has become ever more important to understand the dynamics of land-use changes, specifically their future evolution and their impacts on sustainability.

Land-use changes are determined both by environmental factors and, more so, by human use of land. To project future land-use changes requires understanding the interactions of the basic forces that affect land-use related decisions. Specifically, it requires an understanding of the two fundamental issues in land-use, namely, the integration of human and environmental driving factors of land-use change and the study of land-use system behavior with respect to these factors. Moreover, each of the identified human-environment interaction processes operates over a range of scales in space and time. Many interactions and feedbacks occur between these processes at different levels of organization. Methodologies for analysis of land-use change need to address these human-environment complexities in land-use systems.

Understanding land-use dynamics is not in and of itself a means to achieve sustainability. To make progress towards sustainability also requires understanding the means by which we can influence these changes through effective agricultural policies and making informed and sustainable choices. Given the impact of human actions on land-use and land cover it is
necessary that people understand the consequences of choices that they make today. Individuals and decision makers need to be aware of the ways that lifestyle, consumption patterns and decisions, made with respect to use of land, affect the environment. Decision makers need to know what changes in policy and technology can help in reducing land-use conflicts, and in balancing agricultural development with minimum environmental impacts. If people have a clear understanding of the links between choices and consequences they are more likely to make informed and sustainable choices.

Understanding how human choices will affect consequences in the overall context of sustainability is an overwhelmingly complex process. This requires decision support tools and techniques that can assist in making these informed land-use decisions based on sound technical information, while also increasing public involvement in the process.

The development of decision-making tools and methodologies, particularly related to land-use and assessment of sustainability, has been a focus of much research after the United Nations’ Conference on Sustainable Development, or the Rio Summit, in 1992. This summit set out a comprehensive plan of actions to be taken at global, national and local levels in a desire to promote sustainable development (Agenda 21) and highlighted the need for generation of information in a manner that assists in planning and monitoring and decision-making related to sustainable development.

There have been extensive efforts in the field of land-use aimed at understanding past, current and future land-use changes. However, crucial deficiencies exist in this research area. Most land-use studies have been ad hoc in nature; they have been carried out for specific conditions and regions and were not designed to be used as operational decision support tools for sustainability. This is due to the fact that these research efforts have focused on land-use analysis and evaluation of their impacts in an independent manner. There are land-use models that enhance our understanding of land-use and their driving forces, but they fail to provide indicators to assess the impacts on sustainability. There is extensive research on the development of sustainability indicators, but these have been rarely incorporated into models to provide an end-to-end evaluation of the consequences of land-use changes. There is also an issue of presenting the multi-dimensional and detailed nature of information provided by these indicators which has hampered their usefulness in these models.
Most land-use studies have been ‘disciplinary’ in nature, addressing either the natural (physical) or the social perspective of land-use systems. They fail to explicitly address the interactions and feedbacks between different components of the ecosystem. The approaches used do not adequately account for the complexity of human-environment relationships, and interactions among human-driven forces of land-use changes. Therefore, they fail to provide the holistic perspective required for examining the sustainability of the system.

These studies have often used deterministic and predictive modeling approaches, basing their predictions on the extrapolation of trends or optimizing around the "most probable" future. They do not incorporate human choice and decision-making and uncertainty as fundamental to understanding the future (Biggs et al., 1999). Also, the technical details and complexity of the models restrict their interpretation and use to a small community of experts.

In order that land-use models can be used as decision support tools for sustainability it is necessary that they not only address human decision making complexities in land-use systems but also allow users and decision makers to explore alternate futures. The capability to ‘explore’ futures is necessary because there is no single ‘right’ path (or set of choices) for achieving sustainability. Different paths reflect different needs and wants that may be conflicting and competing. Any successful quest for sustainability will therefore have to be a collective, uncertain and adaptive endeavour by society (NRC, 1999). In the context of agriculture, various scenarios of agricultural development, based on different choices, will need to be explored and examined for their effects and trade-offs with respect to sustainability objectives as defined by different stakeholder groups.

Thus, there is an urgent need for development of models that allow users to explore the consequences of a range of policy options and choices in order to explore alternative futures. These models should have the capability not only to create plausible alternative futures by linking policy choices and user preferences with land-use changes, but also provide a systematic method for the evaluation and comparison of alternative pathways with respect to their social, economic and environmental consequences.
1.2 Thesis Outline

1.2.1 Objectives

The over-arching goal of the research described in this thesis is to develop a model that allows a wide array of users ranging from stakeholders to policy makers to generate and assess alternative agricultural futures in an effort to make a transition to agricultural sustainability in the Lower Mainland, BC. To this end, I develop an integrated land-use model, called AgFutures, that is capable of generating a wide range of possible agricultural futures in response to users' choices related to land-use policy in the region, agricultural management practices and food consumption preferences. It forecasts land-use changes and quantifies their impacts on sustainability, under different user-defined scenarios. It provides tools to: generate alternative agricultural scenarios; project regional land-use areas and livestock numbers until 2040 under these scenarios; simulate spatial patterns of land-use changes; and evaluate alternative scenarios of development for their impacts on sustainability. The model addresses methodological gaps related to land-use change models and sustainability assessment, identified above, and is developed with the objectives of: addressing multi-scale interactions of driving forces of land-use change; better addressing complexities of human decision-making process in land-use models; and presenting multi-dimensional information on sustainability indicators in a flexible manner.

The model is based on a systems perspective integrating physical and social dimensions of land-use systems and overtly considers human decision-making through choices that affect the land-use and impact outcomes.

In the research, I analyze past land-use changes and their causes and develop methods for simulating future patterns of land-use change and their impacts on sustainability. A relatively new approach, that of the integration of cellular automata techniques with multi-criteria decision making techniques in a Geographic Information System, is used to simulate future land-use changes as a function of factors that affect human decision-making. Remote sensing techniques are used to derive the most current land-use information that drives the future evolution of land-use changes. I then identify and develop sustainability indicators to build an aggregated sustainability index that is used for evaluating and ranking alternative scenarios.
This model is applied to the Lower Mainland region of British Columbia, Canada in order to develop and assess agricultural land-use scenarios based on possible economic, social and ecological transitions up to the year 2040. Consequently, the specific objectives of this thesis are:

1) to identify key issues/policies of concern affecting agricultural sustainability in the Lower Mainland;

2) to develop a methodology for spatio-temporal simulation of land-use changes and implement it in a GIS;

3) to analyze past agricultural trends and their driving forces in the Lower Mainland;

4) to generate a land-use / land cover map of the Lower Mainland for the year 2000 using remote sensing data and organize a GIS database of factors affecting land-use changes;

5) to simulate land-use changes under alternative pathways of agricultural development;

6) to identify and develop social, economic and environmental indicators; and

7) to analyze and evaluate alternative pathways using the sustainability indicators and the sustainability index

1.2.2 Structure of This Thesis

The thesis is presented in seven chapters. In this first chapter I provide a general introduction outlining the need for development of land-use models as tools for sustainability and also set out the objectives of this research. The context of this research in the setting of the broader and comprehensive framework of the integrated assessment model called GB-QUEST is also discussed.

In chapter 2, various concepts and terms used in the study are presented. This is followed by a discussion on agricultural sustainability and the impacts of agriculture on the environment. A review is provided of different efforts and approaches to land-use modeling, highlighting the gaps in the development of models for exploring alternative pathways to sustainability.

A description of the study area is provided in chapter 3, with a detailed discussion on key agricultural issues of concern and various challenges faced by agriculture in the region.

In chapter 4, I present an overview of the AgFutures model, describing its characteristics and components and also describe in detail the CA-MCDM-based spatial methodology for simulation of land-use changes.
In chapter 5, I analyse past trends of agricultural land-use in order to make regional-level projections and then present the results of the CA-based simulation, at grid-level, to describe land-use patterns obtained under four alternative scenarios.

In chapter 6, different indicators and sustainability indices used for assessing sustainability are described along with the methods used for their calculation. The impacts of land-use changes on sustainability, under different scenarios, are then assessed through the use of these indicators. I also describe two indices, the Outcomes Index and the Relative Sustainability Index, that are developed and used for a quantitative comparison of different scenarios.

In chapter 7, I discuss how I have achieved the various research objectives set out in the beginning of the thesis, and highlight various ways in which the model can be used. I conclude with some suggestions for further research in this area.

1.3 Context of This Research

AgFutures was developed as a module within an integrated assessment model called ‘Georgia Basin Quest’, or ‘GB-QUEST’ of the broader Georgia Basin Futures Project (GBFP) which aims to explore how in the next 40 years, we as citizens can learn to live within the limits of natural ecosystems, while improving human well being in the Georgia Basin region on the west coast of British Columbia. GB-QUEST is a computer-based simulation tool that enables people to construct alternative futures of the Georgia Basin and view the trade-offs and consequences of their choices. It allows the public to explore future scenarios of the region through the lens of environmental, economic, and social sustainability (Tansey et al., 2002). A user or group of users chooses among several potential paths for a variety of topics including urban growth, transportation, and economic growth, with the goal of creating their most desirable future, forty years from now. GB-QUEST fosters an understanding of sustainability by placing the group in the position of making decisions that impinge upon regional development, and allowing them to reflect upon the consequences and tradeoffs associated with those decisions. The tool includes several integrated sub-models including agriculture, urban growth, demography, transportation, macro economy, energy and forestry.

The research described in this thesis aids the development of agriculture sub-model of GB-QUEST, which is a spatial model that simulates land conversions under user-defined
preferences of agricultural policies and presents the consequences of these decisions to the user.

1.4 Contribution to Knowledge

Through this research I contribute to knowledge in the field of land-use modeling and sustainability on both theoretical and applied fronts. Theoretically, I develop an innovative spatio-temporal approach for integrating human decision-making and multi-scale interactions between various factors in order to simulate future land-use changes. I also develop indicators of sustainability, and provide ways to present this multi-dimensional information from indicators in a flexible manner, including generation of two new sustainability indices. The aggregated sustainability index allows even users, without extensive knowledge and expertise, to analyze the outcomes of different alternatives and provides a basis for choosing among these alternatives. There has been a dearth of such scientifically-based, but publicly-accessible models that allow one to understand possible future consequences of present actions and choices. On the applied front, the research successfully demonstrates how science and technology can be used to build tools that help society in its journey of transition towards sustainability. It helps in building a decision support tool that allows decision-makers to explore alternative futures of agricultural sustainability in the Lower Mainland by providing an integrated assessment of consequences of policies and choices that were not previously possible. It allows users to examine the impacts of their lifestyles and preferences regarding agricultural development on sustainability. The AgFutures model provides the user with an easy end-to-end holistic analysis required for informed decision-making to chart a successful pathway to agricultural sustainability. The model not only directly assesses the impacts of changes in current policies (such as those related to preservation of agricultural land), but also provides indirect policy-support for sustainable agriculture by helping formulation of guidelines for future policies.

The innovative methodology developed for the simulation of land-use changes and assessment of alternatives has been implemented in the GB-QUEST agriculture sub-model, and is linked to other sub-models in GB-QUEST, such as water quality and air pollution, to give an integrated assessment of sustainability in Georgia Basin.
2 Background – Concepts and Review

This chapter is divided into two sections which correspond to different fields addressed in this research. In the first section I present the basic concepts related to sustainable development and agriculture. I discuss agriculture in the context of the framework of sustainable development and discuss various ways in which agriculture can affect environmental sustainability. The second section relates to land-use models. In it I discuss the role of land-use models as tools for sustainability and review the concepts and approaches of modeling land-use systems that guide the development of the AgFutures model.

2.1 Sustainable Development and Agriculture

2.1.1 Sustainable Development

In the 1980s, increasing concern about the effects of economic development on health, natural resources and the environment led the United Nations to publish the Brundtland Report in 1987. This report alerted the world to the urgency of making progress toward economic development that could be sustained without depleting natural resources or harming the environment. It famously defined sustainable as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). The “adoption” or pursuit of sustainable development and its consideration in the formulation of government policies accelerated following the Earth Summit in 1992 that established Agenda 21. Agenda 21 is a blueprint for sustainability in the 21st century. It is the global framework that guides the way we move along the pathways to sustainable development.

Sustainable Development is not just about the environment, but about the economy and society as well. Sustainable Development encourages the conservation and preservation of natural resources and of the environment, and the management of energy, waste, and transportation. It is development based on patterns of production and consumption that can be pursued into the future without degrading the human or natural environment. It involves the equitable sharing of the benefits of economic activity across all sections of society, to enhance the well-being of humans, protect health and alleviate poverty. If sustainable development is to be successful, the attitudes of individuals, as well as of governments, with regard to our current lifestyles and the impact they have on the environment will need to change.
The concept of sustainability is thus multidimensional. It includes ecological, social and economic objectives. Between these different elements there are interdependencies and these relationships are strong, numerous and complex. Economic, social and environmental objectives are not always mutually supportive. These can compete with each other. In such cases the concept of sustainability refers to the need to strike the right balance between its three elements. Political choices concerning one of these elements must at least ensure that certain minimum standards with respect to other two objectives are met.

2.1.2 Sustainable Agriculture

Agenda 21, among other things, highlighted the need for promoting agricultural development within these broader principles of sustainable development. Sustainable agriculture is a complex, multi-dimensional concept, which represents a societal goal rather than a farming practice. It represents a fundamental paradigm shift in the way we think about food and agriculture. The belief that agricultural development can take place without harming its resource base, while maintaining or improving farm profitability, forms the basis of this concept (MacRae et al., 1990). As the concept of sustainable agriculture has evolved, agricultural production has moved from a technology focus to a focus that is situated within the broader context of social, economic and environmental systems.

There are many diverse goals and criteria for “sustainable agriculture”, ranging from concerns for the environment to those addressing the socio-economic issues of hunger and poverty. Nevertheless, the basic underlying principles remain the same. Sustainable agriculture integrates three main goals--environmental health, economic profitability, and social and economic equity. A set of criteria given by FAO (1995) for sustainable agriculture defines these basic goals of sustainable agriculture:

- meeting the basic nutritional requirements of present and future generations;
- providing employment, income and a decent living to those in agricultural production;
- maintaining the productive capacity of the natural resource base, without causing contamination of the environment;
- reducing the vulnerability of the agricultural sector to adverse natural and socio-economic factors, and other risks, and strengthening self-reliance.
2.1.3 Ecological, Economic and Social Dimensions

The core issues of sustainability are the maintenance of a certain level of stocks (natural, human and man-made capital), as well as achieving efficiency and equity (inter- and intra-generational). In this context, sustainable agriculture entails maintaining sufficient resources (both natural and human) for current and future demands. Maintenance of human resources includes consideration of social responsibilities such as working and living conditions of laborers, the needs of rural communities, and consumer health and safety both in the present and the future. Maintenance of land and natural resources involves maintaining or enhancing this vital resource base for the long term. This requires stewardship of both natural and human resources which is of prime importance in achieving sustainability (SAREP, 1997).

Based on these considerations, the three dimensions of sustainable agriculture can be summarized as follows. The ecological dimension of sustainable agriculture refers to the management of natural resources with a view to ensuring that they are available in future. However, it also includes issues such as the protection of landscapes, habitats, biodiversity as well as the quality of drinking water and air. The economic dimension relates to the efficient use of resources and the competitiveness and the viability of the sector. Efficient agricultural structures, appropriate technologies, as well as the diversification of income sources are elements of this dimension. The social dimension relates to questions of labour opportunities and access to resources and services for agricultural households. It also includes the issues of equal opportunities and society’s ethical concerns regarding agricultural production methods.

2.1.4 Agriculture in the Context of Human and Natural Systems

In the context of this research it is important to understand how agriculture is situated within the broader environmental and human systems. In this section I describe the Driving Force-Outcome-Response framework used for identifying the linkages between these systems and examine different ways in which agriculture can affect environmental sustainability.

2.1.4.1 Driving Force-Outcome-Response Framework

Agriculture depends on a multitude of independent issues – social, political, institutional, economic and environmental. Agriculture not only has to meet the food demands of society but it also has to minimize environmental impacts, compete with other uses and operate within changing social, political and economic climates. A desire to make a transition to agricultural sustainability will need to consider interactions among all of these driving factors, as well as
its impacts on the social, economic and environmental systems. This will require identification and quantification of linkages among driving forces (particularly human) and outcomes of agriculture.

The linkages between agriculture and these systems can be better understood through the Driving Force-Outcome-Response (DOR) framework used by Agriculture and Agri-food Canada for examining the environmental sustainability of Canadian agriculture (McRae et al., 2000). This framework has been modified from the Driving Force-State-Response framework adopted by UN Commission for Sustainable Development (UNCSD, 1996) and OECD (1999) for the development of environmental indicators of agriculture.

The DOR framework consists of a vast array of human-environmental interactions, as illustrated in Figure 2.1, involving different feedbacks and linkages.

**Driving forces** are those elements which act at the farm level and at the societal level to affect agriculture. These include:

- natural environmental processes and factors, including the agro-ecological system, the physical attributes of the land, meteorological conditions, and random events such as hailstorms;

- biophysical inputs and outputs at the farm level, covering the use of chemical inputs, energy and water resources, farm management practices, and decisions taken in terms of the level and mix of agricultural commodities produced;

- economic and societal driving forces, including policies, markets, commodity prices, consumer preferences, technological changes, social structures and population growth.

**The Outcomes** refer to changes in environmental, economic and social conditions that may result from agriculture. Outcomes related to agriculture can be either beneficial or adverse. Beneficial outcomes include: social benefits (e.g., employment, rural development, and food security); economic benefits (e.g., agri-business and farm income); and ecological benefits (e.g., the provision of wildlife habitat). Adverse outcomes of agriculture include declining farm employment and income, and adverse environmental impacts. The impact of agriculture on the environment can occur both on-farm and off-farm (e.g. the effects on biodiversity and
Figure 2.1 Driving Force-Outcomes-Response framework for Agriculture

Source: Adapted from McRae (2001) and OECD (1999)
climate change), and operate at various temporal and spatial scales from the field through to the global scale. An important issue/aspect in this context is that while agriculture can affect the state of the environment, changes in environmental conditions, such as acid air emissions or ozone depletion, can also impact agricultural production activities.

Responses refer to the reaction by groups in society and policy makers to the actual and perceived changes in the outcomes and driving forces. The responses include:

• farmer behaviour -- changes in input use, farm management practices, such as integrated pest management, and cooperative approaches between farmers and farmers and other stakeholders;

• consumer reactions -- through altering food consumption patterns;

• sector responses -- such as changes in technology, with changes in technology to produce less toxic pesticides, more efficient crops and better production practices;

• government actions -- through changes in policy measures, including regulatory approaches, the use of economic instruments such as subsidies and taxes, training and information programmes, research and development, and agricultural policies.

Responses and driving forces are closely linked, as responses can manipulate or manage key driving forces in order to achieve desired outcomes related to social, economic and environmental goals.

A transition to sustainability will require a balance between agricultural production and related environmental risks. This can be achieved if environmental risks from agriculture-related land-use changes can be controlled through the management of driving forces affecting agriculture. At present the supply of quantitative information on these agri-environmental linkages is inadequate. This information is required by policy makers and users in order to allow them to formulate policies or responses to the environmental effects of agriculture in the pursuit of sustainability. In this context, the DOR framework can be used to improve our understanding of the complexity of linkages and feedbacks between the causes and effects of agriculture’s impact on the environment, and the responses by farmers, policy makers and society to
changes in agri-environmental conditions. In this thesis, I use this framework to identify indicators that can be used to explain and quantify these linkages and feedbacks.

2.1.4.2 Agriculture and Environment

Agriculture has many diverse effects on the environment. The pattern and trends in agricultural land-use can have significant impacts on natural resources, biodiversity, wildlife habitat and landscape aesthetics. Changes in agricultural land-use may include land permanently retired from production and maintained for environmental conservation purposes, and also the shift of agricultural land to urban, industrial or recreational uses. Moreover, while agricultural land-use can lead to degradation of the environment, certain agricultural practices can also play a role in conserving natural resources. For example, certain nutrient management practices can help to enhance soil fertility and soil structure; some cultivation practices such as terracing can minimise soil erosion; crop and pasture land may provide wildlife habitat; and certain irrigation practices, for example paddy rice fields and construction of dykes, can contribute to the stabilisation of river flow, help prevent floods and landslides and improve the recharge of groundwater reservoirs. Some major environmental impacts of agriculture are discussed below.

Water Quality

The link between agriculture and the quality of surface and groundwater has long been recognized. The main pollutants of water coming from farmland are sediments, nutrients, pesticides, bacteria, and salt. Agricultural inputs such as fertilizer, livestock manure and pesticides may cause water contamination when improperly stored, applied or disposed of (AAFC, 2003). High concentrations of organic matter, phosphorus and nitrogen in surface water can lead to its eutrophication and deoxygenation, which in turn can destroy aquatic habitat and produce taste, odour and aesthetic problems. Intensive agriculture in areas of high soil permeability and high water tables may cause groundwater contamination from the percolation of chemicals and nutrients through the soil profile. There is also concern that where certain bacterial or nitrate concentrations exceed drinking water guidelines in surface or groundwater, there may be negative health effects. While agriculture has the capacity to adversely affect water quality, it can also enhance it through management practices that reduce erosion and reduce flows of agricultural contaminants into water.
Air Quality

Agricultural practices can potentially affect air quality through the emission of nitrogen compounds, particulate matter, offensive odours and other substances (AAFC, 2001). Nitrogen compounds emitted from agricultural sources that impact air quality are ammonia, primarily from fertilizers and livestock, and nitrogen oxides from fuel combustion in farm equipment. Ammonia emissions from fertilizers and livestock are the key producers of fine particulate matter. Dust from the cultivation of agricultural land and soil erosion is responsible for a large portion of the coarse particulate matter in the air, which causes haze and visibility problems. Odour, particularly from manure produced by intensive livestock operations, is an increasing public concern.

Soil Quality

Degradation of soil results from a variety of processes, such as wind and water erosion, loss of soil organic matter, structural breakdown, salinization, and chemical contamination. Some of these processes are affected by agricultural practices, such as inappropriate irrigation and soil management practices, land clearing, excessive use of chemical inputs, and the mis-use of heavy agricultural machinery. Soil erosion on farms reduces land productivity, which partly depends on soil structure, and water-holding capacity; erosion off farms, affects air and water quality, causing damage to aquatic habitats and human health. Erosion also reduces the capacity of soil to fix carbon dioxide and act as a greenhouse gas sink, and impairs the water storage capacity in rivers, lakes and reservoirs, increasing the risk of flooding and damaging water systems. Some agricultural land-uses and management practices (such as various tillage methods, cropping systems, and nutrient management plans) help to stabilize or improve soil quality. The issue of soil degradation is important in agriculture as it may lead to a reduction in fertility, lower yields and a decrease in farm profitability.

Biodiversity

Biodiversity, including genetic, species and ecosystem diversity, is an issue of great importance to agriculture since it provides many environmental and economic benefits to agro-ecosystems. Agricultural practices such as tillage, land drainage, grazing, and use of fertilizers and pesticides can affect biodiversity, although, when applied properly, the impact on wild flora and fauna is minimized. At the genetic level, agriculture affects biological diversity as a
reservoir of genes for improving plant and livestock productivity. Monocultural farming systems may lead to an impact on biodiversity at the species level through exposure to excessive use of nutrients and pesticides. Agriculture may impact biodiversity at the ecosystem level which may involve changes to wildlife habitats through the modification of agricultural landscapes. The quality of wildlife habitats might also be affected by agriculture through increased fragmentation, which can lead to damaging effects on species population size and distributions, and the potential loss in species diversity. The loss and fragmentation of habitat in agro-ecosystems are major factors in the decline of many North American wild flora and fauna (AAFC, 2003).

Climate change and ozone depletion

Agriculture contributes to climate change through the emission of greenhouse gases (including methane, nitrous oxide and carbon dioxide) and ozone-depleting substances. Methyl Bromide, an agricultural soil and space fumigant used in Canada and throughout the world, has been identified under the Montreal Protocol as a significant ozone-depleting substance (AAFC, 2003; AGR, 2003).

2.2 Land-use Change Modeling

In this section I begin by addressing definitions and concepts in land-use modeling. I discuss the role and requirements of land-use models in order to address land-use complexities and to serve as policy support tools. Existing models are reviewed and gaps in the land-use modeling research are examined. I then review various approaches to modeling, highlighting their strengths and weaknesses.

2.2.1 Definitions

At the outset it is necessary to define the terms 'land-use' and 'land-cover' as these are not synonymous. "Land-cover is the biophysical state of the earth's surface and immediate subsurface" (Turner II et al., 1995: 4). In other words, it is defined as the layer of soils and biomass, including natural vegetation, crops and human structures, that cover the land surface. "Land-use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation – the purpose for which the land is used" (Turner II et al., 1995: 4). Land-use refers to the purposes for which humans exploit the land-cover. Land-cover change is the complete replacement of one cover type by another,
while land-use changes also include the modification of land-cover types, e.g., intensification of agricultural use, without changing its overall classification.

2.2.2 Role of Land-use Change Models

Land-use change models are useful tools that support the analysis of the causes and consequences of land-use changes in order to better understand the functioning of the land-use systems and to support land-use planning and policy (Verburg et al., 2003). They are useful for identifying and putting into perspective the complex interactions of socio-economic and biophysical factors that affect the rate and spatial distribution of changes, as well as for estimating the impacts of changes. More specifically, they can be used to describe the spatial and temporal relationships between the drivers and the resulting patterns of land-uses and their changes. Land-use models represent only a part of the complexity of land-use systems, but they can provide valuable information on the system's behaviour under a range of conditions. They can also allow one to assess and project future impacts of land-use changes. Land-use modeling, especially if done in a spatially explicit and integrated manner, is an important technique for the projection of alternative pathways into the future. It offers the possibility to test the sensitivity of land-use patterns to changes in selected variables and can support the exploration of future land-use changes under scenario conditions. Scenario analysis using these models can allow decision makers to formulate effective policies for sustainable development.

2.2.3 Basic Concepts in Land-use Modeling

Land-use is determined by the spatial and temporal interactions of biophysical factors (constraints) such as soils, climate, and topography, and human factors like population, technology, and economic conditions (Veldkamp and Fresco, 1996a). Space, time and human factors are the critical elements in this process. Researchers have focused on a number of different features of land-use systems that need to be considered in the development of land-use models. In a comprehensive review of land-use models Verburg et al. (2003) identified those features that are considered to be of importance in land-use modeling based on work by the land-use and land-cover change research community (e.g., (Turner II et al., 1995; Veldkamp and Fresco, 1996a; Moran, 2000; van der Veen and Rotmans, 2001; Geist et al., 2001). These relate to the driving factors of land-use changes, scale dependencies, spatial interactions and temporal dynamics in land-use systems. A discussion of these features is
presented below, along with a discussion of implementation issues in land-use models. This review is aided greatly by previous reviews, especially by Verburg et al. (2003) and Agarwal et al. (2001) and includes a review of the requirements of models used as policy support tools.

2.2.3.1 Driving Forces of Land-use Change

Land-use and land-cover change are the result of many interacting social and environmental processes. Land-use is determined by the so-called 'driving forces' of land-use change which can generally be subdivided in three groups (Turner II et al., 1995): socio-economic drivers, biophysical drivers and proximate causes (land management variables). The socio-economic drivers comprise demographic, social, economic, political and institutional factors and processes and can be grouped into six categories: population, level of affluence, technology, political economy, political structure and attitudes and values. These include other socio-cultural/socioeconomic organization factors such as economic institutions and the market, and political institutions. The bio-physical drivers include characteristics and processes of the natural environment such as: weather and climate variations, landform, topography, soil types and processes, drainage patterns, and availability of natural resources. Proximate causes are the factors that are most immediate to actual change, such as land management. Examples of proximate sources of change are: fertilizer application, biomass burning, plowing, irrigation, drainage, livestock pasturing, pasture improvement, urbanization, and urban fringe development. Proximate causes are a result of human actions and decisions. Although biophysical factors mostly do not 'drive' land-use change directly, they can cause land-cover changes (e.g., through climate change) and they influence land-use allocation decisions (e.g., soil quality). Land-use change that drives land-cover change is thus shaped mainly by human driving forces that determine the direction and intensity of land-use.

As land-use decisions are based on opportunities and constraints affected by both biophysical and socio-economic drivers, land-use change needs to be modelled as a function of socio-economic and biophysical variables. Decisions made by land managers are major factors in land-use change and it is important that the attitudes and behaviours of humans be addressed in land-use models. Not only individual decisions, but interactions between multiple individuals and land managers also need to be addressed.

Not all variables can be included in any model; therefore a prerequisite to modeling land-use is identification of the most important drivers of land-use change and their appropriate
representation. The selection of the driving forces is very much dependent on the discipline of the researcher (social vs. physical), theoretical assumptions, scale of study, as well as the simplifications made in the model. For example, in economic models of land-use change, demand and supply functions are the driving forces of land-use change. Macro-scale or regional models cover a larger extent and commonly use a larger set of driving forces because of the larger diversity of land-use situations.

Although some land-use change modeling efforts have focused primarily on biophysical attributes due to easy availability of such data, there seems to be an increasing interest in including socio-economic drivers and human decision-making in the models. However, the complexity at which the social factors are included in the model is variable. The General Ecosystems Model (GEM) (Fitz et al., 1996) addresses 14 biophysical sectors such as hydrology, nutrients, etc. and captures feedback between units and across time, but does not explicitly include any socio-economic variables. Some models include specific aspects of social drivers such as demography (population size, density), markets (land profits and rent), institutions (zoning and tenure), and technology (e.g. California Urban Futures Model (CUF), Landis, 1995); California Urban and Biodiversity Analysis (CURBA) (Landis et al., 1998); Land-use Change Analysis Systems (LUCAS) (Berry et al., 1996)). These models are based on the rationale that human decisions related to land-use are dependent on socio-economic and demographic conditions and hence such factors are representative of human actions. Some models, such as the Patuxent Landscape Model (PLM) (Voinov et al., 1999), the Land Transformation Model (LTM) (Pijanowski et al., 2000), and that of Geoghegan et al. (1997) go one step further and have well-developed ecological sectors and socio-economic elements, as well as feedback among sectors. The CLUE (Conversion of land-use and its effects) model (Veldkamp and Fresco, 1996a) covers a wide range of biophysical and human drivers at different temporal and spatial scales, but has a limited consideration of institutional and economic variables. However, none of these models explicitly model human behaviour and different types of actors.

The NELUP (NERC/ESRC Land-use Programme (O'Callaghan, 1995)) model does, overtly model the choices of farmers, while actions of other actors are included in the form of technology or policy constraints. It has ecological and economic components and farming decisions, and can serve as a decision support tool to provide feedback on the impact of
collective-level policies. Agent-based models, which have been developed to explicitly simulate the decisions made by the actors, are discussed in detail in next section under the integrated models category.

Driving forces are most often considered exogeneous to the land-use system to facilitate modeling (Verburg et al., 2003). Land-use change models also need to account for endogeneity of variables such as land management technologies, infrastructure or land-use policies. Various researchers have emphasized endogeneity of driving forces in land-use studies (Chomitz and Gray, 1996; Mertens and Lambin, 2000; Irwin and Geoghegan, 2001).

Modelling decisions has proved to be the most difficult aspect of all. Inclusion of social, political and economic factors is hampered by a lack of spatially explicit data and by methodological difficulties in linking physical and social data (Veldkamp and Lambin, 2001). The spatial units for biophysical processes are different from the spatial units of decision making by actors. Also, humans act both at an individual level as well as through social and political systems that operate at a different scale. This scale dependency of human factors makes it difficult to model socio-cultural factors.

Agarwal et al. (2001) observed that models that are modular in nature make it easier to consider multiple disciplines by assigning a particular disciplinary aspect of the model to a separate module. Such models could also consider the effects of many different driving variables and address the complexity of land-use drivers in a better way.

2.2.3.2 Scale Issues

'Geographic Scale' is defined as the relation between distances on a map and the corresponding distances on the earth's surface, often expressed as a fraction or a ratio. "Scale" is used to refer both to the magnitude of a study (e.g., its geographic extent) and also to the degree of detail (e.g., its level of geographic resolution) (Goodchild and Quattrochi, 1997). A large-scale map (e.g., a map of a small town at 1:10,000) usually shows more details but covers a small area. Small-scale maps (a map of Canada at 1: 1,000,000) usually show less detail but cover large areas. Land-use is the result of multiple processes that act over different scales. At different scales of analysis, different driving forces have a dominant influence on the land-use system. At the local (farm) scale land suitability and accessibility influence land-use. At the landscape scale topography and agroclimatic potential are the key drivers, while at regional
and national scale climatic variables as well as macro-economic and demographic factors drive land-use. These processes need to be studied at the corresponding scale level. Moreover, there are many interactions and feedbacks among these processes occurring at different levels. While seeking answers at a local level, it should be kept in mind that driving forces at other levels also influence decisions at the local level and vice-versa. For example, market prices and policies developed at the national scale may affect a farmer’s decision to grow cash crops instead of food crops. Given the scale dependency and dynamic nature of drivers, these should be analyzed at various spatial and temporal scales (Turner II et al., 1995). Thus, it is necessary to use a multi-scale approach that identifies and quantifies land-use driving forces and their interrelationships at various spatial scales (Holling, 1992).

Most present land-use studies are limited to a single scale, depending on the micro- or macro-level perspective adopted by the researcher or the discipline addressed. Social science researchers study individual behaviour in human-environment interactions at the micro-scale using qualitative or quantitative approaches, while geographers and ecologists focus on land-cover and land-use at the macro-scale, using remote sensing and GIS, and using social factors that identify macro-scale patterns (Veldkamp et al., 2001). At a micro-scale, it is easier to identify the factors of land-use change and process-based relations can be determined. However, it is not possible to study land-use systems based on the micro-scale components only. At macro scales exploring and predicting land-use becomes complex, as it becomes increasingly difficult to identify key processes. The information derived at local scale cannot be simply aggregated to higher levels. Direct up-scaling or aggregation of processes and factors from the micro-scale to a higher aggregation level (macro-scale) is not reliable because of scale dependencies (Rastetter et al., 1992). This scale dependency is caused by non-linearity, feedbacks in the system, and interactions at the micro scale. Individual behaviour or decisions made at an individual level cannot necessarily be upscaled to group behaviour. These structural complexities need to be addressed in macro-scale models.

There is yet another issue of scale which is related to scale of observation. Observations of land-use, in practice, are constrained by the extent and resolution of measurement. Studies covering large spatial extents usually have a relatively coarse resolution, due to methods of observations, data costs and analysis capacity. At coarse scales, the high level of aggregation of data obscures local variability, but can show patterns not apparent at detailed scales. On the
other hand, small extent studies often lack information about the context of the study that can be derived with coarser scale data. Scales of observation usually do not correspond with the scale/level at which the process studied operates, providing only a partial description of the whole land-use system.

Different models cover different areas, ranging from micro or farm level (e.g. NELUP-Extension model, (Oglethorpe and O’Callaghan, 1995) to macro or sub-continental level (e.g. FASOM (Adams et al., 1996). Macro-scale models generally tend to severely simplify the land-use system. Some regional level models such as the LUC model of IIASA developed for China (Fischer and Sun, 2001) have included complexities at the aggregate scale in the model. This model is designed to establish an integrated assessment of the spatial and temporal interactions among various biophysical and socio-economic drivers of land-use change. The model has a low spatial resolution (8 regions in China) and is very data-demanding due to the multiple sectors of the economy that are taken into account.

Micro-level models that depend on geographic data often use a regular grid to represent all data and processes. The resolution of these models is mostly in the range of 30 - 80 m, broadly mirroring the pixel size of common remote sensing data (e.g. Landsat TM and MSS) and their extent is generally limited to the area covered by one or two Landsat scenes (185 km x 185 km) (e.g. Mertens and Lambin (1997)). The scale of analysis in these raster models is determined by the resolution of data instead of the processes, and may lead to loss of information. The issue of multiple scales and interscale dynamics has received increasing attention recently in some studies (Veldkamp and Fresco, 1996b; de Koning et al., 1998; Verburg and Chen, 2000; Walsh et al., 2001).

2.2.3.3 Spatial Considerations

Land-use being inherently spatial in nature, models of land-use change should address not only quantity but also locations of change. This necessitates the development of spatially explicit models based on quantification of spatial determinants of change. There are two general types of spatially explicit models: spatially representative and spatially interactive (Agarwal et al., 2001). A model that is spatially representative can incorporate, produce or display data spatially, but cannot model interactions between geographic features. In contrast, a spatially interactive model is one that explicitly defines spatial relationships and their interactions.
Land-use patterns nearly always exhibit spatial autocorrelation. This is due to the clustered
distribution of landscape features and also due to the spatial interactions between land-use
types. For example, urban expansion is often situated right next to already existing urban area.
In agricultural landscapes adoption of particular farming technology or cultivation patterns
might also exhibit observable spatial effects.

Spatial interactions in land-use are scale dependent. The existence of different causal processes
at different scales means that spatial interactions should be studied at multiple scales, while
relations found at a particular scale can only be used at that scale. Spatial interactions can also
act over a larger distance; a change in land-use in the upstream part of a river might affect
land-use in the downstream part through sedimentation of eroded materials leading to a
functional connectivity between the two areas. It is essential to understand and include these
spatial dependencies and neighbourhood effects in models.

Most sophisticated land-use models provide for spatial interaction and demonstrate the
advantages of spatially explicit models that move beyond simple spatial representation. These
models have extensively used GIS and remote sensing techniques. Spatial interactions have
been taken into account in some models through use of cellular automata. These have been
mostly used in urban studies (e.g. (White et al., 1997; Clarke et al., 1997; Wu, 1998; Li and
Yeh, 2000) but have now also been used in models that simulate multiple land-use types
(Hilferink and Rietveld, 1999; White and Engelen, 2000). Some models (e.g. CURBA) have
included effects of variation on processes as well as feedback between neighbouring units.
Some models have used simple measures of neighbourhood composition (e.g. the area of the
same land-use type in the neighbourhood) as explanatory factors of land-use change in
regression models (Geoghegan et al., 1997; Nelson and Hellerstein, 1997). In some other
models neighbourhood effects have been implemented through advanced measures of
autocorrelation (Bell and Bockstael, 2000; Brown et al., 2002). In many models, spatial
interactions are modeled over larger distances through inclusion of travel times or distance to
markets and other important facilities. Multi-scale models like CLUE can generate spatial
interactions through feedback over a higher scale. If the demand for a particular use is not met
at the local level, it will feed back to the regional level and allocation to another location will
proceed. This type of modelling can include the trade-off of a measure at a certain location.
2.2.3.4 **Temporal Dynamics**

Land-use changes not only have a spatial dimension; they also have a temporal dimension. There are many driving forces of land-use that change over time; however, these may not vary spatially, for example prices, subsidies and tenure rules. These affect individual choices related to land-use. Land-use decisions are affected by factors operating at different time scales. Some are based on short-term dynamics, such as daily weather fluctuations, while others are based on long-term dynamics, such as market changes. The temporal scale of analysis often decides which driving forces are endogeneous to the model and which are exogeneous. For example, prices in the short term can be considered as exogeneous but in longer time spans they can be considered as endogenous. Predicting future land-use changes require methodologies that integrate understanding of the processes affected by these drivers at different time scales.

Land-use changes are often non-linear in time. Land-use models need to take into account how the evolution of changes takes place; that is, they should address the path-dependency of the system. These cannot be simply explained as the result of the present set of driving forces. Land-use change is dependent on initial conditions and small random events that may affect the outcomes, thus making prediction problematic. For example, development of a road in an area may lead to urban growth near it, which in turn may necessitate or bring about some other infrastructural changes. Thus there exists feedback in the system.

In some land-use models, temporal dynamics are taken into account by considering the initial state of the land-use as a factor that determines what changes may take place in the future. In the SLEUTH urban growth model (Candau, 2000) even more explicit functions to enforce temporal autocorrelation are implemented that also take the ‘age’ of a new urban development centre into account. The economic land allocation model of the Patuxent Landscape Model (Irwin and Geoghegan, 2001) also explicitly considers the temporal dimension. The land-use conversion decision is posed as an optimal timing decision in which the landowner seeks to maximise expected profits by choosing the optimal time of conversion.

Temporal and spatial dynamics together often cause a complex, non-linear behaviour in the land-use systems; however, many models do not account for temporal dynamics. These models are simply based on extrapolation of trends through regression models (Pijanowski et al., 2000; Mertens and Lambin, 2000; Schneider and Pontius, 2001; Serneels and Lambin, 2001; Geoghegan et al., 2001). These types of models are therefore only valid for the
conditions and patterns of land-use changes on which they are based and are therefore not suitable for scenario analysis. They do not reflect the competition between uses that may arise due to random events.

Some models use coarse time steps in their calculations (e.g. decadal time step in the FASOM model). However, due to the non-linear behaviour of the changes, some information on processes that occur at finer time scales may be lost in aggregating time intervals. Also, this will hamper decision-making at shorter time intervals which requires dynamic modelling with relatively short time steps. There are few multiple time step models (e.g. GEM, PLM, NELUP) that span both fine and coarse time steps and reflect the temporal complexity of various driving forces effectively. Some of the more complex models such as CLUE also incorporate time lags and take into account the time taken by different crops to provide returns as well as provide a two-year buffer against food shortages by carrying over yield surpluses from previous years.

2.2.3.5  *Land-use Models for Policy Support*

In the previous sections I examined requirements of land-use models in order to address functional and structural complexities of land-use systems. In this section I present the requirements of land-use models used as policy support tools.

Decision makers are interested in land-use models that are relevant to their need, that is, identifying policies that lead to sustainable land-use options. Land-use changes are affected by various policies such as those related to price liberalization, price support, subsidies on agricultural inputs, environmental regulations, land-use regulations and land tenure. Changes in policy can affect land-use conflicts, minimize adverse environmental impacts and maintain or increase agricultural production. Land-use studies should be able to indicate the changes that these policies may cause on land-use.

Land-use models are not expected to be "answer machines", rather they are expected to be good enough to be taken seriously in the process (Couclelis, 2001). They should be able to clarify the issues in the debate, must be able to enable analysis and negotiations among stakeholders and must provide some "advice" to policy makers, primarily in the form of what not to do (King and Kraemer, 1993). Furthermore, a good policy model should be transparent, robust, have reasonable data needs, have appropriate spatio-temporal resolution and include
enough key policy variables to allow for exploration of likely and significant policy questions (Lee, 1973).

In order for land-use models to be useful for policy makers, they should be multi-disciplinary in nature (Jansen et al., 2000). Integration of social, economic and environmental dimensions is necessary for a successful policy-making process. However, land-use modellers have traditionally adopted a 'disciplinary' approach or a 'generic' approach (Veldkamp and Lambin, 2001). Disciplinary approaches address a single discipline (natural science or social science; e.g., economic models (Bockstael, 1996)) or a single process (e.g., deforestation (Lambin, 1994)). These approaches provide scientifically robust methodologies for modeling a specific process, but they do not address interactions with other systems. Thus, they do not fit into the larger picture that is required for policy analysis. While generic approaches incorporate and link a large number of factors by severely simplifying the land-use systems (Zuidema et al., 1994), they lack the robust methodologies required for forecasting future land-use changes.

Moreover, models for policy support should address real issues and choices faced by the community or that are of interest to the community. It is impossible to understand land-use changes without considering the people and the institutions that play a role in the region. Consultation with policy makers and other stakeholders is necessary during the development of the model for the identification and evaluation of relevant policy scenarios. The stakeholders are the parties that directly affected by or can affect the land-use changes. These could include farmers, landowners, planners, governments and the wider public. Besides the possible consequences of agricultural policies, stakeholders have to identify policies that are socially acceptable and economically viable. It is important to include different stakeholders in the decision making process as they make the designed land-use plans become a reality.

Land-use models may, at best, result in a realistic simulation of future land-use changes and can therefore help in development of alternative land-use patterns. However, to be used as effective policy tools for sustainable development, they need to integrate causes with the consequences and also provide a means for evaluating alternative options' effects on environmental, social and economic systems. Finally, methodologies for land-use analysis can only become operational if, among other things, they allow for results to be presented in a way that appeals to the user (Stoorvogel and Antle, 2001).
2.2.4 Approaches in Land-use Modeling

Different models have used different mathematical techniques and designs. Based on the dominant feature of the model design and solution techniques these can be classified loosely into five, somewhat overlapping, categories (Lambin et al., 2000): statistical and econometric models; stochastic models; optimization models; dynamic systems models; and integrated models.

2.2.4.1 Statistical and Econometric Models

Using statistical techniques in land-use models is the most common approach due to ease of use and wide acceptance. These models normally involve a variety of regression techniques. The application of multiple regression techniques to the analysis of problems involving economic demand and supply has given rise to what are known as econometric models. In econometric models the rate or quantity of change is driven by demands for different commodities. These models are based on economic input-output analysis (Waddell, 2000; Fischer and Sun, 2001) using theories based on the processes involved. A large number of econometric land-use change models begin from the viewpoint of individual landowners who make land-use decisions with the objective of maximizing expected returns or utility derived from the land, and use economic theory to guide model development, including the choice of functional form and which explanatory variables to include. Economic models that simulate land-use change spatially are mostly based on the land-rent theory. Any parcel of land, given its attributes and location, is assumed to be allocated to that use which earns the highest rent (Berry et al., 1993). However, these models are unable to quantify socio-economic factors without the use of empirical data. Statistical techniques using cross-sectional or historical data are therefore often used to quantify the relationships between different components of human and environmental systems (Chomitz and Gray, 1996; Bockstael, 1996; Geoghegan et al., 1997; Pfaff, 1999). Chomitz and Gray (1996) developed an econometric model (multinominal logit) that predicted land-use aggregated in three classes: natural vegetation, semi-subsistence agriculture and commercial farming. The logit model developed by Wear et al. (1999) predicts the probability of land being classified as potential timberland. It includes several biophysical variables such as site index and slope, but does not include any human decision making variables.
Statistical techniques, mainly regression, have also been used to quantify the relations between driving forces and land-use change in spatially-explicit models that are not based on economic theory (Turner et al., 1996; Veldkamp and Fresco, 1996a; Mertens and Lambin, 2000; Serneels and Lambin, 2001; Pontius and Schneider, 2001). These models describe historic land-use conversions as a function of changes in several driving forces related to biophysical properties of land and other socio-economic forces, through one or more regression equations. Such statistical models provide insight into the empirical relationships over a system's history, or at one time, but they also have drawbacks. Statistical models are unable to establish the causality of relationships. Rich datasets and elaborate statistical models are required to address feedbacks among system components. Results from such statistical models are affected by data availability, the estimation techniques used and other factors such as correlation between independent variables. Regression techniques do not take into account the multi-collinearity and spatial autocorrelation effects. The capacity of statistical models to predict future patterns is low, as they are often based on short time series of data and a relatively small sample size (Veldkamp and Fresco, 1997). Cross-sectional analysis of the land-use pattern based on a long history of land-use changes results in more stable and robust explanations for land-use patterns (de Koning et al., 1998). Moreover, these models cannot be used for analyzing a system's future development pathways under alternative management strategies, as they do not allow one to examine effects of changes that may not have occurred in the past.

2.2.4.2 Stochastic Models

Stochastic models consist mainly of transition probability models that describe processes that move in a sequence of steps through a set of states. These models include Markov models and cellular automata models. Markov modeling is a simulation technique in which the process moves successively from one state to the other with some probability which depends only on the current state and not on the previous states. The probability of moving from one state to another state is called a transition probability, and it is given for every ordered set of states. Transition probabilities are computed on the basis of observed data between time periods, which show the probability that a cell will change (or, move) from one land-use type to another within the same period in the future. This probability depends only on the state in which a cell is at any given point in time (i.e., its current land-use type) and not on the land-use types by which it was occupied in the past. In other words, history plays no role in the future (Parzen, 1962). Markov models have been used for urban land-use/land cover change
modeling (Bell, 1974), forest and vegetation succession modeling (Horn, 1975), and more recently in modeling landscape change (Flam and Turner, 1994; Boerner et al., 1996).

Markov models are mathematically compact, easy to implement with empirical data, and lend themselves well to simulation. However, they have their weaknesses. One of the shortcomings of the Markov transition probability approach is that it assumes stationarity (i.e., the probabilities are assumed to be constant over space and time). The second limitation is its inability to account for the spatial context of a grid cell in characterizing transition. To overcome this, Wood et al. (1998) developed a spatial Markov model that explicitly modeled temporal and spatial land-use changes. Markov analysis of land-use change is an aggregate, macroscopic modeling approach as it does not account for any of the drivers (i.e., the causes) of land-use change process. Instead, it assumes that all forces that worked to produce the observed patterns and governed their transition probabilities will continue to do so into the future. Brown et al. (2000) developed a method that uses Markov transition probabilities that were calculated as a function of land-use conditions and land-use change to simulate forest cover changes.

Cellular automata (CA) models are spatial-temporal extensions of Markov models. They explicitly assume that neighbouring areas influence the transition probability of a cell. These types of models operate on a lattice of regular cells. In these models, cells change state as a function of their previous state and the state of local neighboring cells, in accordance with a specified set of heuristic transition rules. These transition rules could be quantitative or qualitative or both (Engelen et al., 1995). Detailed description of CA is given in Chapter 4. CA has been used for modeling spatial interactions and dynamics of land-use changes in many studies. They have been used for modeling urban changes (White et al., 1997; Clarke and Gaydos, 1998; Wu, 1999; Li and Yeh, 2000) and also used for simulating multiple land-use types (White and Engelen, 2000). Often CA and Markov models have been combined for land-use modeling (Li and Reynolds, 1997).

A limitation of the CA approach is the difficulty of determining and quantifying decision criteria used in the model in a reproducible way. At present, these decision rules are mainly based on expert knowledge. CA models assume that the actions of human agents are important, but do not expressly model decisions. Both pure CA models and Markov models underplay decision-making and institutions.
In AgFutures a spatial transition methodology based on CA is adopted, as this approach produces more realistic landscape patterns than regression-based models (Theobald and Hobbs, 1998).

2.2.4.3 Optimization Models

Optimization models are exclusively oriented towards producing solutions which optimize certain objectives defined by users/decision makers. In other words, they are fit to provide support in decision situations where the aim is to choose a solution to a decision problem which satisfies one or more objectives and takes into account various constraints. Hence, they are prescriptive models, although they are used also as evaluation tools. They have found important applications in the analysis of land-use, especially land-use planning applications, and they appear to be useful tools in the search for land-use solutions which contribute to sustainable development and use of environmental and human resources. Optimization techniques used include linear programming, goal programming, dynamic programming or non-linear programming techniques.

Linear programming (LP) models are the most common of the optimization models. These models are aimed at designing alternative land-use systems to optimize land-use configuration and management under a number of technical, food security, socio-economic and environmental objectives (e.g. Schipper et al., 1995; Bouman et al., 1999). Results from such models give optimized objective values (e.g. economic returns) and the associated land-use patterns. The NELUP-Extension model (Oglethorpe and O'Callaghan, 1995) uses LP model at the farm level to maximize income with fixed resources considered as constraints. Dynamic non-linear programming models are not very common. An example of this type of model is FASOM developed for allocation of land to competing activities in the forest and agriculture sectors. The objective function maximizes the discounted economic welfare of producers and consumers in the US agriculture and forest sectors over a nine-decade time horizon.

LP models are not spatially-explicit and have been linked to GIS for spatial allocation of land-uses (Campbell et al., 1992; Chuvieco, 1993; Jansen and Schipper, 1995; Cromley and Hanink, 1999). These GIS-linked models are sensitive to the distribution of environmental conditions in the study areas and provide for mapping of the optimal solutions produced by the model. Stoorvogel (1995) provides details on the development of a GIS-model interface which
makes possible the translation of the results of external model calculations into a GIS and, hence, the visualization of their spatial distribution.

A major drawback of optimization models is that a numerical or analytical solution to the system of equations must be obtained, limiting the level of complexity that may practically be built into such models. Another problem with this type of models includes an underestimation of the role of institutions, population, and biophysical factors, all of which play an important role in reality. Some efforts have been made to better include these factors, valuing the ecosystem and societal services (Rabbinge and van Ittersum, 1994). These models are primarily designed to work at the micro-level and hence there are difficulties when attempting to scale these models. Hijmans and van Ittersum (1996) demonstrated the scale problems that result when these models are used at aggregated levels.

2.2.4.4 Dynamic Systems Models

These models have been developed to simulate land-use change processes and their evolution and are also sometimes referred to as process-based models. They emphasize the interaction, relationships, and linkages between different components of a system. They condense and aggregate complex ecosystems into a small number of differential equations to represent stocks and flows of information, material, or energy among different components of a system (Gilbert and Troitzsch, 1999). System components are described by a set of state variables (stocks), such as the amount of sediment accumulated on a landscape. These variables are influenced by controls (flows), such as sediment fluxes. The nature of the controls (the size of the flows), in turn, may depend on the stocks themselves and other parameters of the systems. Time is broken into discrete steps to allow feedback. These are based on a priori understanding of the forces driving changes in a system, that is, they represent aspects that actually exist in a system. Unlike statistical models, dynamic systems do not rely on historic or cross-sectional data to reveal those relationships.

Human and ecological interactions can be represented within these models, but they are dependent on the explicit enumeration of the causes and their functional representation, and they accommodate spatial relations with difficulty (Baker, 1989; Sklar and Constanza, 1991). In applying a systems approach to land-use models, one difficulty lies in deciding how to incorporate model complexity. Social science researchers may add complexity on the social side while generalizing the biophysical components. Natural science researchers may do the
opposite (Agarwal, 2001). Another challenge is to incorporate scales into this systems approach.

Examples of models that have used the dynamic systems approach include the IMPEL model (Rounsevell, 1999) and the NELUP model which utilized a general systems approach. A number of other models such as GEM and PLM (Geoghegan et al. 1997; Voinov et al. 1999) are also based on this approach and have provided great insight into highly complex systems.

2.2.4.5 Integrated Modeling Approaches

Newer approaches are increasingly based on combining one or more of the above-mentioned approaches. These types of models are often referred as integrated models, although the level of integration may not always be very high, in which case they are referred here as hybrid models. For example, the GEOMOD2 (Pontius et al., 2001) and CLUE (Velkamp and Fresco, 1996a) models combine statistical techniques with systems and cellular models. White et al. (1997) demonstrated the use of a land-use change model that combined a stochastic, CA approach with dynamic systems models of regional economics.

Recently, some approaches have emphasized the role of humans and decision-making. Models based on this approach are also included in hybrid models. An example is dynamic spatial simulation (DSS), which portrays the landscape as a two-dimensional grid where rules represent the actions of land managers based on factors, such as agricultural suitability, to determine how cells change (Southworth et al., 1991; Gilruth et al., 1995). DSS typically does not represent heterogeneous actors, institutional – actor relations, or multiple production activities. However, due to their ability to represent individual decision making and temporal and spatial dynamics, they represent an important advance over previous models (Lambin, 1994).

A variant of DSS models is agent-based models that focus on human actions. These models include human decision making through agents. An agent is "a real or abstract entity that is able to act on itself and on its environments; which can, in a multi-agent universe, communicate with other agents; and whose behaviour is the result of its observations, its knowledge and its interactions with other agents" (Sanders et al., 1997). An individual is the smallest single decision making agent. These models seek to define the nature and rules of individual agents’ behaviour in their daily decision making as well as the behaviour of
individuals at collective and higher levels. Central to this perspective is the significance given to human agents in determining land-use decisions. Agent-based models simulate decisions of agents in regard to choices made about variables that affect other processes and outcomes. Multi-agent models simulate decision making by individual agents of land-use change and explicitly address interactions among individuals. However, a problem with agent-based models is that individual behaviour does not necessarily scale up to group behaviour. Manson (2000) coupled an agent-based model and generalized CA model to create an agent-based DSS, or ADSS. Rajan and Shibasaki (1999) used an agent-based approach to simulate land-use changes in Thailand.

Integrated models of land-use change are diverse as integration takes on different meanings in different contexts. Other integrated models of land-use change attempt to integrate spatial levels, sectors, land-use types or society-economy-environment integration (Briassoulis, 2000). A large number of such integrated models have been developed, but their purpose has been for modeling climate change; they are often referred to as integrated assessment (IA) models (e.g. IMAGE2 (Alcamo, 1994) and DICE (Nordhaus, 1992)). These models integrate a wide range of sectors and process descriptions. Their purpose has not been to model land-use changes and so they severely simplify the land-use systems. These models are usually developed at global scales and have coarser spatial and temporal resolution. Therefore, where local heterogeneity and interactions are important, such models may have limited explanatory power.

It is only recently that regional integrated models of land-use change have been developed. Examples of regional-level integrated models include IIASA-LUC model (Fischer and Sun, 2001), the PLM model (Voinov et al., 1999) and the IMPEL model (Rounsevell, 1999). These integrated land-use models consist of many sub-systems and model the interaction between these systems. For example, the PLM model simulates fundamental ecological processes at the watershed level, in interaction with an economic component that predicts the land-use patterns. The IMPEL model has a modular nature and consists of a set of four interlinked modules: a climate module, soil and crop module, land degradation module, and socio-economic module. Together, these were used to assess the impact of climate change on the distribution of agricultural land-use in Europe.
These models provide great insight into highly complex systems. However, inclusion of too many sub-systems, interactions and feedbacks can sometimes make these models too complex to operate, besides having high data requirements (e.g., the IIASA-LUC model).

The essence of integrated models is providing a systematic way of integrating knowledge across disciplines, styles, resolutions, and degrees of certainty. However, this integration also carries some costs. The rigor of forcing disparate domains into one model can result in simplifying the complexities yielding aggregate results (CIESIN, 1995).

Based on this classification of models, the AgFutures model can be considered as an integrated model, as it integrates human and physical dimensions and uses a combination of stochastic (CA-based) and regression techniques.

2.2.5 Scope of Land-Use Models

Studies that involve modeling the future can be divided into four categories on the basis of their objectives: projections, predictions, explorations, and speculations (van Ittersum et al., 1998). This classification is based on two criteria: level of uncertainty and level of causality. Uncertainty relates to the processes involved, to model parameters or to exogeneous developments that are assessed and used in the forecast. The level of causality is reflected in the type of model that is used for the study: models can be based on statistical analysis, or these can be mechanistic models with information on causes of certain developments. Figure 2.2 shows these four categories of studies for future research. ‘Projections’ are based on a low level of causality. ‘Predictions’ are possible when more information on causality and relations behind a projection is available. If level of uncertainty increases, for example, when considering longer time horizons, a projection might become a ‘speculation’ and if more information is available about how different processes and developments are related, a speculation becomes an ‘exploration’ of the future. I discuss below the role of projective, predictive and explorative land-use models in policy-making.

*Projective:* These models study past land-cover and land-use changes in relation to biophysical and socio-economic parameters and project future trends given certain changes in the parameters. These are generally unable to capture abrupt changes in agricultural land-use such as those caused by natural disasters or collapse of markets (Stoorvogel and Antle, 2001).
Figure 2.2 Types of land use studies based on degree of uncertainty and causality
(Source: van Ittersum et al., 1998)
However, such studies are important to policy makers because they indicate possible changes without policy interventions or as a result of technological changes. Policy makers can decide whether these changes are desirable or not and whether policy intervention is justified. For example, the CLUE methodology gives projections of likely developments in future land-use based on regression relationships between drivers of land-use change (such as climate, soil population) and changes in land-covers (Veldkamp and Fresco 1996a). Changing the values of the land-use drivers by extrapolating past trends or by projecting their expected future developments generates likely land-use patterns. A limitation of this model is that discontinuities in trends (e.g., policy changes) cannot be taken into account.

**Predictive:** These models actually predict land-use changes as a result of changes in driving forces, such as agricultural policies or technologies. These allow researchers to evaluate a wide spectrum of policies related to taxes, subsidies, infrastructure, etc. However, due to uncertainties in determining the behaviour of land-use change drivers, these models can only be applied for a short time horizon. The UNA-DLV methodology utilizes this to predict the likely short term effects of policy measures on farmers' land-use decisions (Roebeling et al., 2000a).

**Explorative:** These studies allow for the exploration of the aggregate effects of alternative policies on the regional level, as well as for the quantification of trade-offs between policy objectives, over a long time horizon (20-30 years) (e.g. the SOLUS methodology (Bouman et al., 1999); Stoorvogel et al. (1995)). These studies can answer 'what-if' questions to allow us to understand possibilities and limitations of land-use in relation to certain objectives. These models show viable options of land-use to the stakeholders which they may not be aware of. This type of methodology can point out biophysical constraints of land-use, revealing possible land-use options under socio-economic constraints, and the combined effect of bio-physical and socio-economic constraints (Bessembinder et al., 2000).

In short, projective and predictive models tell us about the plausible land-use changes in future if trends do not really change, and as such, reveal the likely developments in the future, while exploratory models show options for future developments given certain assumptions about uncertain developments.
Jansen *et al.* (2000) observe that these methodologies have a large complimentary value and despite being independent entities they can together form a coherent toolbox to address issues related to likely changes in future land-use, options for future land-use and effective agricultural policies.

The AgFutures model is mainly exploratory in nature as it shows consequences of user-defined options of agricultural developments, but it also uses projective and predictive methodologies to examine future land-use changes and their impacts.

### 2.2.6 Lessons Learnt, Gaps and Research Priorities in Land-use Change Modeling

There are different modeling approaches and techniques, emphasizing different concepts and disciplines, that have been used to model land-use changes. However, there is a need to integrate different approaches and techniques to make further progress in land-use modeling. Various lessons learnt and gaps brought out in the discussion in the previous sections are summarized here with respect to different issues, highlighting the research priorities for the generation of new land-use models. Subsections 1-3 below are related to the characteristics of the land-use systems, whereas subsections 4-5 refer to the requirements of these models for use as tools for decision-makers.

#### 2.2.6.1 Multi-Disciplinary Aspects

In order to address the complexity of land-use systems, models should use a multi-disciplinary approach involving both biophysical and social sciences, and incorporate data on a wide range of socio-economic drivers of change (*Turner II et al.*, 1995; *Musters et al.*, 1998). It is particularly important to incorporate human dimensions (i.e., the decision-making processes and role of policies and institutions). Even though the multi-disciplinary nature of land-use changes is widely recognized, the institutional powers of the disciplines remain strong and land-use models are often based on the concepts and methods of a single discipline. This is further hampered by methodological difficulties in linking physical and social data. Research on methods for integration of these types of data is necessary for addressing changes in land-use.

#### 2.2.6.2 Multi-Scale Characteristics

Most existing models only consider interactions among driving forces of land-use change that operate at a similar spatial scale. A major problem in land-use modeling is addressing the
effects of drivers that operate at different scales and aggregating the effects of factors
operating at fine scales to higher levels. Along with biophysical and economic factors, the
human decision-making dimension is scale dependent too. A number of capabilities need to be
addressed in multi-scale land-use models. These include: the identification of the optimum
scale and resolution for modeling underlying social and ecological patterns and processes of
land-use change, and dis-aggregation and reaggregation of data among different units of
analysis (implying scales). Most regional level land-use models, except the CLUE models, do
not address these structural complexities of the system. The challenge is to develop nested,
hierarchical approaches that address upscaling and interactions and feedbacks amongst
different scales.

2.2.6.3 Temporal Dynamics
The spatial nature of land-use change has received much attention, but the temporal aspects
have been not dealt with to the same extent, especially the interactions between the spatial and
temporal dimensions. Consideration of time lags and non-linear relationships among social
and ecological processes of land-use change deserve more attention in future land-use studies.
Connected with this issue is the issue of the validation of models (i.e., how good are the
models that are used for future projections). Validation can be done using historic data, but
often these data are not available at the temporal resolution for which the model is developed.
Methods for model validation should evaluate the performance of the model in terms of the
quantity of change and location of change (Pontius and Schneider, 2001) in addition to
validation at multiple scales (Kok et al., 2001).

2.2.6.4 Policy Support
Most of the land-use studies have been strictly scientific exercises. In order to be useful tools
for the public, as well as for policy makers, they should allow for the inclusion of enough key
policy variables to allow for likely and significant policy questions to be explored and be able
to clarify the issues in the debate. These models should provide for a user-friendly
environment and present information to the users in a flexible, simple manner. Consultation
with policy makers and other stakeholders is necessary during the development of the model
for the identification and evaluation of relevant policy scenarios. In other words, we need to
move from a data-driven approach that involves predictions with the data, to a demand-driven
approach that answers how land-use decisions can be better informed.
2.2.6.5 **Integration**

Integration underpins the success of the policy-making process. Land-use models not only need to integrate disciplines. Additionally, in order to be useful as tools for policy makers, they need to integrate the assessment of the effects of land-use change and their feedback on land-use (e.g. soil degradation, water resources and infrastructure development). However, few integrated land-use models exist that can be used as operational tools. Furthermore, in most land-use models there is no integrated treatment of all land-use types. Few models explicitly address the interactions between urban and agricultural uses. Development of integrated models that examine the impacts of different drivers of change on multiple land-uses and examine the effects of these changes on social, economic and environmental systems is essential for making a transition to sustainable agriculture.

2.3 **Summary**

In this chapter I clarified basic concepts of sustainable agriculture and examined various land-use change models with respect to their approach and methodologies. Drawing from the experience of these studies, I defined gaps and research needs in land-use modeling and described the requisites of a land-use modeling methodology. I conclude that in order to be useful for exploring alternative pathways to sustainability, land-use models should be: multi-disciplinary, addressing biophysical and social factors affecting land-use change; include analysis at various spatial and temporal scales at which the different driving factors operate; allow for the intervention of policies; and include stakeholders in the formulation and evaluation of scenarios. As no approach is by itself capable of addressing all of these factors, including human decision-making, different approaches will need to be combined or new approaches developed. Moreover, in order to be used as operational tools for sustainable development, land-use models should be designed to help stakeholders and users answer specific policy and development related questions. The development of the AgFutures model is based on some of the lessons learnt from this review and will be described in Chapter 4.
3 Agriculture and Sustainability Concerns in the Lower Mainland

One of the major steps in the development of a model is to identify driving forces of agriculture and related sustainability concerns in the region that should be included in the model. This is necessary in order to determine what type of scenarios should be constructed in the model, what key variables should be provided in the model for generation of scenarios, and what outcomes need to be considered in sustainability assessment. In this chapter, I first describe the agricultural profile of the study area (i.e., the Lower Mainland) and then discuss the key issues and challenges faced by agriculture here.

3.1 Agricultural Profile

The Lower Mainland, for the purpose of this thesis, is defined as the area covered by two regional districts: the Greater Vancouver and the Fraser Valley Regional Districts of British Columbia (Figure 3.1). It covers an area of almost 17000 sq km, but most of its current population of around 2.3 million people is based in the Lower Fraser River valley, an area of roughly 7000 km², extending from the town of Hope in the east to Vancouver in the west. Some of Canada's most important agricultural land and wildlife habitat is located in this region. This area forms part of the nation's limited supply of prime renewable resource lands, lands with a high capability for agriculture, wildlife and forestry. While competition between urban and other uses of land resources is common in the urban-rural fringe of most cities in Canada, it is particularly acute in the Lower Fraser Valley.

The Fraser valley is one of the most agriculturally productive areas in Canada, with excellent soil and climate conditions for agriculture. About 7 percent of the province's prime agricultural land is located here. It is the province's most concentrated farming region, having over 5500 farms covering an area of 88405 ha. These represent over one-fourth of the total provincial farms, yet they occupy only 3.4 percent of BC's total farmland. Despite occupying a relatively small proportion of farmland in BC, the Lower Mainland accounted for about 62 percent of BC's gross farm receipts in 2001, amounting to over 1.4 billion dollars (SC, 2001).

Agriculture here is distinguished by its diversity; more than 80 different commodities are produced. Various statistics related to type of farms and land-use are presented in Figure 3.2. In terms of farm numbers, miscellaneous specialty (35%) farms are highest; the other top four
Figure 3.1 Study area – Lower Mainland
Figure 3.2 Agriculture in the Lower Mainland – 2001
(Source: Statistics Canada, Census of Agriculture, 2001)
farm types are beef cattle (15%), fruits (13%), poultry (12%), and dairy (11%). Dairy products produce the greatest revenue of agriculture production and account for nearly one-quarter of farm cash receipts, followed by poultry and hogs. The region also generates substantial revenues from greenhouse, nursery, vegetables and berry crops.

The majority of farmland is used for pasture and hay crops, primarily to feed the large dairy herds in the region. In 2001, about 55000 ha of the region's farmland were under cultivation with the chief crops being hay, corn for silage, berries, and grapes and vegetables.

There are several factors that contribute to the significance of agriculture in this region. These include the mild climate, nearby areas of large and increasing populations, the ethnic diversity of populations, and the proximity to export markets, particularly the USA. Well-developed transportation systems enable rapid and low cost movement of commodities. These factors allow the area to produce a wide diversity of crops and meet an ever changing market demand. A high level of technology governs this sector, including greenhouse vegetables, floriculture, nursery, dairy and poultry. Many of these industries use advanced technology in crop nutrition, climate control, plant/animal health, marketing, and management. Proximity to universities and research centres further facilitates product and technology development here. Access to food processors helps to increase the production of higher value-added products for other markets (BCMAF, 1998).

3.2 Challenges to Agriculture

Despite the significant contribution of agricultural production revenue to the province’s total revenues, agriculture in this area is undergoing great changes associated with a number of social, economic and environmental factors that affects its sustainability. Some of these are discussed below.

3.2.1 Urban Growth and Agricultural Land Reserve

One of the most pressing and contentious issues related to agriculture is the present rate of population growth and related urbanization in the valley. The region is one of the most rapidly growing population centres in North America, with a growth rate of about 2 percent per year. It faces constant pressure to use agricultural land in order to accommodate urban growth. Rapid increases in population occurring in Vancouver and other cities of this region have resulted in loss of prime agricultural lands in the region. Environment Canada (1985) reported
that between the mid-1960s and the mid-1970s, agricultural lands in the Lower Fraser Basin decreased from about 24% to less than 20% of the total area.

To protect and maintain the dwindling agricultural land base, a special land-use zone called the Agricultural Land Reserve (ALR) was established in 1973. The purpose of the ALR was to protect high quality agricultural land for food production. This slowed down the rate of conversion of agricultural land to non-agricultural uses, but did not completely stop it. Prior to the inception of the ALR, an estimated 6000 ha of prime agricultural land were being lost to urban growth in BC, most of which was in this region where growth in population and demand for land was greatest. Moore (1990) showed that between 1980 and 1987, one out of every four hectares of land converted from rural to urban uses in the Lower Fraser valley were agricultural lands. Since 1974, over 10,000 ha of land have been withdrawn from ALR in the Lower Mainland (Table 3.1). Most of these were prime agricultural lands of which 19 percent belonged to the high capability class (classes 1 and 2) and 59 percent had moderate capability (classes 3 and 4) (Lavkulich et al., 1999). During the period of 1974-1994, 7% of the total ALR was lost in the region, with an average annual loss of 472 ha per year (FBMP, 1997). However, the ALR has displayed growing stability, and the average rate of loss has decreased since then to about 200 ha per year in 1999 (ALC, 2000). At present, around 128000 ha of land are protected as ALR in the Lower Mainland, which represents under 3 percent of the total provincial ALR. Most of this area is situated in the Fraser Valley around the Lower Fraser River, in proximity to growing urban centres (Figure 3.3). Agricultural lands are threatened as population grows and developers lobby for the removal of lands from the ALR.

3.2.2 Urban / Rural Land-use Conflicts

There are urban/rural land-use conflicts in which agricultural operations affect, or are affected by, the urban activities. A check-list of the common urban/agricultural conflicts can be found in a report by Agricultural Land Commission (ALC, 1998). Some of these conflicts are related to the use of resources. For example, there is an increased demand and competition between agriculture and urban users for limited but critical water resources. Also of concern is the inherent shift in decision making related to water allocation in favour of non-farm users. Other examples include the effects of flooding from urban developments, and runoff of pollutants entering ditch systems used as water sources for farm purposes.
Figure 3.3 Agricultural Land Reserve (ALR) and Census Subdivisions in the Lower Mainland
Table 3.1 Inclusions and exclusions from the ALR by regional district

<table>
<thead>
<tr>
<th>Regional District</th>
<th>Area at designation (ha)</th>
<th>Inclusions (ha)</th>
<th>Exclusions (ha)</th>
<th>Net change (ha)</th>
<th>Area as of March 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Fraser Valley(^1)</td>
<td>29,111.8</td>
<td>n/a</td>
<td>650.0</td>
<td>-650.0</td>
<td>28,461.8</td>
</tr>
<tr>
<td>Dewdney Alouette (^1)</td>
<td>23,765.2</td>
<td>n/a</td>
<td>574.5</td>
<td>-574.5</td>
<td>23,190.7</td>
</tr>
<tr>
<td>Fraser Cheam (^1)</td>
<td>36,761.1</td>
<td>n/a</td>
<td>594.0</td>
<td>-594.0</td>
<td>36,167.1</td>
</tr>
<tr>
<td>Fraser Valley</td>
<td>n/a</td>
<td>412.5</td>
<td>3,742.0</td>
<td>-3,742.0</td>
<td>n/a</td>
</tr>
<tr>
<td>Greater Vancouver</td>
<td>58,782.9</td>
<td>248.3</td>
<td>5,258.4</td>
<td>-5,010.1</td>
<td>53,772.8</td>
</tr>
</tbody>
</table>

\(^1\) These regional districts have since been amalgamated into the GVRD and FVRD. Inclusion data for these has been included into its correct jurisdiction (FVRD or GVRD). (Source: Agricultural Land Commission, BC)

Other conflicts arise at the urban-rural edge. For persons living next to farms, complaints related to agriculture often centre on the odour of manure spreading, background noise, slow moving farm vehicles on the local roads, pesticide spraying and early morning or late evening operation of machinery. This makes the urban-rural edge the most difficult, least favoured and highly challenging area to farm due to the potential for conflicts (Smith, 1998).

### 3.2.3 Economic Challenges

While the ALR has helped maintain the agricultural land base to a great extent, it has not ensured the affordability of farming. Not all land in the ALR is farmed. Among other reasons, some of the issues that affect farmers' decisions to farm are: the high costs of production, including economic costs of meeting environmental regulations; increased competition from global markets; and fragmented and disparate farms. There is an underlying notion that land-use transition of agricultural lands to urban uses is inevitable, which has resulted in increasing the costs of agricultural land. Land prices have risen dramatically, with an acre of farmland in Richmond now costing more than $90,000, a twenty-fold increase over the last thirty years (Western Producer, 2000). Many farmers see the incentive to sell valuable land, while others feel these housing developments threaten their way of life and the local agricultural industry.
These high costs prevent farmers from owning the land they farm, which affects the stability of the broader farm community (Smith, 1998) and also has environmental implications.

Agricultural activities in the region are governed by provincial and federal regulations that ensure the protection of social, economic and environmental values that are important to communities. For example, there are environmental regulations regarding the management of farm wastes and the use of pesticides; employment and labour standards ensure fair wages for farm workers and minimum health and safety requirements. However, farmers have to bear additional production costs for meeting these standards and criteria, and are often at a disadvantage as compared to non-local producers. Many farmers perceive environmental regulations to be a major and growing constraint on viability (CAC, 1999). Key issues for farmers include manure management, odours and smells, runoff into ditches, manure spreading windows and ditch maintenance.

Farmers have also been facing increased competition from global markets as a result of major international trade agreements and a move towards an increasingly global economy (FBMP, 1997). Trade liberalization has resulted in an increase in export marketing and the easing of restrictions on domestic markets for commodity crops, which has increased competition for farmers in the Fraser Valley. The opening of domestic markets to foreign chicken, egg, and milk producers puts pressure on provincial marketing boards to respond competitively. These outside stimuli force the agricultural producers of the region to respond to the changing market conditions. International trade agreements limit the amount of support that government can give to producers; while at the same time, government is unable to provide incentives to farmers that help them to remain competitive in global markets. These affect the affordability of farming.

3.2.4 Environmental Challenges

Some of the environmental challenges in the area arise from the intensity of agricultural activities. To remain competitive in the global markets, the land is being intensively farmed with high inputs of energy and chemicals and outputs of waste products. Agricultural intensification in the area has resulted in a shift in production from dairy and vegetables to berries and livestock (mainly chickens and hogs). The intensification of agriculture in the Lower Fraser Valley means that much of the present agricultural production is decoupled from the land base. This is particularly the case with the livestock industry which relies more on
importing animal feed rather than producing it locally (Lavkulich et al., 1999). Livestock farms here are little more than a housing site for the animals and a storage and disposal site for their wastes. This has effects on water quality. Water pollution from nitrogen in animal manure is a major issue in this area because of the concentration of animals and a limited land base for disposal. A recent study examined manure production and agricultural land-use in the Abbotsford aquifer area to understand the causes of elevated nitrate concentration in the aquifer (Zebarth et al., 1998). They found that there was a large increase in nitrogen surplus resulting from changes in land-use. During the study period, there was an increase in animal manure production but a decrease in the agricultural land base and a shift from pasture and hay crops to berries that have a low nitrogen removal rate. Estimates of nitrogen were negligible prior to 1971, indicating that the system was capable of absorbing all of the inputs. Another detailed study on environmental effects, specifically pollution of water bodies due to agricultural activities, carried out by Schreier et al. (1999) also showed that excessive fertilizer applications and excessive livestock manure production were the main sources of non-point source pollution from agriculture in the Fraser Basin. Producer organizations like the Sustainable Poultry Farming Group, in partnership with the government, are involved in moving excess manure from areas having nutrient surplus to those where additional nutrients are required. However, there are costs of transportation associated with these activities.

Agricultural intensification has also given rise to wildlife concerns in the region. The use of land for non-traditional (read non-soil based) but intensive agricultural systems such as greenhouses and livestock facilities pose challenges for the co-existence of agriculture and wildlife. Millions of migratory and wintering shorebirds and waterfowl rely on open-soil agriculture and natural habitats for food and cover, especially around Boundary Bay and Roberts Bank in Delta. Greenhouses shrink this available habitat and also fragment the landscape which affects these birds (EC, 2002).

Some of the other environmental concerns in the region are related to soil management (e.g. soil compaction). Soil erosion risk has been controlled in the past decade by promoting soil conservation through government-funded programmes such as the National Soil Conservation programme, the Green Plan for agriculture and the Greenfields project (a co-operative initiative involving Delta farmers, wildlife agencies and UBC researchers). Withdrawal of funds for these programmes may hamper soil conservation efforts by farmers (FBMP, 1997).
3.2.5 Social Challenges and Policies

Policies supportive of sustainable farming practices, while being synchronous with the priorities of other sectors, are critical to achieving the economic, environmental and social potential of the communities. These policies must respect and recognize the needs of agricultural and non-agricultural communities and balance concerns regarding economic development, environmental protection and development and maintenance of liveable communities. Various policies affecting agriculture apply to the region, for example, the Agricultural Land Commission Act, the Farm Practices Protection Act, Municipal Official Community Plans and environmental regulation acts. Integrated policies such as the Farm Practices Protection (Right to Farm) Act provide protection to farmers under accepted farm practices and address concerns related to rural-urban edge farming conflicts such as farm odours, and dust and noise.

While these policies are necessary to support and facilitate the development of sustainable agriculture, it is essential to engage the agricultural and non-agricultural communities in the formulation of these policies. However, broad participation in policy development by different communities is hampered due to a lack of food systems awareness in the general population (Holbek, 1998) and the lack of understanding of the importance of farming in the officials in non-agricultural agencies, which results in conflicting and/or inconsistent policies affecting farmers.

Besides addressing the challenges described above, agriculture has to meet social demands, preferences and expectations too. In the Lower Mainland, the changing demographics have resulted in demands for different types of food, such as an increase in fresh food and vegetables, and a shift from red meat to chicken. In addition, many consumers place heightened emphasis on the nutritional content and value of food products. There is a demand for healthy, high quality food. Food buying decisions are often affected not only by health benefits and prevailing prices, but also to some extent by public and individual concerns regarding issues such as environmental health, animal welfare, family farming and genetic modification. These social factors directly affect the agriculture industry and shape the nature of farming.
3.3 Community-identified Issues

The identification of issues for inclusion in the model was also aided by multi-stakeholder workshops conducted by the Georgia Basin Futures Project (GBFP). It was recognized that the process of identification of issues should take place in consultation with local communities and key stakeholders in the region rather than being based on objectives that are economy-oriented. Several workshops were organized by the GBFP to engage in discussions with people concerned in order to shortlist the issues and the outcomes that need to be addressed in the model. These workshops were held in Richmond in October 2000, which were attended by farmers, researchers, local people and government officials responsible for making policy decisions. Van Wynsberghe et al. (2003) describe in detail the workshop process for community engagement in design of archetypes or potential alternatives for future scenarios.

A preliminary list of sustainability concerns or objectives as identified in these community workshops is given in Table 3.2. Some of these addressed in the development of AgFutures were: abundance of food, minimize vulnerability, minimize environmental impacts and support the local economy.

<table>
<thead>
<tr>
<th>Safe food</th>
<th>Living wage – global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-limiting</td>
<td>Support local economy</td>
</tr>
<tr>
<td>Joy celebration</td>
<td>Maximize health</td>
</tr>
<tr>
<td>Abundance</td>
<td>Maximize security</td>
</tr>
<tr>
<td>Social and ecological justice</td>
<td>Increase community interaction</td>
</tr>
<tr>
<td>Adaptability of system</td>
<td>Community involvement in decision-making</td>
</tr>
<tr>
<td>Understanding food systems</td>
<td>Considering eco-centric options</td>
</tr>
<tr>
<td>Increasing stakeholder responsibility</td>
<td>Strategies for transformation</td>
</tr>
<tr>
<td>Minimize vulnerability</td>
<td>Clean environment</td>
</tr>
<tr>
<td>Fair distribution</td>
<td>Diversity of choice</td>
</tr>
<tr>
<td>Process to state “ethical” choice</td>
<td>Education about alternatives</td>
</tr>
<tr>
<td>Minimize environmental impacts</td>
<td>Affordability</td>
</tr>
<tr>
<td>Goals of production = nutrition</td>
<td>Access to local resources</td>
</tr>
<tr>
<td>Intimate commodity</td>
<td>Biodiversity - dynamic</td>
</tr>
</tbody>
</table>

While some of the issues identified in this chapter have been included in AgFutures as variables for defining alternative future scenarios, such as preservation of ALR, diet, and intensity factors, some (e.g., environmental concerns) were included as outcomes. Concerns of the farming community with respect to urban/rural conflicts and infrastructure were represented in the evolution process of land-uses. It was not possible to include certain issues
such as food quality, which were difficult to quantify, or issues such as fair distribution, which were about a process rather than an outcome.

3.4 Summary

In this chapter I identified key issues related to agriculture and sustainability in the Lower Mainland. The need for transition to a scenario of sustainable agriculture assumes importance here because of three factors: a small existing agricultural land base that is under threat from adjacent urban development; the significance of the agriculture sector and its contribution to the province's economy; and the effects of agricultural intensification on the environment, particularly on water quality and wildlife habitats. These issues were translated to appropriate criteria in AgFutures for assessing sustainability and guiding the assessment of various scenarios of agricultural development in this study.
4 The AgFutures Model – Overview and Methodology

In this chapter I first present an overview of the AgFutures model developed in this research and then discuss the spatial framework, that is, the CA-MCDM-GIS approach and methods for land-use simulation in detail.

4.1 Overview

4.1.1 Main Features

The AgFutures model is an integrated model that projects land-use changes under alternative scenarios of agricultural development and examines the effects of these on sustainability. It has various features that are described below.

Integrated model. The complexity of land-use systems and the associated sustainability analysis demands integration of physical and social sciences. While disciplinary models are complex, with a sound theoretical basis and examine issues in a depth, integrated models are easy to use and implement and present broader, but less detailed, consequences for important issues. The essence of integrated modeling is to provide a systematic way of integrating knowledge across disciplines, styles, resolutions and degrees of certainty (CIESIN, 1995). Most previous land-use models have been disciplinary in nature addressing either human or physical dimensions of land-use change or addressing one part of the complexity of land-use systems (Veldkamp and Lambin, 2001). In contrast, this model is based on a systems perspective that considers land-use as one component of a socio-bio-physical system. It integrates human and natural dimensions of land-use system at multiple scales, and examines the impacts on social, economic and environmental outcomes and the trade-offs among these, through selected indicators of sustainability. It links human actions to consequences and thus provides end-to-end integration. It assigns a central role to human driving forces and addresses human decision-making through inclusion of policy variables and by explicitly modeling future land-use conversions based not only on bio-physical and socio-economic factors, but also as a function of human choices and preferences regarding development in the region. Inclusion of variables related to all three components of sustainability provides a balanced perspective required for sustainability assessment.
Scenario-based. Moving into the future means traveling into uncharted waters. It is difficult to foresee how events will unfold in the future. Uncontrolled forces, both human and natural, will affect future events. Models for exploring alternative futures need to address this uncertainty surrounding the behaviour of systems in a manner that is transparent to the user. Predictive models often focus on predicting a single future based on past trends and are valuable where changes are governed by past behaviour. However, they fail to address uncertainty and recognize that the future can be a result of present and future choices. For example, changes in certain policies can result in unanticipated environmental consequences. So, instead of making predictions of likely future changes in land-use the model relies on users to build 'desirable' scenarios and explore the outcomes of their choices. The use of scenarios, which often relates to a backcasting approach to decision making (Robinson, 1990), recognizes that our society has significant control over future outcomes, and suggests that decision making should take place in this context, rather than viewing the future as an inevitable and hence predictable outcome. The scenario-based approach treats uncertainty as unavoidable and is useful to study situations when trends depart from the past behaviour. It allows users to explore different assumptions concerning human behaviours and values, institutions and technology, which are seldom jointly considered in predictive models. Scenario analysis can help informed decision-making that can play a vital role in shaping future.

Multiple land-use types. The model explicitly takes into account urban conversions as well as agricultural land-use changes, including greenhouse and livestock operations. The major land-use categories modeled include: urban; agriculture (food crops, hay/forage crops, greenhouses); managed pasture; unmanaged pasture; and forest. Food crops category includes berries, vegetables, grains, and other crops. Different livestock types considered in the model include cattle, pigs, and chickens.

Dynamic spatial simulation. It simulates spatial patterns of land-use change and considers spatial interactions and neighbourhood effects. Land-use simulation is based on the temporal evolution of land-use, which takes into account land-use changes occurring at each time step of the simulation.

Quantification of impacts on sustainability. In order to improve transparency in the policy-making process, as well as in communal decision-making, it is necessary to quantify the
impacts on various social, economic and environmental goals under different scenarios. AgFutures provides sustainability indicators and indices to assess and compare scenarios.

**Multi-scale approach.** Simulation of land-use changes considers the interaction among factors operating across two different scales (local and regional). Two different approaches can be distinguished for implementing multiple scales in the model. One approach takes into account the scale dependency of the quantitative relations between land-use and its driving forces. In these models, the data are artificially gridded at multiple resolutions and at each resolution the relations between land-use and driving forces are statistically determined (Veldkamp and Fresco, 1997; de Koning *et al.*, 1998; Verburg and Chen, 2000; Walsh *et al.*, 2001). In the second approach, used in models such as CLUE-CR (Veldkamp and Fresco, 1996b) and LTM (Pijanowski *et al.*, 2000), the model is structured hierarchically to take multiple levels into account. In this approach, the total amount of change is determined for the study area as a whole and allocations are made at a grid-level using a suitable allocation procedure. This is the approach adopted in AgFutures.

As discussed earlier, many studies have used regression methods for spatial forecasting of land-use changes. However, in AgFutures, a spatial transition methodology based on cellular automata (CA) is adopted, as this approach produces more realistic landscape patterns than regression-based models (Theobald and Hobbs, 1998).

### 4.1.2 Conceptual Framework of the Model

Figure 4.1 illustrates the main components of the model, along with required inputs and the methods used in its development. The model consists of two major components: land-use evolution and impact assessment. The land-use evolution component simulates likely changes/conversions in land-use up to the year 2040 and predicts how much of, and where, different land-uses will develop over time. In this step, livestock numbers and future projections of various land-use category areas are calculated at a regional level from 2000 to 2040, at decadal intervals. These projections are based on analyses of regional historical land-use trends, empirical relations between driving factors and land-use changes, or exogeneous models of demand for a particular category. The allocation of land-use is then carried out at the grid level (size 100 x 100 m), based on transition probabilities for different land-uses determined on the basis of local and regional factors affecting land-use changes. The allocation
Figure 4.1. Framework of AgFutures model
uses integration of CA and multi-criteria decision making techniques within a GIS to compute these probabilities. The CA procedure attempts to allocate uses to cells based on competition among different uses while meeting the demands projected by the regional model. It uses land-use information that is derived from remote sensing data. The spatial simulation methodology is explained in detail in the next section.

The second component of the model provides a regional-level assessment of the impacts of these land-use changes on sustainability. The sustainability issues considered in the model are based on the various environmental and socio-economic concerns of agricultural sustainability in the region. Specifically, indicators related to food security (represented by the agricultural land base availability and land production potential), water quality, wildlife habitats and economic production and costs are developed and used for assessment of different scenarios. The micro-scale and regional-scale land-use results from the land-use evolution component are used in the calculation of these sustainability indicator values. An aggregated sustainability index is also developed and used for comparison of different scenarios for their overall impacts on sustainability.

Model inputs represent those environmental and socio-economic factors that affect or drive the development of agriculture. The values of some of these parameters are affected in the model by scenarios defined by the users. For example, agriculture intensification changes the values of crop yields which in turn affect the values of fertilizer use. The scenario-building component of the model provides key variables related to policy, management practices, and consumption patterns for building alternative scenarios to examine different policy options in the region. Through scenario formulation and assessment, the model allows the users to examine the trade-offs involved among alternative development pathways to make wise choices for moving to a sustainable future.

### 4.2 Methodology for Simulation of Land-use Changes

In this section I describe the CA-MCDM-GIS methodology that has been used for simulation of land-use changes. Before presenting this, I present the basic concepts of the MCDM and CA methods and discuss their advantages.
4.2.1 Introduction

GIS have been widely used in land-use models to develop spatial patterns of land-use. GIS are described as systems for the storage, manipulation, analysis, and display of geographically referenced data (Maguire, 1991). These systems offer a wide range of spatial analytical functions and they have proven extremely useful in modeling spatial processes such as land-use. However, contemporary GIS have yet to attain their full potential for spatial analysis and decision support (Openshaw, 1991). Powerful decision support and analytical tools have been integrated with GIS in order to extend its functionalities for decision support systems.

Amongst these efforts, integration of multi-criteria decision making (MCDM) approaches with GIS has received considerable attention (Janssen and Rietveld, 1990; Carver, 1991; Eastman et al., 1993; Pereira and Duckstein, 1993; Jankowski and Richard, 1994; Jankowski, 1995).

GIS-based MCDM methods are able to integrate multiple, disparate, socio-economic and environmental factors that affect land-use changes, but they are still inadequate for use in land-use models, as contemporary GIS are inefficient in dealing with dynamic spatial models and the temporal dimensions of environmental processes. On the other hand, dynamic modeling approaches such as CA are efficient in representing spatial dynamics and scale effects, but cannot be used by themselves in decision support systems as they represent a process simply through transition rules and are agnostic about the type of the process. Most CA models consider the actions of humans as important, but are unable to explicitly model decisions. These models thus downplay decision making and institutions (Manson, 2000; Parker et al., 2003) and lack consideration of multiple activities. The approach used here integrates these three techniques to address human decision-making and scale issues in the land-use change process.

4.2.2 Multi-criteria Decision Making

MCDM problems involve “a set of alternatives that are evaluated on the basis of conflicting and incommensurate criteria” (Malczewski, 1999 p.81). In situations that involve a large number of alternatives and multiple conflicting criteria, MCDM techniques provide systematic methods of identifying the best alternatives. They provide methodology for guiding decision makers through the critical process of clarifying evaluation criteria and/or objectives, and of defining values that are relevant to the decision situation.
MCDM techniques fall into two categories – Multi-Attribute Decision Making (MADM), (also called Multi-Criteria Evaluation (MCE)) and Multi-Objective Decision Making (MODM). MCE techniques have three elements: a set of alternatives, a set of criteria that constitute a decision matrix, and a vector of preference over criteria. MCE involves the computation of an evaluation score that is calculated by either weighted summation or pair-wise comparison of alternatives. In raster-based systems where each cell is viewed as an alternative, pair wise comparison of alternatives is nearly impossible. Thus, a weighted summation is often used to compute the final score of suitability. MCE techniques, by themselves, are only mathematical formulae with no in-built means of spatial data handling. However, when integrated with GIS, these offer a means of spatial decision making in situations involving multiple criteria (Carver, 1991).

MODM approaches typically use mathematical programming techniques to determine the optimal solution to a multi-objective decision problem. These techniques aim at optimizing an objective function. However, it is usually difficult to implement MODM methods within a GIS as decision alternatives are defined in terms of causal relationships and constraints. This implies that the alternatives are not defined explicitly, but rather have to be generated implicitly within the spatial multi-objective procedure. Typically, it requires a combination of mathematical programming software and GIS capabilities. The decision problem is solved by the mathematical programming software and GIS serves as the tool for visualizing the results of MODM procedures.

MCDM techniques have several strengths, which led to their use in this study. Being interactive in nature, they enable a realistic representation of the decision problem and allow users to learn more about the problem. Also, they are structured approaches that are flexible enough to allow the use of value judgments. They provide a mechanism for representing decision-maker’s choice and preferences/priorities in the context of evaluating conflicting criteria and objectives.

4.2.3 Cellular Automata

CA were first used by von Neumann (1966) for studying self-reproducible systems. CA are discrete dynamic systems in which the state of each cell at time t+1 is determined by the state of its neighbouring cells at time t according to pre-defined transition rules. Essentially, conventional CA consists of (White and Engelen, 2000):
i. A grid of regular cells
ii. A set of discrete states that characterize the cell
iii. A definition of a neighbourhood of the cell
iv. A set of transition rules, which determine the state transition of each cell as a function of the state of cells in its neighbourhood
v. Discrete time steps, with all cell states updated simultaneously

The grid

Grid space is typically assumed to be two dimensional, rectilinear, and homogeneous; however, these assumptions are frequently dropped. For most land-use applications a two dimensional grid is used. Although non-rectilinear grids can be used, often a rectilinear grid is preferred because of its obvious advantages in terms of its compatibility with raster GIS and in terms of computational efficiency. However, the regular structure introduces artifacts into the spatial structures. Despite this fact, these are the most widely used systems.

The cell states

Cell states can represent any spatially distributed variable for which spatial dynamics need to be modelled. In land-use models cell states commonly represent land-cover and land-use. However, different models, for example those related to hydrology, can use soil moisture and sediment loads; population models can use population density as cell states.

The neighbourhood

Most CA applications adopt either a Von Neumann neighbourhood (consisting of the four cells adjacent to the sides of the cell) or the Moore neighbourhood (the eight adjacent cells). However, in land-use models, local or neighbourhood effects may extend to a larger distance. Hence some researchers (e.g., Uljee et al., 1996) have used the idea of an extended neighbourhood.

The transition rules

These form the core of a CA and represent the logic of the process that is being modeled. The rules determine the spatial dynamics which result. These rules could be simple, based on the
majority of states in the neighbourhood, or complex, considering interactions between different factors. Typically in a CA, a stochastic element is introduced into the transition process in order to capture the imperfections and subjectivity involved in the definition of rules.

The time step

In CA models, changes in states of cells take place in discrete time steps. At each time step, a simultaneous updating of all cells takes place after the rules have been applied. In land-use models, a time step of 1 year is normally considered appropriate to model land-use changes, whereas in other models, such as a model of traffic flow, time steps could be in minutes or seconds.

4.2.4 Constrained Cellular Automata

A constrained CA approach embeds some constraints into the transition rules of the CA in order to reflect actual development patterns. Usually the constraints are related to land suitability for a use. Land accessibility factors such as distance to roads and city centers are often used as suitability constraints. In a pure CA, the number of cells in a particular state is determined endogenously in the model. However, to model realistic situations the CA can also be constrained to generate a particular number of cells in each state, with the target cell numbers being determined exogenously by another model based on demands (White et al., 1997).

4.2.5 Advantages of Using Cellular Automata

CA are inherently spatial and dynamic, which makes them ideal choices for the representation of spatial and dynamic processes. Because of these properties they have been widely used in land-use simulations. Furthermore, they are simple and computationally efficient and therefore make it possible to model land-use dynamics at high resolution. Being rule-based, they can capture a wide variety of spatial behaviours (White and Engelen, 2000). The transition rules allow interactions that go beyond the immediate effect of neighbouring states; these include the behaviour of the socio-economic agents that affect the spatial structure. While transition rules may be simple, CA can result in new, complex spatial structures (Couclelis, 1985; White and Engelen, 1993). These models apply a 'bottom-up' approach such that local rules can create complex patterns. Because of the explicit attention given to neighboring cells, CA can
realistically mimic scale effects by changing the number of neighbors affecting a state transition. General versions of CA use nonlocal neighbourhoods (Takeyama and Couclelis, 1997). They are therefore able to simulate spatial patterns in a very realistic way.

CA thus offer a flexible platform to represent meaningfully a variety of interactions among the various components of the complex land-use system – social, economic, environmental.

The similarities between CA and raster GIS data structure have led to the implementation of CA models inside GIS by many researchers (e.g., Batty and Xie, 1997; Clarke and Gaydos, 1998; Wu and Webster, 1998; Li and Yeh, 2000). CA serve as analytical engines to enable dynamic modeling within GIS (Park and Wagner, 1997). Integrated GIS and CA models allow for the dynamic simulation of land-use changes and can generate realistic simulations of land-use patterns and spatial structures (White and Engelen, 2000).

4.2.6 Conceptual CA-MCDM-GIS Procedure

Conventional CA models simulate land-use changes based on the state of the cell and that of its surrounding cells, evolving in discrete time steps. Each cell acquires a new state according to transition rules. These models assume homogeneity within the cell space that is characterized by the state of the cell. However, geographical processes are affected by many other factors than the state of surrounding cells. Hence, very often CA models consider heterogeneous cell space; that is, they characterize the cell space by a set of attributes representing these factors. These models rely heavily on the calculation of suitability based on these factors. It is through computation of this suitability that effects of human decision making on allocation of land-use to a cell can be introduced into the model. Also, it is through this suitability that the links between CA and GIS-MCDM are established, since the calculation of suitability is based on weighted sums of multiple spatial criteria. The approach used in AgFutures is based on this rationale.

The use of a cell for a particular crop, for instance, can be conceptualized here as the result of a MCDM process that links the state of a cell with the intrinsic suitability of land and other human decision making factors that act at different scales. The intrinsic suitability of land may include land characteristics such as capability and slope, and also proximity factors such as distance to markets and roads. Human decision making factors may include demands for that use, an individual’s preferences and values regarding resource use, and institutional policies.
(e.g., those related to use of land). The state of a cell in a CA model can then be determined as a function of these factors, neighbouring land-use effects, and transition rules by aggregating them into a composite suitability value.

Mathematically, in a CA, the state of a cell is given as:

$$S_{t+1} = f(S', N, T)$$

(4.1)

where $S_{t+1}$ and $S'$ are states of cell at time $t+1$ and $t$ respectively, $N$ is the neighbourhood effect, and $f$ is the transition function governed by the set of transition rules $T$. Cell states typically represent land-use/cover in land-use models.

In MCDM methods, the suitability of a cell is determined as:

$$SS_k = f(Z_i, U)$$

(4.2)

where $SS_k$ is the suitability of a cell for use $k$, $Z_i$ are factors affecting suitability of a cell and $U$ is the set of rules representing decision makers' preferences or value judgements.

In the CA-MCDM model, the state of the cell can then be determined based on the transition probability of a cell for a given use $k$, which in turn is determined by the composite suitability of the cell for that use:

$$S_{t+1} = f(P_k)$$

(4.3)

$$P_k = f(CS_k')$$

(4.4)

$$CS_k' = f(S_t, N, T, Z_i, U)$$

(4.5)

where $P_k$ is the probability of conversion of a cell to use $k$ at time $t$, and $CS_k'$ is the composite suitability of a cell with use $k$ at time $t$. Human decision making is incorporated in computation of these suitabilities in two ways: Firstly, by defining the transition rules of the CA that consider spatial adjacency conditions of a land-use and decide under which conditions the cell converts to a particular state. Secondly, by assigning the decision maker's preferences with respect to evaluation criteria in the MCDM process. The term 'decision maker' here refers to the user or group of users who are using this tool and imposing their preferences across the entire landscape; it does not represent individual land owners whose decisions will result in heterogeneous preferences over space.
Furthermore, the CA model is constrained not only by the land suitability constraints, but also by the land-use demands and policy constraints operating at the regional level.

The conceptual procedure adopted in this research is shown in Figure 4.2. The first step is to identify the land-use categories that define the cell states for the CA model. Driving variables or factors affecting the suitability of a cell for each of these uses are then identified and corresponding spatial data layers, as well as a base land-use map, are generated using remote sensing and GIS techniques. A number of transition rules are defined that are based on expert knowledge, user preferences regarding conversion of uses, and scenario definitions. The next step consists of translating CA rules to scores using spatial and neighbourhood operations of a GIS. Scores of suitability are also assigned to other factors that affect land-use conversions. These are then used to evaluate the composite suitability using the MCE technique – Weighted Linear Combination – as follows:

\[ CS_k = \Sigma W_{ik} X_{ik} * \Pi C_i \]  
\[ (4.6) \]

where \( W_{ik} \) are weights associated with each factor \( i \) for use \( k \) and \( X_{ik} \) are scores of factors with respect to use \( k \), and \( C_i \) are Boolean scores of restrictive factors (i.e., scores are set to zero for certain locations if they are considered as constraints for development, such as urban areas and lakes where agricultural development cannot take place). The weights in this equation are determined using the MCDM technique – Analytical Hierarchy Process (Saaty, 1980) – which is based on decision-makers’ preferences with respect to evaluation criteria or factors.

This suitability is dynamic in nature as the constraints and the neighbourhood states are dynamic, and in each time step of the CA model the transition rules gets updated. The maximum value of suitability \( (CS_{\text{Max}_k}) \) changes in each iteration, and a relative measure of the suitability is used to determine the probability of conversion of a cell to use \( k \) at time \( t \):

\[ P_{kl} = \exp [\alpha (CS_k/CS_{\text{Max}_k} - 1)] \]  
\[ (4.7) \]

where \( \alpha \) is the dispersion parameter that is determined on the basis of transition rules. Its value determines how the site selection proceeds. The higher the value of \( \alpha \), the more stringent the site selection process or the lower the probability that the cell will be used for that type. This approach has been used earlier by Wu (1998) to study urban development in Guangzhou, China. However, Wu and many other researchers used CA models for allocations to one use...
Identification of factors and constraints affecting suitability for each use

GIS and RS
Generation of:
- Data layers
- Initial land use
- Spatial constraints

Demands for each land use type for the time step

Next iteration

CA
Definition of transition rules
Assignment of suitability scores
Computation of suitability for each use
Calculation of probability of conversion
Spatial allocation of different uses
Update land use map

MCDM
AHP techniques for calculation of weights
Multi-objective land allocation techniques for conflict resolution

User's choices and preferences

Final land use for 2040

Figure 4.2. Schematic overview of CA-MCDM-GIS procedure for land use simulation
only. The present approach can be considered as an extension of the approach used by Wu (1998) as it considers allocations for multiple uses which requires computation of probabilities of transition among different states in a spatially-dependent manner and addresses competition between different uses in the allocation process.

Spatial allocation of land-use is done by assigning the highest probability cells to each state. The number of cells assigned to each state is based on the demands for each use that are computed by the macro-scale module and are affected by the scenario-driving variables. In the case of conflicts, where a cell is assigned to more than one state, a decision heuristic procedure developed by Eastman et al. (1995) for multi-objective land allocation problems is used for resolving the conflicts. In this procedure, the competitive advantage of the cell for a use is decided on the basis of importance assigned to it by the user. At the end of the allocation process, the cell states are updated and the new land-use patterns generated are used as the initial state of the cells for the next iteration. In each step the constraints and the transition rules are updated to reflect the land dynamics in the previous step. The final land-use scenario is thus a result of temporal evolution, not only of the initial land-use but also of other local and regional factors that affect the land-use change process.

4.2.7 Advantages of the CA-MCDM-GIS Approach

The CA-MCDM-GIS approach exploits the advantages offered by all three techniques. GIS provides a platform for implementing the CA-MCDM model through its functionalities to store, manage and create spatial databases. MCDM techniques implemented within GIS provide a means for aggregating the geographical data and decision maker's preferences for evaluating the suitability of a cell for a particular use. They also provide a mechanism for spatial allocation based on competition between different uses, while CA acts as the spatial engine that drives the temporal evolution of land-uses.

This approach captures the trends and policies at the macro/regional level and translates these into effects at the grid level that represent the behaviour of individuals or decision makers (in this case, farmers) at specific situations. For example, an increased demand for fresh vegetables may translate into a cell becoming more suitable for greenhouse operations than for pasture. Certain other regional policy regulations, such as preservation of ALR, can be introduced as constraints for urban development in the suitability evaluation. Thus, it is able to
address human factors operating at the regional scale, while simultaneously taking into account local decision making factors.

4.3 Methods

In this section the methods for implementing the CA-MCDM-GIS procedure for the Lower Mainland are presented.

4.3.1 Model Parameters

Land-use categories

Eleven land-use/land-cover categories were considered in the model (Table 4.1). That is, a cell could be in any one of these 11 states in the CA model. Although urban use was taken as just one category, detailed agricultural land-use categories were considered in the model. Full dynamics were modeled only for six active uses – urban, food crops, hay/forage, pasture, natural pasture and greenhouses – for which the demands were computed by the macro-level module. The idle land and forest/natural categories were treated as passive, in the sense that their dynamics were not driven by demands, but represented residuals of the dynamics of the active uses. The remaining categories, such as water, built-up land and other, were assumed to be constant throughout the simulation period.

<table>
<thead>
<tr>
<th>Table 4.1 Land-use/Land-cover categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main category</td>
</tr>
<tr>
<td>Urban</td>
</tr>
<tr>
<td>Agriculture</td>
</tr>
<tr>
<td>- Food crops</td>
</tr>
<tr>
<td>- Hay/Forage</td>
</tr>
<tr>
<td>- Greenhouse</td>
</tr>
<tr>
<td>- Idle land</td>
</tr>
<tr>
<td>- Improved pasture</td>
</tr>
<tr>
<td>- Natural pasture</td>
</tr>
<tr>
<td>Forest/Natural (mature and young forest, and other natural vegetation)</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Built-up land (roads, barns, and other buildings)</td>
</tr>
<tr>
<td>Other</td>
</tr>
</tbody>
</table>
The food crop category is comprised of berries, vegetables, grains and other crops. Although the computation of demand for this category was based on the area requirements of all these crops, in the simulation module the food crops category was considered as only one state. This was done to reduce the complexity in the model arising from formulation of multiple transition rules for a large number of states. This was also necessitated by the lack of data for assessing the agronomic suitability of land for each of these individual uses.

CA model configuration

The CA model was defined on a grid of 1300 x 1900 cells of 1ha (100 x100 m) size. This cell size was chosen as it is small enough to capture heterogeneity in agricultural land-use in the Lower Mainland, but large enough to keep the data set down to a manageable size. In a CA-based land-use model it is desirable to consider neighbourhood effects over a large area as land-use decisions are affected by processes that operate not only in the immediate neighbourhood but also operate at a larger range. Parameterized range and decay functions are often used to capture these effects. However, in an effort to keep the model simple, it examined neighbourhood effects in an immediate neighbourhood (adjacent 8 cells). Since it is the immediate neighbourhood of the cell that most strongly influences its transition in this study (for example, to ensure compatibility between adjacent uses), not using extended neighbourhoods would not affect the results significantly. Five different transition rules were considered: 1) defining the probabilities of conversion for each use (value of $\alpha$); 2) rules related to constraints of development; 3) the attraction and repulsion effect of neighbouring uses of a cell; 4) rules regarding the importance of factors for determining weights, and 5) heuristics for conflict resolution in spatial allocation. The constraints in this model were introduced in two ways: 1) in the suitability evaluation that considers spatial constraints; and 2) in the allocation process where number of cells converting to a particular use is governed by the demand for that use. Simulation of land-use was done for a period of 40 years (2000 – 2040) at one-year time steps.

Factors and constraints affecting land-use conversions

A number of geographical factors are important for determining the conversion of land to a particular use. The model evaluates composite suitability of a cell on the basis of following factors: 1) land characteristics: land capability, slope, climate, land price; 2) infrastructure
considerations: accessibility to markets, proximity to core centers, proximity to towns, proximity to roads; 3) neighbourhood land-use; and 4) relative cost of conversions.

The factors in the first two categories are termed static factors, as their values do not change over the simulation period. The last two factors (neighbourhood land-use and relative cost of conversions) depend on the evolving land-use in the simulation and hence are referred to as dynamic factors. Not all factors were used in the evaluation of urban and agricultural use suitability (Table 4.2). In agricultural land-uses, the suitability of a cell is assumed to be affected by the inertia of existing land-use. For example, it is more likely that a food crop cell will continue to be used for food crops than for any other use. This implies that suitability of a cell should include consideration of the conversion costs associated with changes within agricultural uses. However, this factor was not considered for urban suitability, where it was assumed that all land-uses have an equal probability of conversion to urban use. It is important to note here that preferences regarding policy considerations in the model may preclude conversion of agricultural land to urban, which is treated differently as constraints.

Table 4.2 Factors affecting transition probabilities

<table>
<thead>
<tr>
<th>Urban use</th>
<th>Agricultural use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land price</td>
<td>Land capability</td>
</tr>
<tr>
<td>Proximity to core centre</td>
<td>Slope</td>
</tr>
<tr>
<td>Proximity to towns</td>
<td>Climate</td>
</tr>
<tr>
<td>Proximity to major roads</td>
<td>Land price</td>
</tr>
<tr>
<td>Slope</td>
<td>Proximity to markets</td>
</tr>
<tr>
<td>neighbouring land-use</td>
<td>Proximity to roads</td>
</tr>
<tr>
<td></td>
<td>Land-use conversion costs</td>
</tr>
<tr>
<td></td>
<td>Neighbouring land-use</td>
</tr>
</tbody>
</table>

Two types of spatial constraints were considered in the model: policy constraints and land-cover constraints. Policy constraints considered here were concerned with land-use, such as preservation of existing protected areas and preservation of ALR. Inclusion or exclusion of these constraints depended on the scenario definitions derived from user inputs. Land-cover constraints considered for development are water, snow, and other built-up areas such as roads. It was also assumed that agricultural development is restricted to the ALR and other current agricultural areas. That is, no additional areas from outside the ALR would convert to
agriculture use. This is a reasonable assumption, as all potential areas suited for agriculture have been included in the ALR. Information on static land-cover constraints (which do not change during the entire simulation period), such as water and rocky areas, was obtained from the classified land-use map, while the effects of dynamic constraints (e.g., urban areas for agricultural use) were embedded in the rules of transition.

### 4.3.2 Creation of the Spatial Data Base

#### 4.3.2.1 GIS Layers

GIS and remote sensing techniques were used for creating, storing and deriving various spatial layers required for the model. Spatial data were available in digital formats from the GBFP project and basic GIS operations were used to convert these primary data into the required formats for the model. All data layers were converted to grids of cell size 100x100 m and projected to a common projection system – UTM Zone 10 NAD83. Details of primary spatial layers and derived layers used in the model are given in Table 4.3. Continuous data were classified into fewer meaningful categories. A detailed description of the data sets is given in Appendix I. In the case of factors where the required data were not available or were insufficient, proxy variables were used. For example, distance to core urban centers was used as proxy for land prices, as land prices generally increase near the core urban centers such as Vancouver, in this case. Also, due to lack of data related to multiple climatic parameters (e.g., light levels, rainfall, and humidity), it was decided to use relative proportions of land-use categories in each census sub-division as the proxy variable for determining climatic suitability. Thus, each cell in a census sub-division was considered to be equally suitable for a use with respect to the climate factor.

#### 4.3.2.2 Generation of Land-use Map Using Satellite Data

#### 4.3.2.2.1 Procedures

The land-cover map available from Baseline Thematic Mapping by Natural Resources Canada was outdated and did not have the crop level information required for this study. Hence Landsat-7 TM data, acquired during July 2000, were analysed to generate a digital land-use map of the area for the base year (2000) using PCI Geomatica image processing software. Ground truth collection for the area was carried out during the same period in order to identify the types of land-use and their sites in the Lower Mainland. This was supplemented by additional information from the Ministry of Agriculture, Fisheries and Food, Abbotsford, BC.
regarding location of crops in order to perform a supervised classification of satellite data. Data from other GIS layers such as ALR, and Land-Cover were also used to aid in the classification process to improve the classification accuracy. This was achieved by binary masking of the area to reduce spectral confusion between different classes. Accuracy assessment was then carried out for the classified image. Post-classification generalization of the image was carried out before it was imported to the GIS database.

Table 4.3 Metadata of spatial layers used in the model

<table>
<thead>
<tr>
<th>Layer</th>
<th>Source</th>
<th>Attribute Description</th>
<th>Attribute type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land-cover</td>
<td>Baseline Thematic Maps (BTM)</td>
<td>Land-cover categories</td>
<td>Nominal</td>
</tr>
<tr>
<td>Land Capability</td>
<td>Canada Land Inventory</td>
<td>Land capability class</td>
<td>Nominal - 9 classes</td>
</tr>
<tr>
<td>Digital Elevation</td>
<td>TRIM*</td>
<td>Elevation</td>
<td>Interval - continuous</td>
</tr>
<tr>
<td>Models</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural Census</td>
<td>Statistics Canada</td>
<td>CSD code</td>
<td>Nominal</td>
</tr>
<tr>
<td>Subdivisions (CSD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural Land</td>
<td>Agricultural Land Commission, BC</td>
<td>ALR designation</td>
<td>Nominal - Boolean</td>
</tr>
<tr>
<td>Reserve (ALR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major Roads</td>
<td>NTDB</td>
<td>Road types</td>
<td>Nominal - Boolean</td>
</tr>
<tr>
<td>Cities/Towns</td>
<td>NTDB</td>
<td>Cities and towns</td>
<td>Nominal - Boolean</td>
</tr>
<tr>
<td>Derived Data layers</td>
<td>Source Data Layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>DEM</td>
<td>Slope in degrees</td>
<td>Continuous</td>
</tr>
<tr>
<td>Proximity to markets</td>
<td>Cities/towns</td>
<td>Distance from cities /</td>
<td>Continuous</td>
</tr>
<tr>
<td>Proximity to Roads</td>
<td>roads</td>
<td>towns</td>
<td></td>
</tr>
<tr>
<td>Land price</td>
<td>Core centres, land costs</td>
<td>Price zones</td>
<td>Ordinal</td>
</tr>
<tr>
<td>Land-use proportions</td>
<td>CSD layer and Census of Agriculture data</td>
<td>Percent of total area of areas in different CSDs (for each land-use)</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

* Terrain Resources Inventory Mapping, Ministry of Sustainable Resource Management, BC

Supervised Classification

The supervised classification procedure involved three steps: selection of training areas, generation of the spectral signatures for training areas, and classification of the spectral data.
based on these spectral signatures. Training areas were based on the following sources of information: ground visits in the area; field-level crop information from Ministry of Agriculture, Fisheries and Food, Abbotsford, BC; and the land-cover map from the Baseline Thematic Mapping project at a 1:50,000 scale. Information on old growth forest, young forest, urban areas and recreation areas was extracted from the land-cover map and was used in training site selection, as well as in the generation of binary masks.

Image classification was then carried out using a maximum likelihood method on six spectral bands of TM data. This used the information on the spectral signatures of different classes obtained by the spectral signature generation module of PCI software. Details on the supervised classification using maximum likelihood methods have been described in detail by Lillesand and Keiffer (1994). The training and classification were iterative processes based on comparison of classification results with known ground truth sites and subsequent modification (merging, deleting, adding) of training sites until reasonable matches were obtained. Besides using the maximum likelihood method, the classification was also based on binary masking of the image. Boolean (0/1) images were generated for forest, recreation and urban areas, and also for areas designated as ALR. By applying these masks over the image it was possible to identify subtle features in the image which were otherwise not discernible through supervised classification. For example, pasture and golf areas could not be discriminated through automated supervised classification, but with the help of visual analysis and binary masks these could be identified and classified as a different category.

**Accuracy Assessment**

Accuracy assessment was based on comparison of the classification map with the training sites. An error matrix was generated containing errors of commission, errors of omission and overall accuracy. Errors of commission occur when the classified image shows a class/category which does not exist in training site. This measure is also called user's accuracy and it is representative the probability that a pixel classified on the image actually represents that category on ground (Story and Congalton, 1986). Errors of omission occur when the classification algorithm fails to classify the category that actually exists on ground. This measure is called producer's accuracy because the producer is interested in how well a certain area can be classified. Overall map accuracy is obtained from the matrix by dividing the number of pixels that are correctly classified by the total number of pixels.
Post classification generalization

The maximum likelihood supervised classification method was used to classify Landsat data into 16 classes, which contained all crop categories. However, for use in the simulation model, the final land-use map was generated by aggregating all food crops into one category to produce the 11 categories described in an earlier section. Pixel-based supervised classification approaches usually result in a salt-and-pepper effect in the classified images. Map generalization techniques such as sieve operations available in the PCI software were therefore used to smooth the classified image. Landsat TM data are acquired at 30 meters resolution. To match the cell size of other grids, the final land-use map was resampled to 100 m cell size, before it was imported in GIS database. This land-use map served as the initial state of cells in the CA model.

4.3.2.2.2 Results

The classified land-use map for the base year (2000) is shown in Figure 4.3. Both types of accuracy measure were generated from the error matrix. Almost all classes were identified with both accuracies greater than 80%, except for the pasture and hay class. These classes had similar spectral characteristics which resulted in poorer discrimination between these two classes. The overall classification accuracy was 84 percent.

4.3.3 Assigning Scores of Suitability to Factors

All cells in a data layer corresponding to different factors were assigned scores representing the suitability of the location with respect to that factor. As discussed earlier, the transition rules for neighbourhood effects were also converted to scores. Each cell in the data layer was assigned a score between -10 to +10, depending on its suitability for that use. A score of -10 suggests a ‘repulsion’ (or push) for that use while a score of +10 suggests an ‘attraction’ (or pull) for that use. Expert knowledge and literature sources were extensively used for this purpose. For assigning scores, all land-use related to livestock (i.e. hay/forage, improved pasture and un-improved (natural) pasture) were grouped into one category (i.e. livestock use). Hence the scores were assigned to different factors for four categories of land-use (urban, food crops, greenhouse and livestock). As the factors considered for urban and agricultural uses were different, these scores are presented in two different sections in Appendix 2.
Figure 4.3 Land-use in the Lower Mainland in 2000

Source: Landsat-7 TM data
For static factors, the attributes of the factor were considered in assigning this score. For example, a cell having a slope of 10 degrees was assigned a score of -10 for Crops (indicating its non-suitability or repulsion), while it was assigned a score of +5 for livestock operations (indicating fair suitability or attractiveness). To consider neighbouring effects, the scores were based on the knowledge and information on the local processes. All cells within a Moore neighbourhood (3 * 3 window) were assigned a score based on their state (i.e., land-use). For urban suitability, the score was based on the number of developed urban cells in the neighbourhood, while in case of agricultural uses the score was based on the likelihood of adjacent uses avoiding urban-rural conflicts. For example, a cell in the neighbourhood of an urban cell is deemed to be more suitable for greenhouse operations than for livestock operations. An aggregate score for the cell was then computed as the mean of scores assigned to its neighbourhood. In case of the factor related to cost of conversions, the scores were based on the existing land-use of the cell. These scores represented the inertia effect in agricultural land-use discussed earlier.

4.3.4 AHP Procedure for Determining Weights

Multi-criteria problems typically involve criteria of varying importance to decision makers. Consequently, information about relative importance of the criteria is required. This is usually achieved by assigning a weight to each criterion. The Analytical Hierarchy Process (AHP) method developed by Saaty (1980) was used to compute the weights for different criteria (i.e., factors). AHP decomposes a decision problem into a hierarchy that consists of the most important elements of the decision problem and is based on pair-wise comparisons of alternatives or criteria to convert a preference into a numerical value. It involves three steps: development of a comparison or relative importance matrix at each step of the hierarchy; computation of the weights for each element of the hierarchy; and estimation of the consistency ratio (Malczewski, 1999).

The method employed an underlying scale (Table 4.4), suggested by Saaty (1980), with values from 1 to 9 to rate the relative preference or importance of two criteria to compute the weights. For example, if land price was considered to be more important than the slope of the land in determining land-use transition, then the comparison results in a value of 5 for land price. Consequently its reciprocal (1/5) is assigned to slope which indicates that it is strongly less important than the price. Likewise a comparison was made for all criteria and a relative
importance matrix of different factors was determined for all uses. Information from, and judgments of, experts in the field, and literature sources were used in deciding the relative importance of factors for different uses. These importance matrices were used to determine weights and consistency ratios by using standard methods. Details of these methods can be found in any text dealing with MCDM techniques and are not discussed here. The weights were accepted only if the consistency ratio was less than 0.1. The relative importance of different factors for the livestock-related land-uses (hay/forage, improved pasture and unimproved pasture) was considered to be the same, resulting in using the same weights for these uses.

<table>
<thead>
<tr>
<th>Importance of factor A relative to B</th>
<th>Value assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally important</td>
<td>1</td>
</tr>
<tr>
<td>Moderately more important</td>
<td>3</td>
</tr>
<tr>
<td>Strongly more important</td>
<td>5</td>
</tr>
<tr>
<td>Very strongly more important</td>
<td>7</td>
</tr>
<tr>
<td>Overwhelmingly more important</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4.5 shows weights obtained for different uses based on inputs, from planners and land-use specialists, on the importance of different factors for each of the uses. These values imply that foodcrop suitability is affected most by relative cost of conversions, while greenhouse suitability is affected most by climate. Land price seems to be the most important factor for livestock use. However, it should be noted here that the set of weights derived and used in the model represent just one view of the stakeholder preferences. In reality, different stakeholders may have different opinions regarding the importance of these factors in future land-use developments. As the model is AHP-capable, it is possible to recover these user preferences in the operational implementation of the model.

The advantage of using the AHP method is that it can be easily implemented in a decision support tool to recover preferences from decision makers. It can be used to examine effects of different development strategies based on user preferences. For example, higher weights could be assigned to the ‘distance from town centers’ factor, by increasing its level of importance in the comparison matrix, to emphasize a user’s preferences for nodal patterns of urban development.
Table 4.5 AHP-derived weights for factors affecting suitability of different uses

<table>
<thead>
<tr>
<th>Factors</th>
<th>Weights</th>
<th>Factors</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Food crops</td>
<td></td>
</tr>
<tr>
<td>Land price</td>
<td>0.173</td>
<td>GH</td>
<td>0.162</td>
</tr>
<tr>
<td>Proximity to core centre</td>
<td>0.234</td>
<td>Livestock</td>
<td>0.145</td>
</tr>
<tr>
<td>Proximity to towns</td>
<td>0.187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.087</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.147</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neighbouring land-use</td>
<td>0.173</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consistency Ratio</td>
<td>0.049</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.5 Spatial Allocation

Spatial allocation was based on competition between different uses and used a multi-objective allocation process. In multi-objective problems one of the methods used for land allocation is the priority-ranking method. In this method, objectives are prioritized and allocation starts with the highest suitability cells and proceeds until the demand for the first use is satisfied, after which allocation starts for the next use. This approach assumes that one use is more important than the other. Another approach is based on a decision heuristic procedure developed by Eastman et al. (1995) for solving multi-objective, conflicting allocations. This method provides a solution through iterative reclassification of suitability values, checking for conflicts and allocating the cells according to a relative weight given to each objective. In practical terms, the suitability values are first ranked for each objective (use). Then, the cells having highest scores for each use are allocated to that use temporarily. In the case of a cell being assigned to two or more uses, the conflict is resolved by assigning the cell to the use for which its suitability value is closer to its ideal point. The ideal point is the highest suitability score for that use. This is an iterative process, which continues until all of the demands for the different uses are met. This way the procedure attempts to allocate in a manner that maximizes overall suitability in the land-use allocation process. This decision heuristic is available in the multi-objective land allocation module of IDRISI, but is not available through...
ArcInfo GRID commands. Implementing it with ArcInfo (AML) proved to be a challenging task, but it was achieved through a close approximation of the method as explained below.

A nested allocation approach was adopted that used both of the methods described above. In the first step, allocations were done for urban use, which determined the available land base for agricultural use. Allocation at this level depended on the policy choices regarding preservation of ALR, which determined whether ALR areas could be used for urban development. The second step allocated specific uses within the agriculture category such as food crops, hay/fodder, pasture, natural pasture and greenhouse uses. Allocations in this step were based on competition between different uses, and used the decision heuristic procedure for multi-objective land allocation. The weights in the multi-objective allocation process were defined on the basis of demands for a use. A cell having high suitability for conversion to a food crop, for instance, may have competitive disadvantage over other uses due to its low demand, which would result in its allocation to a use other than that for which it is most suited. In other words, a cell does not get converted to a use based on the rules related to its probability of conversion alone; cell conversions also are affected by changes in demands.

All cells were ranked first according to their probability values. Allocation then proceeded by assigning the highest probability cells to each of the active uses. Different layers were generated for each use. A comparison was then done to determine cells that were allocated to more than one use. To facilitate the decision heuristic for conflict resolution through AML, the remaining cells were first put in different bins of probabilities for each use. In each iteration the algorithm first allocated a cell from the highest probability bin until it was exhausted or until the demands were met. At the end of each iteration a check was again made for conflicting cells and the process continued until the demands were met or until there were no more suitable cells to be allocated to a use. The number of cells assigned to each state was based on the demands for each use that were computed by the macro-level demand module. Also, in the allocation process, a stochastic disturbance was applied to the probability values so that even cells with low probability had some chance of being allocated to a use. The probability of conversion to a use was compared to a random number between 0 and 1, and the cell was assigned a state from the active uses only if its value was greater than the random number. In the case of agricultural uses, all cells that were no longer found to be suitable for any of the agricultural uses were allocated to 'idle' category.
Although this did not always result in optimal solution, the heuristic procedure, in combination with the CA-based allocation procedure assured some degree of near-optimality, contiguity and compactness in land-use allocations. The CA-MCDM based simulation procedure was coded in AML (given in appendix 3) and implemented in the ArcInfo GRID environment.

4.4 Calibration of the Model

This CA-based simulation model determines the land-use of the cell on the basis of probabilities of conversion to that use, which in turn are based on suitability factors and weights considered in the model. Calibration of this model requires finding the appropriate weights and finding the value of parameter \( \alpha \). In order to do this, it is necessary to compare the simulation results with actual data. The model can be applied to a database of an earlier year to make predictions of a later year. In an iterative process, the weights and parameter values can be modified in order to find the combination of values that result in the best possible fit between the predictions and the actual observed land-use. However, this method will require a detailed land-use map for an earlier base year, as well as the year for which the predictions are made. These were unfortunately not available. Therefore, the model’s ability to simulate reality was checked only for the initial simulation period. Furthermore, calibration was done only for \( \alpha \). As explained in an earlier section, it is the transition rules which determine the weights in this model. These rules were based on judgments of experts in this field and/or literature sources. The rules were assumed to be valid for the purpose of determining the \( \alpha \) parameter.

The model was applied to the initial land-use in 2000 and the results of the simulation obtained with four different values of \( \alpha \) (= 1,3,5,10), for different uses, were compared with their observed values in 2000 itself. Simulations were carried out for just one time step representing one year span. It was assumed that the land-use would not have changed in 2001 and comparisons were therefore made with the land-use of 2000. The model simulations for urban conversions in 2000 merely represent the effect of stochasticity in the model, as it does not allow for redevelopment of existing urban areas which are excluded from future conversions. However, this is not the case for agricultural uses, where inter-use conversions are allowed and hence these provide the basis for model calibration.
A goodness-of-fit between the predicted and observed land-use was used to select the appropriate value of $\alpha$. Ideally, the slope in the regression equation should be equal to 1 and the intercept should be equal to 0. On the basis of regression results, the value of $\alpha$ was chosen as 3 for food crops and 1 for all other uses (slope = 0.97; intercept = .11; $R^2 = .99$; Std. err = .05).

It is obvious that this method of calibration does not test the ability of the model to predict changes, but serves to identify the values of $\alpha$ that represent the most expressive allocation for the starting year. Such estimation may not be applicable in a dynamic context, but can be improved if detailed data from different years become available. It is also worth noting that calibration and testing of CA models is a challenging task. Most CA models include stochasticity, which makes it difficult to compare the observed and predicted maps because the predicted map is just one of the many possible outcomes of the stochastic process. Pixel-by-pixel techniques are not appropriate for assessing predictability of these models, as these are unable to capture patterns and often misrepresent the degree of similarity, while other measures, such as fractal dimensions, are too general (White and Engelen, 2000). There is, in general, a lack of methodologies that address testing the robustness of CA-based models.

### 4.5 Summary

An overview of the AgFutures model was presented in this chapter. Two main components of the model were identified: land-use evolution and assessment. To simulate the evolution of land-use changes, a land-use simulation module was developed that integrated CA and MCDM techniques in a GIS environment. The approach for simulation was based on: multi-scale dynamic simulation of land-use changes; integration of physical factors and human factors affecting land-use change; consideration of spatial interactions and neighbourhood effects; and explicit linkages with the decision-making process. Various spatial inputs required for its use were generated through the use of GIS techniques and a maximum likelihood supervised classification method was performed to generate the land-use map to be used as initial state in the CA model. A tight coupling between the CA and MCDM was achieved by implementing the process through an AML in ArcInfo GRID. The results of the application of this module for generating patterns of land-use under alternative scenarios of agricultural development for the Lower Mainland are described in next chapter.
5 Simulation of Land-use Changes Under Different Scenarios

In this chapter, I describe the application of AgFutures to simulate future land-use changes under different scenarios. I first describe the scenario-building process and the various scenarios formulated and examined in this research. I then describe the methods used for projection of livestock numbers and areas of different land-use types, followed by the results of projections under different scenarios. Finally, I present the results of the simulation model showing land-use changes under these scenarios.

5.1 Scenario-Building

Scenarios are alternative plausible futures. UNEP (2002, p.320) defined scenarios as "descriptions of journeys to possible futures. They reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play." It is important to note that they do not predict the future. However, they do provide a way to address uncertainties related with the future and also serve to guide policy makers in evaluating and modifying policies.

The formulation of useful scenarios is dependent upon identifying concerns and the related driving variables that will affect outcomes significantly, as well as being important to policy makers. Changing the values of selected driving variables in a model allows for the formulation of different scenarios. These variables are of two types: 1) those that affect spatial patterns of land-use change (for example, policies related to protected areas) and 2) those that affect rates or extent of land-use change (for example prices of commodities). In the present study both types of variables were considered for formulating scenarios.

5.1.1 Scenario-Driving Variables

In this land-use model it is possible to change the values of any spatial or non-spatial variable in order to examine the effects related to uncertainty of that factor. The model in its present state provides choices with respect to four policy options, described below, for the creation of scenarios. These options were chosen to represent the chief regional concerns regarding agricultural development and intensification that are affecting agricultural sustainability in the Fraser Valley.
i) Preservation of Agricultural Land: The ALR preservation option implies that the ALR land is exclusively set aside for agricultural purposes and cannot be used for urban development. This variable affects the scenarios spatially.

ii) Scale of Agricultural Economy: This variable affects the cropping intensity, yield, and livestock density parameters in the model.

iii) Diet: This is a non-spatial variable reflecting preferences for meat and non-meat diets. It affects the number of livestock and area requirements for food crops. Change in diet patterns (meat or vegetarian diets) affects production systems that drive land-use changes. For example, increased meat diets would affect livestock number and subsequent feed requirements that result in land-use shifts.

iv) Management practices: This variable affects fertilizer use in the model.

Combination of these choices can be used to build different agricultural scenarios in the model.

5.1.2 Scenario Definitions

Four different scenarios have been developed for this study:

i) Baseline or continuing trends scenario – This scenario is constructed to provide a picture of the future in the absence of any policy intervention. This scenario assumes that agricultural development will largely follow trends of past 20 years. Current policy regarding preservation of ALR, current diet preferences and management practices are expected to continue. Yields are expected to follow current trends. In this scenario demands for different land-use types are based on extrapolation of current trends and projections of diet at the national level.

ii) Agribusiness scenario – This scenario is considered in order to examine the effects of agricultural intensification practices, specifically those related to livestock production and greenhouse production. In this scenario it is assumed that agricultural development is driven by large farms and an increased demand for animal products such as milk and meat. Greenhouse production continues at an accelerated pace. There is less focus on the development of food crops. Yields are expected to reach the potential levels determined by current technology.
iii) Protectionist scenario – This scenario assumes low intensity agricultural development oriented towards protecting the environment. It assumes that the ill-effects of current intensification on the environment will be recognized and there would be a move to maintain current livestock densities.

iv) Vege-business scenario – This scenario assumes a major shift towards vegetarian diets and emphasis on greenhouse vegetable production.

Livestock numbers and land-use demands were computed for each of these scenarios. Spatial allocation of the land-use areas was done under two policy options concerning urban growth for each scenario: one considered preservation of the ALR so that no urban development takes place in the ALR (these are labeled as ‘a’ type of scenarios); the other considered effects of not preserving the ALR and allowing urban development to take place within it (these are labeled as ‘b’ type of scenarios). Thus, eight scenarios (Table 5.1) in all were examined for their effects on environmental and economic systems.

**Table 5.1 Scenario assumptions**

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong> (BL)</td>
<td>Continuing trends of diet patterns, land-use intensification (farm size, livestock density) and management practices (fertilizer inputs); current levels of yield</td>
</tr>
<tr>
<td></td>
<td>a) Preserve ALR</td>
</tr>
<tr>
<td></td>
<td>b) Do not preserve ALR</td>
</tr>
<tr>
<td><strong>Agribusiness</strong> (AgBus)</td>
<td>Agricultural intensification - higher growth in greenhouse and livestock production; 20% increase in farm size and current livestock density; current management practices; Average yields reach potential levels</td>
</tr>
<tr>
<td></td>
<td>a) Preserve ALR</td>
</tr>
<tr>
<td></td>
<td>b) Do not preserve ALR</td>
</tr>
<tr>
<td><strong>Protectionist</strong> (Prot)</td>
<td>Improved management practices – 25% reduction in fertilizer application; 20% decrease in farm size; animal unit density maintained at 2000 level</td>
</tr>
<tr>
<td></td>
<td>a) Preserve ALR</td>
</tr>
<tr>
<td></td>
<td>b) Do not preserve ALR</td>
</tr>
<tr>
<td><strong>Vegebusiness</strong> (Vege)</td>
<td>Shift to vegetarian diets – 20% increase in vegetables consumption; 20% decrease in meat diet; 20% increase in vegetable and greenhouse farm sizes</td>
</tr>
<tr>
<td></td>
<td>a) Preserve ALR</td>
</tr>
<tr>
<td></td>
<td>b) Do not preserve ALR</td>
</tr>
</tbody>
</table>
5.2 Projection of Livestock Numbers and Areas of Different Land-use Types

Demands or area requirements for different land-use types are required as input for the CA-MCDM allocation module that allocates cells to a particular use based on its regional demand. These demands were determined for six active uses: urban, food crops, hay/forage, pasture, natural pasture and greenhouse. Demands for food crops area were computed on the basis of projections made for different crops that comprised this category (i.e., berries, vegetables, grains and other crops). Demands for livestock crops were based on projections of livestock numbers of different types. No demands were computed for the forest/natural and idle land categories as any increases in urban and agricultural areas would come from those two categories. They are thus treated as passive or residual categories in the model. The remaining categories, such as water, built-up land and other, were assumed to be constant throughout the simulation period (i.e., their areas do not change over this period).

5.2.1 Methods for Projections

Using temporal trends to predict future changes is the most common method of generating projections. Trend-based estimates have two advantages. Firstly, they include the effect of multiple driving forces, such as population growth, technological developments, societal preferences and policies. Secondly, they are easily implemented in situations where availability of data related to different factors is a concern. However, trend-based projections are not always an appropriate way for making projections, as they may result in unrealistic values. For example, there has been an exponential growth in greenhouse area in the last 20 years, and it is obvious that any estimates for the not-so-near future (more than 8-10 years) based on these exponential trends would be highly exaggerated. Supporting information from other sources needs to be used for making realistic estimations based on temporal trends. One way to achieve this is through regression analysis, which is a useful tool for making predictions in situations where causal factors can be identified. Using historical data, quantitative relations between predictor variables and land-use changes can be established and future trends of predictor variables can be used for making regional projections. Both these methods have been used to make projections for numbers of different livestock types and areas of different land-use types. All projections were made for four decades from 2010 to 2040.
Livestock numbers

Livestock number and type have a great impact on environmental consequences related to nutrient management issues. These are important inputs for the impact assessment model discussed in a later section. Livestock numbers are projected for three livestock types: cattle and calves, pigs, and chickens. Information on population, meat consumption patterns and projections of per capita meat consumption were used to project the livestock numbers. Regression relations between meat consumption per capita and number of livestock in the region were developed. Linear or logarithmic trends of livestock were also estimated and used in the projections. It was assumed that total meat consumption per capita would stabilize after 2010 as meat consumption in developed countries is reaching a plateau (FAO, 2002). However, preferences for different kinds of meat result in demand for different types of livestock. Agriculture and Agri-Food Canada’s projections for per capita consumption of different types of meat up to 2007 were used (AAFC, 1998), and it was assumed that meat consumption rates would follow the same trends until 2040. Population estimates for 2010-2030 were based on projections made by the Government of British Columbia (BCStats, 2002), while those for 2040 were obtained by extrapolating those trends.

Areas of different land-use types

Urban area requirements were based on an exogenous urban growth model for the Georgia Basin. Details of this urban model are described in a report by Tamsin (2000). The model develops different scenarios of urban development based on population growth and density choices. A high-density scenario was assumed and projected urban area needs were used for this study.

Projections of berry area, field vegetables area and other crop area were based on extrapolation of observed area trends and their relation with population. Most of the grains grown in Lower Mainland are used as feed for livestock. Hence, grain area was determined as a function of total livestock numbers which were converted to animal units.

Total livestock crops area (including hay/fodder, pasture and natural pasture) was determined as a function of predicted cattle number. This is because cattle operations are land based, unlike poultry and hog operations that do not have much impact on land-use areas. The total
livestock area was then used to determine pasture and hay areas based on their current proportions as well as the intensification level in the scenario.

Projection of greenhouse area was based on the temporal trend and its dependence on vegetable consumption.

5.2.2 Historical Land-use Trends and Regression

In order to make projections under different scenario assumptions, I examined the growth in livestock numbers and areas of different land-use types over the past 20 years and also examined how the land-use changes have been affected by population growth, diet patterns and agricultural intensification (farm sizes). In particular, regression relations were developed that were used in the model to compute livestock numbers and target areas for different land-use types as described above. Agricultural Census data, from Statistics Canada, for 1981 to 2001 (covering 5 census periods) were used in this analysis. Population data were obtained from BCStats, while meat consumption statistics were based on those provided by Statistics Canada through the CANSIM data base.

Meat consumption patterns, livestock numbers, and land-use

Population growth in BC during this period is shown in Figure 5.1, while trends in meat consumption are shown in Figure 5.2. According to the available statistics on meat consumption per capita, while there has been little change in total meat consumption per capita, there have been significant changes in the consumption of different types of meat over past two decades. Beef consumption is on the decline, reduced by almost 25 percent in 2001 from a value of 40 kg/year in 1981; pork consumption has declined by about 10 percent, while chicken consumption increased by nearly 90 percent to 30 kg/year. These changes in meat consumption pattern and population growth in BC were examined for their correlations with the livestock numbers in the Lower Mainland.

Cattle and calves

The dynamics of total number of cattle and calves are different for the provincial level and Lower Mainland. While a cyclical pattern is evident at the provincial level, the number has decreased slightly in the Lower Mainland since 1981 (Figure 5.3a). During this period, many cattle farms consolidated, resulting in fewer farms. However, there has been a trend towards
intensification, reflected by the increasing number of animals per farm (Figure 5.4). Cattle operations are land-based operations and the price of land in the Lower Mainland has been one of the primary constraints of growth in cattle operations. In addition, an increase in milk productivity per cow and a decrease in red meat consumption have also played a role in the decrease. Results of regression analysis showed that the number of cattle had a moderate correlation with per capita beef consumption (Figure 5.5). This is probably due to the fact that 70 percent of the total cows in the region are dairy cows.

Pigs

Eighty percent of the total provincial production of pigs is in the Lower Mainland. Pigs are produced mainly for the local market and only 10 percent of pigs produced are exported from British Columbia. The number of pigs has decreased in the province but remained almost constant in the Lower Mainland (Figure 5.3b). Pig production is an intensive farming operation and there are concerns related to waste management and conflicts with urban neighbours due to odour; producers have to follow strict environmental guidelines that are in use. The reduction in the number may reflect the pressure of this conflict on the producers. As in the case of cattle, the number of pig farms decreased while the number of pigs per farm increased during the same period, reflecting the intensification trends in the area. It was observed that consumption of pork per capita or by the population had no significant correlation with the number of pigs (Figure 5.6), suggesting that it is affected by other market forces.

Chickens

Over 80 percent of the provincial production of chickens is located in the Fraser Valley. There has been an exponential increase in the number of chickens during the past 20 years (Figure 5.3c). This is mainly due to the fact that consumer preference has shifted away from beef to poultry. The number of chickens was found to be highly correlated to per capita chicken meat consumption (Figure 5.7) as well as to total chicken meat consumption (Figure 5.8) in British Columbia. This suggests that it has responded to not only increased preference for chicken meat, but also to the population increase in the province. The number of chicken farms has decreased over time, but the number of chickens per farm has increased three-fold during the same period.
Figure 5.1 Population growth in BC

Source: Statistics Canada

Figure 5.2 Apparent per capita meat consumption in Canada

Source: CANSIM, Statistics Canada
Figure 5.3 Historical trends of livestock numbers

Source: Statistics Canada - Census of Agriculture, 2001

Chickens

Pigs

Cattle
Figure 5.4 Size of farms (Number of animals per farm)

Figure 5.5 Relation between cattle number and beef consumption

Figure 5.6 Relation between pigs number and pork consumption
Number of chickens and poultry consumption

<table>
<thead>
<tr>
<th>Per capita poultry consumption (kg/yr)</th>
<th>Number of chickens ('000')</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2000</td>
</tr>
<tr>
<td>15</td>
<td>4000</td>
</tr>
<tr>
<td>20</td>
<td>6000</td>
</tr>
<tr>
<td>25</td>
<td>8000</td>
</tr>
<tr>
<td>30</td>
<td>10000</td>
</tr>
<tr>
<td>35</td>
<td>12000</td>
</tr>
</tbody>
</table>

\[ y = 630790.34 x - 431071.99 \]
\[ R^2 = 0.86 \]

Source: Statistics Canada - Census of Agriculture 2001, and CANSIM
Figure 5.7 Relation between hens and chicken numbers and per capita chicken meat consumption

Total chicken meat consumption

<table>
<thead>
<tr>
<th>Total chicken meat consumption (tonnes)</th>
<th>Number of chickens ('000')</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20000</td>
<td>2000</td>
</tr>
<tr>
<td>40000</td>
<td>4000</td>
</tr>
<tr>
<td>60000</td>
<td>6000</td>
</tr>
<tr>
<td>80000</td>
<td>8000</td>
</tr>
<tr>
<td>100000</td>
<td>10000</td>
</tr>
<tr>
<td>120000</td>
<td>12000</td>
</tr>
<tr>
<td>140000</td>
<td>14000</td>
</tr>
</tbody>
</table>

\[ y = 109.53 x + 1349632.66 \]
\[ R^2 = 0.88 \]

Source: Statistics Canada - Census of Agriculture 2001, and CANSIM
Figure 5.8 Relation between chicken numbers and total chicken meat consumption
Growing forage, as feed for livestock, is the main use of agricultural land in the area. About 60 percent of the total farmland was used for forage in 2001. Forage is available as pasture, hay, silage or green-feed. Figure 5.9 shows the changes in agricultural land-use from 1981 to 2001. While the amount of farmland has decreased by 10 percent, the cropped area has remained constant indicating intensive use of land. This is also evident in the reduction of summer fallow area and the decrease in managed pasture.

Among crops (Figure 5.10), there has been an increase in berry area and the proportion of hay and forage crops has increased steadily in the total cropped area. However, the total forage area, including improved pasture, natural pasture, hay and other forage crops, showed a decline over the years. Grain area decreased from 1981 to 1986, but thereafter increased and has remained almost constant between 1996 and 2001. It showed a moderate correlation with total animal units (Figure 5.11). Vegetable area has remained almost constant from 1981 to 2001, even though vegetable consumption has increased from 96 kg to 111 kg per capita (StatsCan, 2002) between 1981 and 2001. It evidently has a large inertia and does not respond to changes in population and scale of economy. A similar trend was obtained for whole province from 1971 to 2001. Berry area has increased linearly (Figure 5.12) over the period and showed a very high correlation with population growth (Figure 5.13).

The decrease in livestock crop area (hay/forage crops + pasture) was found to be highly correlated to the number of cattle and calves in the region (Figure 5.14). This was expected as cattle operations are land-based, and forage, which is grown as feed for cattle, is usually grown on the same farms on which it is fed to livestock. Hence, a decrease in cattle number would be associated with a decrease in total forage area. Hog and poultry operations are neither land-based nor use forage as feed, and hence do not show any correlation with forage crop area.

**Greenhouse area**

The greenhouse industry comprises two sectors: vegetables and floriculture. Greenhouse vegetables are mainly tomatoes, cucumbers and peppers. Most greenhouse operations (representing 80 percent of the provincial area) are located in the Lower Mainland. The greenhouse vegetable industry has increased almost six-fold in the last ten years, from 35 million dollars in 1992 to 204 million dollars in 2001. Total greenhouse area has shown
Figure 5.9 Agricultural land-use in the Lower Mainland

Figure 5.10 Historical changes in crop areas

Figure 5.11 Relation between grain area and livestock numbers
(in terms of animal units)
(Note: Source for Figures 5.9 to 5.16: Statistics Canada - Census of Agriculture 2001)
Figure 5.12 Growth in area under berries

Figure 5.13 Relation between area under berries and population

Figure 5.14 Relation between total area for livestock use (hay/fodder crops+pasture) and number of cattle and cows
Figure 5.15 Historical growth in greenhouse area

Figure 5.16 Relation between greenhouse area and vegetable consumption
exponential growth from 1981 to 2001 (Figure 5.15). Discussions with the people involved in agriculture sector revealed that this has been due to the preferences for fresh flowers and shifts from meat to vegetarian diets. It is highly correlated to vegetable consumption (Figure 5.16). Part of this increase has also been due to increasing greenhouse sizes that are aimed at benefiting from economies of scale. The average size of a vegetable greenhouse has grown to about 2 ha and is expected to increase in the future (BCMAF, 1999).

These observations and regression relations that were statistically significant with \( R^2 \) value greater than 0.5, were used for making future projections under the Baseline (BL) scenario. Projections for other scenarios were based on their respective assumptions. For example, in the agri-business scenario, size of farms (livestock and greenhouse) was assumed to increase by 20 percent, which translates to a corresponding linear increase in the numbers of livestock and greenhouse area respectively. In the protectionist scenario, total animal units were assumed to be constant (with respect to the base year), while individual livestock types vary as per trends. In the vege-business scenario, all types of meat consumption were assumed to decrease by 20 percent.

5.2.3 Projections Under Different Scenarios

The decadal regional projections of livestock numbers and areas for urban and agricultural uses under the four scenarios are discussed in this section.

Livestock numbers projected under different scenarios are shown in Figure 5.17. In the BL scenario, due to the projected decrease in beef consumption, a decrease in cattle number is projected. However, the decrease is small due to the small proportion of beef cows as compared to dairy cows. The effect of land prices has not been considered in these projections. The number of pigs shows a marginal increase of 5 percent while the number of chickens increases more than two times due to a projected increase in chicken meat consumption.

Projected urban and crop areas under the different scenarios are shown in Figure 5.18. The urban area requirement is not affected by the scenario definitions and is taken as invariant for all scenarios. Projections of urban areas, as obtained from the GB-QUEST urban model and used for all scenarios, show that there is an expected increase of about 40 percent in urban area.
Figure 5.17 Projected livestock numbers under different scenarios
Figure 5.18 Projected areas under different scenarios
Figure 5.19 Projected agricultural area under different scenarios

Figure 5.20 Projected foodcrop area under different scenarios

Figure 5.21 Projected area for livestock crops (hay/fodder+pasture) under different scenarios
While the berry area follows the current intensification trend and increases by more than 80 percent under the BL scenario, the area under grains increases three times that of the base year due to the projected increase in total animal units. Vegetable area remains almost constant. The overall proportion of grains in the total crops is still quite low in all scenarios. The 'other' crops area was taken as constant for all scenarios. The area under hay/forage crops is predicted to increase, while pasture area decreases considerably under the BL scenario as a result of the continuing trends of intensification. The area of greenhouses increases to more than two times that of the base year. Sixty-five percent of this area is projected to be under vegetables due to the rapidly increasing size of vegetable greenhouses.

Changes in total agricultural area resulting from the different scenarios are shown in Figure 5.19. The total food crops area increases by more than 50 percent in the BL scenario due to the increase in berry and grain areas, and is maximum under the Agribusiness scenario (Figure 5.20). The total livestock crop area decreases in all scenarios (Figure 5.21) as a result of the decrease in cattle and calves from the 2001 numbers.

5.3 Simulation Results and Discussions

As urban and agricultural land-uses are mainly situated in the Fraser Valley, the simulations results are shown here only for this area, omitting the upper portions of Lower Mainland. To facilitate comparison of land-use changes from 2000 to 2040, first the spatial distribution of different land-use types in 2000, as derived from remote sensing data, is shown in Figure 5.22. Urban areas are mainly located in the Fraser Valley around Vancouver, with the GVRD having a larger proportion of urban use than FVRD. Most of the food crop areas are located in Abbotsford, Richmond, Delta and Surrey, while hay/forage and pasture areas are mainly located in the Langley, Abbotsford and Chilliwack regions. Langley has a higher concentration of natural areas including forests. Greenhouses were located throughout the study area, with major concentrations in Delta, Langley and Chilliwack. Greenhouse areas are not very apparent on the map at this scale. This is because the average greenhouse size in the Lower Mainland is only 1-2 ha, which is represented by only 1-2 pixels at this resolution (100 x 100 m).
Figure 5.22 Land-use in the Fraser Valley in 2000 – derived from remote sensing data
The simulation results for all scenarios are presented in Figures 5.23 to 5.26. The changes in land-use patterns under the different scenarios depended on the scenario policies, amount of changes projected for the scenario and the competition between land-use classes. Urban growth patterns are affected by the policies related to preservation of ALR, and these affect the land base available for agriculture. In the ‘a’ type of scenarios, which preserve ALR, urban expansion takes place in a manner that does not affect ALR (Figure 5.27a). Higher concentrated growth is observed nearer to metropolitan Vancouver where most of the existing natural areas are converted for development, whereas scattered urban expansion takes place in northern parts of the valley. Growth in this area is largely restricted due to topographic constraints. Most of the Burns Bog area in Delta, which currently is home to unique plants and animal species, is at high risk from urban growth if not protected. In this scenario, however, some agricultural lands in the South Delta that are not protected under ALR at present are also lost to urban growth. Under scenario b, that does not preserve ALR, hot spots of land-use change are found around Richmond, Surrey, Delta and Pitt Meadows (Figure 5.27 b). Most of the urban growth takes place as a result of conversion of existing agricultural lands. Figure 5.28 shows the sources of urban growth under both scenarios. Close to 24000 ha or 18 % of ALR is lost to urban growth in scenario ‘b’. Of this, over 19000 ha are areas that are currently under agricultural use. Figure 5.29 shows the ALR lost by land-use classes. It indicates that areas currently under food crops, mainly vegetables and berries are under highest competition from urban use and most prone to conversions. This is probably due to the fact that these are grown in flat areas which are also highly suitable for urban settlements. Furthermore, there is high concentration of food crops areas in Surrey, Richmond and Delta and their proximity to Vancouver makes these areas ideal candidates for urban conversions. Out of the total area lost to urban growth from the ALR, 43% land belongs to high capability classes 1-3 (Figure 5.30) that are considered as prime agricultural lands.

Agricultural land-use changes are mainly a result of the competition between different agricultural uses and their demands. In scenario 1a, high demands for food crops result in conversion of existing pasture lands to this. Food crops mainly expand in the Pitt Meadows and Abbotsford areas where soils are most suitable for growing berries, while increase in hay/fodder crops is met mostly by conversion of idle lands in Langley and some pasture in Chilliwack. In general, it was observed that remaining pasture areas are pushed further to the eastern side of the Valley. This is particularly true for the b type of scenarios, where
Figure 5.23 Simulated land-use for 2040 in the Baseline scenario: a) Preserve ALR, b) Do not preserve ALR
Figure 5.24 Simulated land-use for 2040 in the Agribusiness scenario: a) Preserve ALR, b) Do not preserve ALR
Figure 5.25 Simulated land-use for 2040 in the Protectionist scenario: a) Preserve ALR, b) Do not preserve ALR
Figure 5.26 Simulated land-use for 2040 in the Vegebusiness scenario: a) Preserve ALR, b) Do not preserve ALR
Figure 5.27 Urban growth in 2040 in the context of ALR: a) 'Preserve ALR' scenario, b) 'Do not preserve ALR' scenario
Figure 5.28 Sources of urban growth in 2040 under scenario a (preservation of ALR) and scenario b (No preservation of ALR)

Figure 5.29 ALR area lost by land use classes

Figure 5.30 ALR area lost by land capability classes
encroaching urban use within the ALR reduces the suitability of surrounding areas for livestock use. These changes help to identify areas where there might be concerns regarding nutrient pollution. Cattle farms mostly grow their own forage and feed, and are self-sustaining units in terms of nutrient management. In the maps, these are assumed to be distributed over the region that represents hay/forage and pasture areas indicating that these areas (e.g. Chilliwack) are at less risk of nutrient excess in the future than Abbotsford which is expected to see a significant decrease in pasture areas. It was not possible to identify the locations of pig and chicken farms in this study as these are not associated with a particular land-use. Hence, the spatial implications can only be based on deductive reasoning.

In the scenarios that do not preserve the ALR (i.e., scenarios 1b, 2b, 3b, and 4b), the loss of agricultural land means that the demands for different crop areas are not fully met (Table 5.2). Figure 5.31 shows target areas and allocated areas for food crops and livestock uses under these scenarios. Food crops allocations are most affected, due to two reasons: 1) current prime areas suitable for vegetables and berries are lost, as discussed in the preceding paragraphs; and 2) these are disadvantaged in the competition for allocation against hay/fodder crops which have a higher demand.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Target area (ha)</th>
<th>Allocated area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario a</td>
<td>Scenario b</td>
</tr>
<tr>
<td>Baseline</td>
<td>79000</td>
<td>78997</td>
</tr>
<tr>
<td>Agribusiness</td>
<td>86654</td>
<td>86657</td>
</tr>
<tr>
<td>Protectionist</td>
<td>69591</td>
<td>69591</td>
</tr>
<tr>
<td>Vegebusiness</td>
<td>79047</td>
<td>79047</td>
</tr>
</tbody>
</table>

Most of the greenhouse growth occurs in Delta, which has nearly 60% of the total greenhouse area in the BL scenario. In 2001, approximately one-third (117 ha) of the total greenhouse area (368 ha) was in Delta. Due to its mild climate and high light levels, it is the best place for the location of greenhouses. However, there is a possibility that the growth in greenhouse industry will be a setback for the soil-based agriculture here. Greenhouses cause an increase in land price, forcing some soil-based farmers to sell their land. Analysis showed that the total area of
Figure 5.31 Crop area allocations under different scenarios- a) foodcrops; b) livestock crops; c) Total agricultural area
soil-based agriculture (including food crops, hay/forage, and pasture) in Delta decreases by 15% in the BL scenario. To protect the soil-based agriculture in the valley it will be necessary to formulate laws that control the amount of land that can be used for greenhouses, as well as direct the growth of greenhouses on low capability soils. There also have been concerns about the adverse effects of greenhouses on migratory birds in Delta (EC, 2002).

5.4 Summary

Land-use changes were projected quantitatively and spatial patterns of land-use change were obtained using the AgFutures model. Results showed that the total food crops area is expected to increase by nearly 50 percent under the Baseline scenario, largely due to an increase in area under berries. The area under hay/fodder crops increases and that under pasture decreases as a result of intensification in this scenario. Greenhouse area increases more than two-fold, with a larger proportion of it dedicated to growing vegetables. While around 3600 ha of agricultural land are lost under the preservation of the ALR scenario, more than 25000 ha are lost in the scenario that does not preserve the ALR. Simulation results showed hot spots of land-use changes under the different scenarios. Areas around Richmond, Surrey and Delta are expected to experience large decreases in agricultural land if the ALR is not preserved. Furthermore, prime areas growing berries and vegetables in these regions are affected by urban growth resulting in insufficient land for allocation to these crops. Results from the AgFutures were also used for the generation of land-use change indicators to assess sustainability, as explained in the next chapter.
6 Evaluation of Scenarios Using Sustainability Indicators

"In nature there are neither rewards nor punishment—there are consequences."
Robert G. Ingersoll 1833-1899

AgFutures produces a set of indicators and indices that can be used to evaluate the outcomes of alternative scenarios for their impacts on sustainability. In this chapter, I first discuss different issues related to measurement of sustainability through indicators and indices. Next, the approach used for sustainability assessment in AgFutures is presented. This is followed by a description of the development of indicators and scenario evaluation criteria and indicators used in AgFutures. I next describe the development of the aggregated indices of sustainability, followed by the results of sustainability assessment for different scenarios.

6.1 Introduction

6.1.1 Indicators

Evaluating impacts on sustainability is a complex problem because sustainability is comprised of an ensemble of multiple concepts that are difficult to quantify. It requires going beyond measurement and dealing with other issues, like commitment to its implementation, that require discussions. However, unless we can strictly quantify what we are trying to achieve, it becomes difficult, if not impossible, to determine by what means we can achieve sustainability. Quantifying sustainability helps to show how effective different strategies are in achieving or increasing sustainability, and also in comparing alternative plans and policies with respect to their impacts on sustainability.

Because sustainability is a multi-dimensional concept, it is difficult to measure sustainability directly. Instead, indicators of sustainability are used, often corresponding to different components of sustainability (viz. social, economic and environmental), and are used for assessing the state or level of sustainability of a system, for monitoring progress towards sustainability, and for evaluating the effectiveness of policies. Indicators are important tools that simplify and quantify complex phenomena, to help us understand the complex realities and translate these into “numerical terms, descriptive measures and action-oriented signs and signals” (IISD, 2002).
There are many efforts all over the world towards the development of indicators of sustainability (see Rogers et al. (1997) for a list of indices developed) and many sets have been constructed. OECD (1994) developed a set of environmental indicators to be used in national, international and global decision-making. This consisted of a core set of environmental indicators that can be used to keep track of environmental progress and several sets of sectoral indicators that could be used to integrate environmental concerns into sectoral policy decisions. Other sets include sustainable development indicators by the UN Commission for Sustainable Development, environmental sustainability indicators of the World Economic Forum, and those by the European commission and the European Union. Specific examples of indicators related to agriculture include national level agri-environmental indicators by Agriculture and Agri-food Canada (McRae et al., 2000) and regional/national indicators for assessing the sustainability of agricultural land management in Canada (Neave et al., 1995).

Most existing indicators have been developed for specific reasons. They are environmental, economic, social and health indicators that are not considered sustainable development indicators per se, but which have an explanatory value within the context of a sustainable development framework. These indicators, although useful to professionals and academics, were not developed for the media and public. The detailed nature of the information hampers its direct usefulness in user-oriented models and policy-making (Brink et al., 1990; IISD, 2002). Inexperienced users often get overwhelmed by the amount of fragmented information provided by different indicators and fail to get an overall picture of sustainability. Complex problems of sustainable development require integrated or interlinked sets of indicators, or an aggregation of indicators themselves.

6.1.2 Issues in Aggregation of Indicators

Indicators can be aggregated to form composite indicators or indices. The general public, stakeholders, as well as high-level decision-makers usually desire a small number of indicators that are easy to understand and use in decision-making. Hence the development of composite indices is necessary. Composite indices serve to reduce the complexity of information presented in its constituent parts. A widely known example of a composite index is the Gross Domestic Product. It provides information on the total value of production in a country in one single index.
Another well-known example is the Human Development Index (HDI), which contains indicators representing three equally weighted dimensions of human development: longevity, knowledge and income (Murray, 1991; UNDP, 1996). Other examples include the Ecological Footprint (Rees and Wackernagel, 1994) and the Genuine Progress Indicator (Cobb et al., 1995). However, aggregation of different indicators into an index has a number of related issues. Aggregation can hamper the correct interpretation of raw data. This aggregation can mask or hide certain pieces of information which may be vital to the decision-makers or users. There are also methodological issues related to the aggregation of data. The question is how to aggregate variables expressed in different units of measurement (e.g., different physical entities) or presented in different time series and referring to different spatial units. Traditionally, aggregation is not a simple average but a weighted average of individual data. However, there can be no universal set of weights because they are value-based, highly subjective and variable, and cannot be uniquely represented across individuals (Hyatt and Hoag, 1997). Furthermore, very often the indices are developed with built-in assumptions that may differ from those of users. Another issue with the generation of such indices is that the combination of data is frequently arbitrary and not based on any structural framework.

A further major debate relates to the development of a single index of sustainability. There has always been a desire to be able to measure sustainable development with a single index, more on line with the Gross Domestic Product (GDP) traditionally used for measuring economic growth. Some experts feel that caution should be exercised with respect to the development of a sustainability index, although it would seem desirable to construct a composite indicator for different dimensions of sustainable development. It is the very purpose of sustainability indicators to show that there are trade-offs between the three dimensions which require appropriate choices. Besides, a concept as complex as sustainable development, involving a series of interactions between society and environment resulting in non-linear relationships, cannot be adequately represented by a single index.

Thus, on one hand, there is the growing complexity related to the vast amounts of information given by different indicators and, on the other hand, there is the need to aggregate and present the information in ways that are simple and effective, while retaining the underlying complexity. Systematic methods based on scientific methodology are required for presenting this information in an effective way to the user.
In AgFutures, sustainability assessment includes considerations of both individual sustainability indicators, as well as an aggregation of indicators, the results of which are presented in a flexible framework to the user. It represents a new way of presenting multidimensional information in a single framework for sustainability assessment of different scenarios. An approach based on a hierarchical framework is used to address some of the problems related to aggregation. It is based on the rationale that sustainability assessment procedures should make transparent the decisions related to the aggregation of indicators, as well as provide a flexible way to aggregate indices as per the users' needs and preferences.

6.2 Approach for Assessing Sustainability

Different approaches can be used for measuring sustainability, based on the central issues that need to be examined, spatial scales and the scope of the study. Figure 6.1 presents some of the approaches to measuring sustainability adopted by the United Nations Commission on Sustainable Development, IUCN, and the International Monetary Fund. Different methods put different emphasis on various components of sustainability. For example, the IUCN approach puts equal importance on people and the ecosystem. Some frameworks group indicators into health, wealth, culture and politics in order to measure the impacts on quality of life. In AgFutures, the three components approach is used, which includes measuring sustainability with respect to economy, society and environment; this is the most widely used approach in sustainable development literature. Secondly, for assessing sustainability, a conceptual model is required in order to organize indicators or indicator sets in a coherent manner. These models suggest logical groupings for related sets of information that are useful for the aggregation of indicators (UNEP-DPCSD, 1995).

One of the ways to organize indicators for aggregation is through a hierarchical structure (IUCN, 1997). For example, the indicator hierarchy of the United Nations Commission on Sustainable Development has four levels: System (country), Category (social; economic; environmental; institutional), Agenda 21 chapter, and Indicator. The hierarchy used in AgFutures has five levels: Goal, Dimension, Issue, Criterion and Indicator. It defines regional agricultural sustainability as the goal at the highest level. Agricultural system sustainability is governed by that of its three subsystems or dimensions: social, economic and environmental. The sustainability of each of these components is assessed with respect to different issues
Figure 6.1 Different ways of measuring sustainability

Source: (Prescott-Allen, 1998)
related to each subsystem, which are in turn based on different criteria that reflect the concerns of communities regarding the different issues.

A suite of indicators is identified that measures changes with respect to the different criteria. Aggregate measures of indicators are then computed at different levels in the hierarchy, which allows users to carry out sustainability assessment at a desired level of aggregation. An aggregated index at the 'goal' level is then computed and used for assessing the overall impacts on sustainability. Two indices based on different decision rules of aggregation were developed and used in AgFutures.

6.3 Development of Indicators

Basic concepts used in the development of indicators are discussed in this section; different issues considered and their respective indicators will be presented in section 6.4.

6.3.1 Purpose and Scale

There is no universal set of indicators that can be used in every context. They need to be specific to the process that they are a part of. Also, different sets of indicators need to be developed for different scales of study. The level at which indicators are to be used has implications for the type of indicators that can be constructed. For example, at the farm level, the depth of soil may be a key indicator but it may be difficult to measure this at the national level. Indicators used in AgFutures were designed specifically to measure the impact of choices on the outcomes of sustainability, and they measure these impacts on agricultural sustainability at the regional level.

6.3.2 Indicator Frameworks

A conceptual framework of indicators is necessary to help in the identification of indicators. It helps to select and organize the issues that will define what should be measured by the indicators and also to ensure that important considerations have not been overlooked. Frameworks also help to identify data collection needs. They are useful tools for decision-makers, as they help to summarize key information related to different issues. Organizing indicators in a framework also helps communities and users to evaluate the effectiveness of the entire set of indicators (Hart, 1998).
Several sets of methodological frameworks have been developed in order to help identify appropriate indicators for sustainability assessment. The main differences among these different frameworks are (Hardi et al. 1997): 1) the ways and means by which they identify measurable dimensions, and select and group the issues to be measured; and 2) the concepts by which they justify the identification and selection procedure.

OECD (1994) used the Pressure-State-Response framework that is based on the concept that human activities exert 'pressure' on resources and the environment - to alter their 'state' - to which society responds through environmental, economic and sectoral responses. There have been several variants of this framework, such as the Driving Force-State-Response (DSR) model that allows for inclusion of social, economic and institutional dimensions of sustainable development (UNCSD, 1996) and the Driving Force-Pressure-State-Impact-Response model used by the European Environment Agency (Jesinghaus, 1999).

The identification and selection of the indicators in AgFutures was based on the D-O-R (Driving force – Outcome – Response) framework explained in Chapter 2 (Figure 2.1). This framework was selected as it has already been adapted for use in assessing sustainability of agricultural systems at the national level in Canada (McRae et al., 2000). Driving forces that produce land-use changes and related agricultural development in the model are various geographical factors, land characteristics, and the scenario choices made by the users regarding policies, food consumption preferences, and agricultural intensification and management practices. These factors affect various outcomes of agriculture, based on which different scenarios are evaluated. Outcomes related to agriculture can be either beneficial or adverse, related to social (e.g., employment, rural development, and food security), economic (e.g., income, costs), and environmental (e.g., degraded soils, water quality) issues. Due to problems related to availability of specific data (e.g. employment by agricultural use types) not all of these outcomes are examined in the model.

6.3.3 Criteria for Selection

Indicators are selected based on context-specific conditions and other criteria that characterize a good indicator. While there are differing definitions of an indicator, there seems to be a consensus on the criteria of a good indicator. Indicators need to be: policy- or issue-relevant, effective, sensitive to changes, analytically sound, aggregated, specific and cost-efficient (Rigby et al., 2000; EC, 2001; IISD, 2002). Furthermore, good indicators should also be user
derived, implying community or participatory involvement. Different research efforts often lead to a generation of a long list of indicators that may not all be useful to the community. It is important that the indicators should be limited in number and be non-redundant in order to be useful to the user.

According to Smyth and Dumanski (1993), good indicators for agricultural systems are measurable and quantifiable environmental statistics that measure or reflect environmental status or changes in condition. There are varying opinions on the use of quantitative versus qualitative indicators. The role of quantification according to many authors (e.g., Glenn and Pannell, 1998) is not universally accepted, since some authors regard qualitative indicators (e.g. visual assessment of soil erosion) as valid tools. However, the major focus of this research effort is directed to development of quantitative indicators that reflect the impacts of agriculture on the whole system, including human and environmental systems.

6.3.4 Indicator Threshold/Target Values

Sustainability indicators make it easier to communicate about sustainability by translating impacts into simple measures. However, an indicator without a context has no value. Indicators are often compared to their threshold or target values in order to assess the sustainability status. Threshold values represent points where significant changes occur in the system. When an indicator crosses this threshold value, the system is considered to be unsustainable. However, there are issues related to setting these values and who should set them, experts, scientists or communities (Rigby et al., 2000). Also, should these be defined at the regional, national or global scale? Target values are concerned with intention. For example, a province or country may set its own target values related to greenhouse gas emissions that may not necessarily be the best or a valid threshold value for the system. There were no available target or threshold values for the indicators developed for use in AgFutures. Therefore, only a relative assessment of sustainability was made for the different scenarios.

6.4 Issues, Criteria and Indicators for Sustainability Assessment

The evaluation of alternative scenarios for their impacts on sustainability was based on four key social, economic, and environmental issues (Figure 6.2). The impacts were assessed through various criteria that were identified in Chapter 3 as chief concerns for agricultural sustainability in the region. Indicators were identified for each criterion to assess the outcomes.
for these issues. These issues and their respective criteria used in scenario evaluation are discussed below.

6.4.1 Food Security

At present, British Columbia produces more than half of the province’s food requirements and 62 percent of this agricultural production comes from the Lower Mainland. In order to provide food for the constantly growing population, it is necessary to protect the dwindling agricultural land base in the province, and particularly in the Lower Mainland where it is under constant pressure from urbanization. Having a secure, home grown food source ensures security and less dependence on sources outside of the province for food needs. It also ensures control over producing a high quality food supply at affordable prices. Besides preserving our foodlands, it is also necessary to make optimal use of land in order to maintain, if not increase, the land’s productivity.

The food security issue is therefore examined in this study from the perspective of two criteria: the availability of the agricultural land base and the production potential of the land. Both of these are essential elements for a secure food supply.

6.4.2 Economic Viability

Agriculture uses many inputs in the production process, including land, labour, capital, water, nutrients, pesticides and energy. Input costs are a significant cost of overall farm operating expenses and determine the net economic benefits to the producers. Indicators related to the economic output of agriculture and input costs are used to assess the economic viability of agriculture under different scenarios.

6.4.3 Water Quality

The application of nutrients, in the form of manure or chemical fertilizers, to soil increases crop growth. Such applications are necessary for preventing soil nutrient mining and for raising crop yields. However, when they are applied in excess of crop needs they can be a major source of environmental pollution. Excessive nutrients (nitrogen and phosphorus) can leave farmlands through run-off or leaching and cause surface and groundwater pollution. There is little potential for phosphorus to leach through soil into groundwater; however, it can be carried off in run-off waters from fields into surface water bodies. The water quality issue of greatest concern in the region is nitrate contamination of groundwater (Zebarth et al., 1998).
Figure 6.2 Indicators in AgFutures model a) Representation in three-components model; b) Representation in hierarchical structure
As already discussed in Chapter 3, nitrogen is the chief source of ground water pollution from excessive fertilizer and manure use in the Fraser Valley, which is documented by high levels of nitrogen concentration in the Abbotsford aquifer. There are concerns of negative health effects if nitrate concentrations exceed drinking water guidelines in the water sources. Furthermore, nitrogen is an indicator of the presence of other important chemicals used in agriculture and other human activities.

The risk of nutrient pollution of ground and surface water is assessed here through an indicator that estimates nitrogen surplus in the region.

6.4.4 Wildlife Habitats

Wildlife use different parts of the landscape for their survival. When natural habitats such as wetlands and forests are converted because of human activities, such as urbanization and agriculture, they usually result in a decrease in wildlife and amenity values. However, agricultural lands offer more benefits to wildlife than more developed urban areas. Within agricultural landscapes, natural land for pasture, wetlands and woodlots are the preferred habitats by wildlife species (Neave et al., 2000). Agriculture affects the quantity and quality of wildlife habitats, mainly through conversion of natural landscapes and changes in land-use resulting in the fragmentation of habitats. Cranberry plantations have replaced much of the bog area and second growth forest in the Lower Mainland. Hundreds of acres of wildlife habitat have been cleared, drained, dyked, and planted with cranberries in the Lower Mainland (Bunbury, 1999). The loss and fragmentation of bird habitats, due to the greenhouse industry growth in the Lower Mainland, is a prime example of this issue. An indicator for wildlife habitats was developed that is related to the availability of natural land. There was no indicator for the fragmentation of landscape that affects the quality of habitats.

It is frequently easier to assess the non-sustainability of a system rather than sustainability. Determining drawbacks or mistakes in a system is useful for corrective measures. Also, it is easier to identify the disrupting forces and measure non-sustainability rather than measuring sustainability, which is dynamic and relative. The indicators are therefore designed to represent the changes that result in negative impacts on sustainability. For example, in the case of food security, the (non)sustainability indicator, for agricultural land base, was designed to reflect area lost in urban conversions. Thus, higher values for all of these indicators, except for the agricultural output indicator, reflected higher negative impacts on the related issue.
When selecting these indicators it was also kept in mind that they should be sensitive to changes in the scenarios defined in this study. The connections between various scenario-driving variables (which are considered here as driving forces of agricultural development in the different scenarios) and the various indicators are presented in Figure 6.3. For example, diet preferences affect the ‘livestock number’ parameter in the model, which in turn affects value of nitrogen surplus, a water quality indicator.

6.5 Methods for Calculating Indicator Values

6.5.1 Agricultural Land Loss

A decrease in availability of land for agricultural purposes may result in eroding the food base in the valley. This indicator was defined as the amount of agricultural land lost to urban growth. It was determined by overlaying the map of existing ALR and other agricultural areas on the land-use map produced for 2040.

6.5.2 Land Marginality Index

Agricultural area may expand on marginal lands, which would not result in a matching increase in production. Such a situation may decrease the eco-efficiency of agricultural systems by increasing the inputs costs.

The indicator was defined as:

\[ L_{mi} = 1 - L_p \]  

(6.1)

where \( L_{mi} \) is land marginality index, \( L_p \) is the proportion of agricultural land under the prime capability class. The classification map of \( L_p \) was achieved by overlaying a land capability map with the land-use map to find the percent of cultivated area on prime agricultural land. Prime agricultural land was defined as the area under classes 1 to 3 according to the British Columbia Land Inventory (BCLI) classification system. The BCLI system uses a scale of 1 to 7 to determine suitability, with Class 1 lands being the best for growing a wide variety of crops, and Class 7 lands being completely unsuitable for agriculture.

6.5.3 Agricultural Output

This was defined as the total output of all agricultural activities in monetary units. It was calculated in terms of real dollars (2000 = 100) and was based on total economic output from
Figure 6.3 Connections between scenario-driving variables and indicators (outcomes) in the model
various agricultural products of a land-use or livestock. For example, economic outputs of poultry include those from eggs and broiler meat; outputs from cattle include those from dairy and beef. It was assumed that the relative proportions of sub-categories (for example, tomatoes, cucumbers, and peppers greenhouses) within an agricultural category (here, vegetable greenhouses) would not change over time. To compute the agricultural value of each product, the physical outputs in terms of tonnes or numbers were computed and these were then multiplied by their respective prices to get the values.

\[
\text{Total Agricultural Value} = \sum A_i \times Y_i \times P_i + \sum M_j \times N_j \times P_j
\] (6.2)

where \(i\) is the number of crop commodities and \(j\) is the number of livestock commodities; \(A_i\), \(Y_i\), and \(P_i\) are area, yield and price per unit production of crop \(i\), and \(M_j\), \(N_j\) and \(P_j\) are physical output per livestock type (in tonnes or numbers), number of livestock, and price per unit output of livestock \(j\).

Some of the commodities have shown a decline in price, in terms of real dollars, over the past 20 years (for example, berries and wheat) and trend-based projection of these prices would result in an unrealistic value for 2040. Hence, prices received by the producers for different commodities in the year 2000 were assumed to stay constant up to 2040 for all commodities and were used in calculations.

Yields of commodities depended on scenario definitions (Table 6.1). For the Agribusiness Scenario it was assumed that average yields would increase to potential yields for each crop, while for all other scenarios yield levels were considered as constant. Information for potential yields was obtained from published sources or a 20% increase was used in cases where this information was not available.

6.5.4 Costs

This indicator calculates total operating costs of various agricultural activities as:

\[
\text{Costs} = \sum (A_i \times E_i) + \sum N_j \times E_j
\] (6.3)

where \(A_i\) is the area under crop \(i\); \(E_i\) is the expense per unit area of crop \(i\); \(N_j\) is the number of livestock of type \(j\) and \(E_j\) is the expense coefficient for livestock \(j\).
Expense coefficients for different types of crops and livestock were taken from published sources (such as, those by Ministry of Agriculture, Food and Fisheries (MAFF), BC) and were used in these calculations. The cost estimates reported by MAFF include various expenses, such as those related to fertilizer, pesticides, fuel costs, seeds, labour, etc. and are based on standard practices in the area. Operating costs for different farm uses were available for different years. These costs were converted to real dollars (2000=100) and expense coefficients (e.g., expenses per unit area or number of livestock) were derived. These were assumed to be constant over the study period and are presented in Table 6.2.

6.5.5 Nitrogen Balance

This indicator was developed for assessing risk to water quality and was defined as the difference between the nitrogen inputs from manure and fertilizer and nitrogen removal by crops per hectare of cropland. It used various data on fertilizer use, livestock type and number, crop areas and coefficients regarding livestock manure and crop uptake, and was measured in kg per hectare of cropland.

\[ N_{bal} = \frac{(N_{fert} + N_{man} - N_{rem})}{A} \]  

(6.4)

where \( N_{bal} = \) nitrogen balance; \( N_{fert} = \) nitrogen from fertilizer application (kg); \( N_{man} = \) nitrogen from manure; \( N_{rem} = \) nitrogen removal by crops; and \( A = \) area of cropland.

Projected areas for crops along with N fertilizer application rates were used to determine the total N fertilizer use in different scenarios. Application rates were affected by yield levels and management practices in the model.

Statistics Canada provides information on amount of area fertilized in a census subdivision in its Census of Agriculture. No information was available on quantity of fertilizers applied to different crops in 2000. Available information on fertilizer application rates for different crops in 1991 (Brisbin and Runka, 1995a) were used instead in the calculation and are presented in Table 6.3.

A linear relation was assumed between the yield levels in the scenario and fertilizer rates. In the Protectionist Scenario, which assumes improved management practices, the application rates are considered to fall to 50% of the original values to account for manure applications.
Table 6.1  Yields of commodities under different scenarios

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Yield - 2040 (BL, Prot, and Vege scenarios)</th>
<th>Yield - 2040 (Agribusiness scenario)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berries (tonnes/ha)</td>
<td>6.76</td>
<td>8.1</td>
</tr>
<tr>
<td>Vegetables (tonnes/ha)</td>
<td>15.35</td>
<td>24.5</td>
</tr>
<tr>
<td>Grains (tonnes/ha)</td>
<td>2.83</td>
<td>4.5</td>
</tr>
<tr>
<td>Hay/Forage (tonnes/ha)</td>
<td>3.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Greenhouse vegetables (tonnes/ha)</td>
<td>396</td>
<td>526</td>
</tr>
<tr>
<td>Milk (litres/cow)</td>
<td>9000</td>
<td>9000</td>
</tr>
<tr>
<td>Pig weight (kg)</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Broiler meat (kg/hen)</td>
<td>1.92</td>
<td>1.92</td>
</tr>
<tr>
<td>Eggs per hen</td>
<td>295</td>
<td>295</td>
</tr>
</tbody>
</table>

Table 6.2  Expense coefficients for different uses/livestock

<table>
<thead>
<tr>
<th>Land use / Livestock</th>
<th>Expense coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berries ($$/ha)</td>
<td>7707</td>
</tr>
<tr>
<td>Vegetables</td>
<td>8274.8</td>
</tr>
<tr>
<td>Grains ($/ha)</td>
<td>313.14</td>
</tr>
<tr>
<td>Greenhouse Vegetables</td>
<td>415405</td>
</tr>
<tr>
<td>Cattle and cows ($$/cow)</td>
<td></td>
</tr>
<tr>
<td>- Dairy</td>
<td>3116</td>
</tr>
<tr>
<td>- Beef</td>
<td>374</td>
</tr>
<tr>
<td>Hogs ($$/hog)</td>
<td>122.28</td>
</tr>
<tr>
<td>Hens and chicken ($$/bird)</td>
<td></td>
</tr>
<tr>
<td>- Broiler</td>
<td>2.33</td>
</tr>
<tr>
<td>- Layers</td>
<td>24.75</td>
</tr>
</tbody>
</table>

Source: Ministry of Agriculture, Food, and Fisheries, BC
Table 6.3 Inorganic fertilizer application rates by crop (kg/ha)

<table>
<thead>
<tr>
<th>Fertilizer Application (kg/ha/year)</th>
<th>N</th>
<th>P2O5</th>
<th>K2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Pasture</td>
<td>120</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>Unimproved Pasture</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Grains and Oilseeds</td>
<td>180</td>
<td>80</td>
<td>115</td>
</tr>
<tr>
<td>Silage Corn</td>
<td>140</td>
<td>95</td>
<td>105</td>
</tr>
<tr>
<td>Alfalfa, Grass</td>
<td>240</td>
<td>55</td>
<td>70</td>
</tr>
<tr>
<td>Potatoes</td>
<td>90</td>
<td>195</td>
<td>195</td>
</tr>
<tr>
<td>Vegetables</td>
<td>100</td>
<td>150</td>
<td>170</td>
</tr>
<tr>
<td>Other Field Crops</td>
<td>132</td>
<td>102</td>
<td>111</td>
</tr>
<tr>
<td>Berries*</td>
<td>73</td>
<td>108</td>
<td>113</td>
</tr>
<tr>
<td>Nursery Prod</td>
<td>60</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>

* - average of strawberries, raspberries and blueberries

Source: Brisbin and Runka, 1995a

Table 6.4 Nutrients excreted by livestock type

<table>
<thead>
<tr>
<th>Livestock Type</th>
<th>Nitrogen excreted (kg/animal/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle and Calves</td>
<td></td>
</tr>
<tr>
<td>Dairy Cows</td>
<td>116</td>
</tr>
<tr>
<td>Beef cows</td>
<td>78</td>
</tr>
<tr>
<td>Bulls</td>
<td>112</td>
</tr>
<tr>
<td>Heifers (Dairy)</td>
<td>42</td>
</tr>
<tr>
<td>Heifers (Beef)</td>
<td>44</td>
</tr>
<tr>
<td>Steers</td>
<td>50</td>
</tr>
<tr>
<td>Calves</td>
<td>20</td>
</tr>
<tr>
<td>Poultry</td>
<td></td>
</tr>
<tr>
<td>Meat - Chickens (1000's)</td>
<td>0.6</td>
</tr>
<tr>
<td>Layers - Pullets (1000's)</td>
<td>0.34</td>
</tr>
<tr>
<td>Layers (1000's)</td>
<td>0.8</td>
</tr>
<tr>
<td>Hogs</td>
<td></td>
</tr>
<tr>
<td>Boars</td>
<td>24.3</td>
</tr>
<tr>
<td>Sows</td>
<td>18.3</td>
</tr>
</tbody>
</table>

Source: Brisbin and Runka, 1995b
To compute the nitrogen from manure, projected livestock numbers for three categories were further categorized into different types, for example cattle were further categorized as beef and dairy cows. It was assumed that the proportion of the subcategories would remain the same as in 2001. Available data on coefficients for nitrogen from manure of each animal per year (Brisbin and Runka, 1995b) (Table 6.4) were then multiplied by livestock numbers to compute the total manure nitrogen. Atmospheric deposition of nitrogen was not considered in these calculations.

6.5.6 Natural Land Conversion

This indicator was developed to assess the availability of wildlife habitat. It was defined as area of forests (mature and young) and other natural land (such as woodlots and wetlands) converted to urban or agricultural use.

An overlay of the land-use map, obtained from the land-use simulation model, and the land-cover information was used to derive the values for this indicator.

6.6 Method for Aggregation of Indicators

The aggregation of indicators into indices requires development of decision rules or aggregation functions. An appropriate aggregation function needs to be selected for ranking and comparing alternatives, as different decision rules can result in different rankings of the alternatives. An aggregation function integrates data and information on alternative outcomes and decision maker’s preferences into an aggregated measure. There are many different ways in which indicator values can be combined to form an aggregated index that can be used for the comparison of different scenarios. Some of the common decision criteria used in aggregation are the simple average, the maximin criterion and the minimax regret criterion. Ascough II et al. (2002) summarized these and used some of them to develop a regret index in their study on evaluation of agricultural systems for sustainability. The regret index gives the maximum regret or loss for each alternative and the alternative which gives the minimum regret is selected as the best alternative. This approach will work well when all criteria are assumed to have adverse impacts.

An alternative approach based on the ‘distance from the ideal point’ decision rule is used in AgFutures and is explained in following section. Three different indices are developed: the Outcomes Index which is based on weighted aggregation; the Relative Benefits Index which is
based on ratios of two indices; and the Relative Sustainability Index that is based on the ideal point decision rule. The various steps that are carried out for calculation of these indices in the hierarchical structure are described below.

6.6.1 Standardization of Indicator Values

The various indicators developed here have different units. In order to aggregate these it was necessary to convert them either to same units or to dimensionless quantities. Conversion to the same units usually requires conversion to monetary units; this is difficult, especially when dealing with environmental impacts. Conversion of indicator values into dimensionless numbers or scores can be done by normalizing them with respect to a reference value. The reference values are normally targets or thresholds for sustainability. However, none of these values were readily available for the indicators used in the study. Instead, they were standardized against the maximum value obtained for a criteria; i.e.

\[ S_i = \frac{I_i}{I_{\text{max}}} \]  

where \( S_i \) is the score of ith indicator, \( I_i \) is the indicator value for the ith indicator and \( I_{\text{max}} \) is the maximum value of the indicator across all scenarios. However, for the agricultural output indicator, which is a ‘benefits’ indicator unlike other indicators, the score was computed as:

\[ S_i = 1 - \left( \frac{I_i}{I_{\text{max}}} \right) \]  

In this case, higher raw indicator values represent higher adverse impacts on sustainability, by subtracting the standardized values from one, higher scores here would also mean the same. This method of standardization results in a proportional transformation of the raw data, unlike the score range method that does not maintain the proportions between original values and instead results in values between 0 and 1.

6.6.2 Assigning Weights

Not all criteria may be equally important to different users in evaluating the outcomes of scenarios. In the hierarchical structure weights can be assigned at each step in the aggregation process. For example, if there are more than one indicator for an issue it is possible to assign different weights to each indicator evaluated for the issue. Similarly, it is possible to define different weights for multiple issues addressed for outcomes related to a particular subsystem.
6.6.3 Aggregation

6.6.3.1 Outcomes Index

The Outcomes Index is the aggregated score for all outcomes of a scenario. Indicator scores are aggregated up the hierarchy from the lowest level (indicator) to the highest level (goal). The Outcomes Index (OI) is computed as:

\[ OI = \sum W_i D_i \]  

where \( D_i = \sum W_j I_j \) and \( I_j = \sum W_k S_k \)

\( W \) represents weights for dimensions or issues or criteria; \( i \) is number of dimensions (i.e., 3); \( j \) is number of issues (i.e., 4); \( k \) is number of criteria (i.e., 6); \( D_i \) is the weighted score at dimension level; \( I_j \) is the weighted score at issue level and \( S_k \) is the standardized indicator score for the criteria. Computation of this index, as well as other aggregate indices at different levels in the hierarchy was based on equal weights at each level.

6.6.3.2 Relative Sustainability Index

Alternative scenarios could be evaluated on the basis of the Outcomes Index and ranked to determine the most preferred or least preferred alternative. However, the Outcomes Index puts equal importance on the outcomes of agriculture with respect to social, economic and environmental systems. While it is simple to compute and use, it fails to answer how the benefits of agricultural production compares with the costs, including environmental costs. Hence, a different decision rule for evaluation of alternatives was used for understanding these trade-offs. This rule used an ideal-point method for comparing alternatives with respect to the selected criteria (Malczewski, 1999). Ideal point methods order a set of alternatives on the basis of their separation from the ideal point. The ideal point represents a hypothetical alternative that consists of the most desirable standardized scores for each criterion. The alternative that is closest to the ideal point is considered the best alternative.

The alternatives were assessed with respect to their performance against two criteria: impacts (environmental and economic) and production (agricultural output). An impact index (II) was first generated that gave a measure of the economic and environmental costs associated with agricultural production. Scores of all indicators, except agricultural output, were aggregated into the II using the hierarchical approach described above for the Outcomes Index. The
agricultural output index (AOI) was simply the standardized scores for the agricultural output indicator obtained according to equation 6.5.

An aggregated index was then developed which assessed how successful a scenario was at minimizing the impacts and maximizing the agricultural production. This aggregated index, called the Relative Sustainability Index (RSI), measured how close a particular alternative was to the 'ideal' point in the two-dimensional space of II and AOI. The RSI was then computed using a distance metric as defined by:

$$\text{RSI}_i = [ \sum w_j^2 (S_{ij} - S_{ij}^*)^2 ]^{0.5}$$  \hspace{1cm} (6.8)

where $\text{RSI}_i$ is the relative sustainability index for the $i$th alternative, $w_j$ is a weight assigned to the $j$th criteria, $S_{ij}$ is the standardized score for $j$th criteria for $i$th alternative, and $S_{ij}^*$ is the ideal value for the $j$th criteria. The ideal point taken for calculations was $(0,1)$ where $0$ is the ideal score for the II and $1$ is the ideal score for the AOI.

### 6.6.3.3 Relative Benefits Index

A third index, the Relative Benefits Index, based on a simple ratio decision rule was also used for assessing trade-offs between agricultural production and its impacts. It indicates relative benefits of increases in agricultural production, over the base year, as compared to its impacts over the base year.

It is computed from the II and the AOI as:

$$\text{RBI}_i = \frac{(\text{AOI}_{2000} - \text{AOI}_i)}{(\text{II}_{2000} - \text{II}_i)}$$  \hspace{1cm} (6.9)

where $\text{RBI}_i$ is the Relative Benefits Index for the $i$th scenario, $\text{AOI}_{2000}$ is the agricultural output index for 2000, $\text{AOI}_i$ is the agricultural output index in the $i$th scenario in 2040, $\text{II}_{2000}$ is the impacts index for 2000 and $\text{II}_i$ is the impacts index for the $i$th scenario in 2040.

### 6.7 Results and Discussions

The results of the sustainability assessment based on the AgFutures model are presented in the form of tables, graphs and composite indices to allow for the analysis of results by different levels (experienced/inexperienced; experts/non-experts) of users. In this section, the intent of the discussion focuses more on how the various results can be analysed, rather than on the
actual numbers obtained for the indicators under different scenarios, which are open to interpretation.

6.7.1 Indicators

Raw values of indicators, as obtained for the different scenarios, are presented in Table 6.5, while the detailed results in the form of graphs are presented in Figure 6.4. The LMI was higher for all scenarios as compared to 2000, except for the protectionist-a scenario (Table 6.5). In general, the 'b' scenarios had a higher LMI implying that most of the prime agricultural land was lost to urban conversions as a result of which agricultural production shifts to non-prime lands in these scenarios.

Areas for different agricultural land-use categories under the different scenarios are shown in Figure 6.4a. In all the scenarios the majority of the agricultural area was allocated to hay/forage crop use, while greenhouses occupied minimal area. There was a nearly 75 percent increase, over 2000 levels, in agricultural output in the Baseline-a scenario. This is mainly due to the three-fold increase in greenhouse vegetable production that accounts for close to 50 percent of the total agricultural value in 2040 (Figure 6.4b), as compared to 25 percent in 2000. Agricultural output related to chicken products (meat and eggs) increased to twice the value of 2000. The highest increase in agricultural output was obtained for the Agribusiness-a scenario, whereas the least increase was obtained for the protectionist scenario. There was a nearly 150 percent increase in agricultural output in the Agribusiness-a scenario. The agricultural intensification in this scenario resulted in a five-fold increase in greenhouse vegetable production, which accounted for more than 50 percent of the total agricultural value in 2040, as compared to 25 percent in 2000. However, the increase in agricultural output in the Agribusiness-a scenario was at the expense of economic and environmental costs which are maximum. The agricultural operations costs increased by 100 percent (Figure 6.4c), nitrogen surplus increased by 60 percent (Figure 6.4d) and there was a maximum loss of natural lands amounting to more than 38,000 ha (Table 6.5). These results clearly indicate the extent of trade-offs between agricultural production and its impacts on economic and environmental sustainability under the various scenarios. Similar inferences and comparisons can be made for other scenarios. Thus, detailed inferences can be made from Table 6.5, which sends action-oriented signals for practical policy development regarding a particular issue. However, it is
Table 6.5 Indicator results for different scenarios

<table>
<thead>
<tr>
<th>Indicators</th>
<th>2000</th>
<th>2040 - scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BL-a</td>
<td>BL-b</td>
</tr>
<tr>
<td>Ag land loss (ha)</td>
<td>0</td>
<td>3653</td>
</tr>
<tr>
<td>LMI</td>
<td>0.45</td>
<td>0.47</td>
</tr>
<tr>
<td>Nat land conv (ha)</td>
<td>0</td>
<td>31953</td>
</tr>
<tr>
<td>N surplus (kg/ha)</td>
<td>99</td>
<td>89</td>
</tr>
<tr>
<td>Op. Costs ('000' $$)</td>
<td>457346</td>
<td>738364</td>
</tr>
<tr>
<td>Ag output ('000' $$)</td>
<td>641173</td>
<td>1112579</td>
</tr>
</tbody>
</table>

Terms used in the table:
- Ag land loss – Agricultural land loss
- LMI – Land Marginality Index
- Nat land conv – Natural land conversion
- N surplus – Nitrogen surplus
- Op. Costs – Operation costs
- Ag output – Agricultural output value
- BL – Baseline scenario
- AgBus – Agri-business scenario
- Prot – Protectionist scenario
- Vege – Vege-business scenario
- a – ‘a’ type scenario (Preserve ALR)
- b – ‘b’ type scenario (Do not preserve ALR)
Figure 6.4 Selected indicator results for different scenarios
(Indicator values for 2000 are also shown for comparison)
difficult to make inferences regarding multiple issues simultaneously when information is presented in this manner.

6.7.2 Sustainability Cobwebs

In order to show the impacts on several goals, while avoiding aggregation, the indicators are also presented in the form of sustainability cobwebs (Swete-Kelly, 1996; Rigby et al., 2000), which can display scores of multiple indicators along different axis. The use of sustainability cobwebs is a very efficient method for displaying large amounts of indicator information in a concise manner. These can also incorporate threshold or target values for each indicator. These diagrams give a visual assessment of conditions and can be used to compare conditions with a reference value. Figure 6.5 presents these diagrams for standardized indicator scores for 2040, along with those for the base year (2000), against which comparisons can be made for outcomes of different alternatives in 2040. Comparisons can be also made across different scenarios very easily. For example, the size of the web is largest for the agribusiness scenario suggesting that it had the highest adverse impacts on sustainability. It is also observed that, the size of the web in ‘b’ type of scenarios is larger than that of ‘a’ type of scenarios, suggesting that impacts on agricultural sustainability under these scenarios, which do not preserve ALR, are higher. The least impacts were observed for the protectionist-a scenario.

These diagrams serve to give an overall visual image of the sustainability under different scenarios and help to track changes in different indicators at the same time.

6.7.3 Aggregated Indices

The values of the aggregated indices at different levels in the sustainability hierarchy are presented, along with the final Outcomes Index for the different scenarios, in Table 6.6. The index at the issue level gives an indication of the impacts due to the different aspects that were considered as the chief concern for defining that issue, while the index at the dimension level gives an indication of the extent of agricultural impacts on the different aspects that defined the dimension. The Outcomes Index gives an overall assessment of the sustainability in each scenario. The Outcomes Index immediately illustrates that impacts on sustainability were greatest in the Agribusiness-b scenario, followed by the Baseline-b scenario. Examination of indices at the ‘dimension’ level reveals that the non-sustainability of the Agribusiness-b scenario was due to higher social and environmental impacts. A further examination of the indices at the ‘issue’ level reveals that the impacts on the environment dimension were more
Figure 6.5 Sustainability cobwebs for different scenarios: a) Baseline b) Agri-business c) Protectionist d) Vege-business
Table 6.6 Aggregated indices at different levels in the sustainability hierarchy framework

<table>
<thead>
<tr>
<th>Index aggregation level</th>
<th>Index</th>
<th>2000</th>
<th>BL-a</th>
<th>BL-b</th>
<th>AgBus-a</th>
<th>AgBus-b</th>
<th>Prot-a</th>
<th>Prot-b</th>
<th>Vege-a</th>
<th>Vege-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Issue</td>
<td>Food security impact</td>
<td>0.43</td>
<td>0.52</td>
<td>1.00</td>
<td>0.54</td>
<td>1.00</td>
<td>0.47</td>
<td>0.97</td>
<td>0.51</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Economic outcomes</td>
<td>0.57</td>
<td>0.58</td>
<td>0.58</td>
<td>0.50</td>
<td>0.50</td>
<td>0.56</td>
<td>0.56</td>
<td>0.57</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>Water Quality impact</td>
<td>0.61</td>
<td>0.55</td>
<td>0.56</td>
<td>0.92</td>
<td>1.00</td>
<td>0.18</td>
<td>0.18</td>
<td>0.44</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>Wildlife habitats impact</td>
<td>0.00</td>
<td>0.84</td>
<td>0.69</td>
<td>1.00</td>
<td>0.70</td>
<td>0.72</td>
<td>0.52</td>
<td>0.82</td>
<td>0.68</td>
</tr>
<tr>
<td>Dimension</td>
<td>Social</td>
<td>0.43</td>
<td>0.52</td>
<td>1.00</td>
<td>0.54</td>
<td>1.00</td>
<td>0.47</td>
<td>0.97</td>
<td>0.51</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>Economic</td>
<td>0.57</td>
<td>0.58</td>
<td>0.58</td>
<td>0.50</td>
<td>0.50</td>
<td>0.56</td>
<td>0.56</td>
<td>0.57</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>0.31</td>
<td>0.69</td>
<td>0.62</td>
<td>0.96</td>
<td>0.85</td>
<td>0.45</td>
<td>0.35</td>
<td>0.63</td>
<td>0.56</td>
</tr>
<tr>
<td>Goal</td>
<td>Outcomes Index*</td>
<td>0.43</td>
<td>0.60</td>
<td>0.73</td>
<td>0.67</td>
<td>0.78</td>
<td>0.50</td>
<td>0.63</td>
<td>0.57</td>
<td>0.71</td>
</tr>
</tbody>
</table>

* - higher values indicate higher adverse impacts on sustainability

Table 6.7 Relative Sustainability Index and Relative Benefits Index for different scenarios

<table>
<thead>
<tr>
<th>Index</th>
<th>2000</th>
<th>BL-a</th>
<th>BL-b</th>
<th>AgBus-a</th>
<th>AgBus-b</th>
<th>Prot-a</th>
<th>Prot-b</th>
<th>Vege-a</th>
<th>Vege-b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag output index (AOI)</td>
<td>0.41</td>
<td>0.70</td>
<td>0.70</td>
<td>1.00</td>
<td>0.98</td>
<td>0.56</td>
<td>0.56</td>
<td>0.83</td>
<td>0.82</td>
</tr>
<tr>
<td>Impacts Index'R' (II)</td>
<td>0.42</td>
<td>0.69</td>
<td>0.82</td>
<td>0.83</td>
<td>0.94</td>
<td>0.54</td>
<td>0.67</td>
<td>0.70</td>
<td>0.83</td>
</tr>
<tr>
<td>Relative Sustainability Index (RSI)</td>
<td>Weights** - 1 : 1</td>
<td>0.73</td>
<td>0.75</td>
<td>0.88</td>
<td>0.83</td>
<td>0.94</td>
<td>0.69</td>
<td>0.80</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>- 2 : 1</td>
<td>1.26</td>
<td>0.91</td>
<td>1.02</td>
<td>0.83</td>
<td>0.94</td>
<td>1.03</td>
<td>1.11</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>- 1 : 2</td>
<td>1.03</td>
<td>1.41</td>
<td>1.68</td>
<td>1.67</td>
<td>1.88</td>
<td>1.16</td>
<td>1.41</td>
<td>1.41</td>
</tr>
<tr>
<td>Relative Benefits Index (RBI)</td>
<td></td>
<td>1.07</td>
<td>0.73</td>
<td>1.44</td>
<td>1.10</td>
<td>1.25</td>
<td>0.60</td>
<td>1.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

* - higher values indicate higher adverse impacts on sustainability
** weights - ag output index : impacts index
due to water quality than due to wildlife habitats impacts. Water quality, in turn, was assessed using the criteria of nitrogen surplus. Thus, nitrogen surplus was identified as the chief factor affecting sustainability in the Agribusiness-b scenario. Similarly, in the Baseline-b scenario, it can be inferred that wildlife habitats was the main factor that affected sustainability. Thus, the aggregated indices provided a general indication of what was happening, without showing the complexities at the underlying levels; nevertheless, they can be used successfully in assessing performance of a system and sending out warning signals.

The Outcomes Index can also be used for comparison of alternatives with respect to their overall impacts on sustainability. Protectionist-a was the best alternative as it resulted in the least adverse impacts on the system. However, an analysis of the indices at the ‘dimension’ level indicated that this scenario does not fare equally well in the social and economic dimensions. On the other hand, the worst scenario, Agribusiness-b, was the best with respect to the economic dimension, but performed poorly with respect to the social and environmental dimensions. A similar analysis can be performed using indices at the issue level. It should be noted that the weights used for the Outcomes Index were equal for each dimension. Different stakeholder groups may assign varying importance to different dimensions of sustainability, which would result in significantly different interpretations of the outcomes of different scenarios. Thus these aggregated indices allow users to evaluate performance of a system at different levels, as well as allow comparison between different alternatives with respect to different criteria, issues and dimensions.

6.7.4 Relative Sustainability Index and Relative Benefits Index

The RSI, used for ranking different alternatives, is presented in Table 6.7, along with the II AOI and the RBI. Results for the RSI are presented for three sets of weights. Figure 6.6 shows the relation between agricultural output and impacts (environmental and economic) for all scenarios. In general, the impacts increased linearly with agricultural production. The RBI was highest for the vegebusiness-a scenario (Table 6.7). This indicates that the relative benefits of increases in agricultural production over its impacts were highest for the vegebusiness scenario. The benefits were, in general, less for those scenarios which did not preserve agricultural land.

Based on the RSI, the best alternative was protectionist-a when equal weights were given to both agricultural production and impacts. That is, deviations from the ideal values of benefits...
Figure 6.6 Trade-off relationship between agricultural output and its impacts
and costs of agricultural production were considered equally important. The second best alternative was the vegebusiness-a scenario. However, when deviation from agricultural production was weighted twice as highly as impacts, then the best scenario was vegebusiness-a followed by agribusiness-a. When impacts were weighted twice as highly as agricultural output, the best scenario was protectionist-a and, surprisingly, the second best rank was shared by the vegebusiness-a, baseline-a, and protectionist-b scenarios.

The sensitivity of RSI to different weights shows how the results of scenario evaluations can be affected by value judgments of people, which may differ very widely, and re-enforces the need for designing tools in a manner that facilitates the involvement of the public as well as other stakeholders in the debate for sustainability.

6.7.5 A Caution

Sustainable development issues are best monitored or assessed with a set of indicators that provides more insight and more accurate information than an aggregation of these indicators. On the other hand, it is acknowledged that the attempt to create and use a single index of sustainable development may be useful because it allows the complexity to be presented in a simple manner. However, it should be realized that the evaluation of alternatives on the basis of the OI or RSI is not an end to itself. While these indices are useful in making comparative evaluations of scenarios and their impacts on sustainability, they do not necessarily indicate that a particular alternative is more sustainable than the others. They only indicate the adverse impacts on sustainability with respect to the issues examined. Other issues (for example, institutional and technical) and criteria (for example, employment) that were not considered in the evaluation may change the results significantly. Another purpose of these indices is to send signals that encourage users to explore the underlying issues, which can be done through aggregated indices at other levels. It is only then that the tool can be really useful in identifying choices and formulating policies that may lead to a sustainable scenario.

6.8 Summary

This chapter discussed sustainability assessment of alternative scenarios through the use of sustainability indicators, cobwebs and indices. A hierarchical aggregation of indicators was used to generate three indices of sustainability which were used for sustainability assessment and comparison of different scenarios. Results showed that the overall impacts on
sustainability were the least in the protectionist scenario that preserves ALR. However, different preferences regarding the evaluation criteria change the rankings of the alternatives. The main advantage of the approach followed is that it makes the aggregation decisions transparent to the user. Also, it is flexible, which allows users to analyze and aggregate the multi-dimensional information as per their needs and understanding level of the issues.
7 Conclusions

In this chapter I first summarize the main conclusions related to the development of the model and its applications to the Lower Mainland, in the context of the objectives of the research. I then describe various ways in which the model is useful. I conclude by noting some future research requirements in the development of the model.

7.1 Development of the Model

Through this research project I have developed and used an integrated land-use and assessment model, AgFutures, for generation and exploration of plausible future agricultural scenarios in the Lower Mainland. The model describes the evolution of agricultural land-use as a result of not only biophysical conditions, but also socio-economic conditions, human behaviour and choices. It links the choices and consequences of changes in land-use policy, management practices, and lifestyle, with future spatial land-use patterns and their impacts on agricultural sustainability.

Instead of making predictions of likely future land-use changes, it relies on users to build 'desirable' scenarios of agriculture and explore the outcomes of their choices. This type of approach recognizes the fact that the evolution of systems as complex as land-use systems is surrounded by tremendous uncertainty in the future levels of the driving forces. It also avoids the uncertainty related to assumptions regarding people's preferences and response to impacts and changes in the environmental system. Rather, it provides users and decision makers with a means to explore how different choices and actions can affect the environmental systems and sustainability.

This integrated model employed different research approaches and tools based on different disciplinary backgrounds, and different scales of analysis for projecting and analysing land-use systems. The multi-scale modeling framework facilitates an integrated regional-level assessment of sustainability, without compromising on the spatial effects of factors operating at the local level. While the use of CA and MCDM techniques helped in integrating the social and physical dimensions of land-use change, remote sensing and GIS techniques aided in generating and organizing the spatial datasets used in the model. GIS also provided a platform to implement the CA model. Besides using natural science methods, the model also used the social science approach of involving stakeholders in the design of the model.
One of the objectives of the research was to develop a land-use simulation methodology that addresses multi-scale interactions between human and environmental systems. The methodology for the evolution of land-use changes (Chapter 4) used a CA-based approach to integrate different scale analyses. Macro-scale (regional) approaches are often criticized for their inadequate representation of local-scale factors and their interactions. On the other hand, micro-scale approaches, while addressing local processes, disregard the impact of factors operating at a coarser scale. A direct upscaling of these processes cannot be done due to issues of emergent properties. However, the methodology used for the evolution of land-use changes allowed for the integration of multi-scale analysis in order to assess regional land-use changes in an effective way. While macro-scale projections of land-use were based on trends and empirical relations between land-use and regional driving forces such as population and diet, the factors operating at local scales, such as neighbourhood effects and human decision-making related to land-use, were captured through the CA model. The CA-MCDM approach captured the trends and policies (for example, preservation of ALR) at the macro/regional level, and translated these into effects at the grid level that represent the behaviour of individuals or decision makers (in this case, farmers) in specific situations. It also included the effects of local factors, such as land suitability, effects of neighbouring land-uses, and proximity to infrastructure, in simulation of land-use changes. Thus the regional level assessment of land-use was a result of not only regional factors, but also of local factors that impinge on the development. This is in contrast to many integrated models (e.g. DICE (Nordhaus, 1992)) that operate at coarser scales and do not incorporate the effects of local factors.

Another objective was to address human decision-making processes adequately in the land-use model. The model considers these in several ways. First, it overtly considered human choices and preferences regarding agricultural development and lifestyles, and also assesses the impacts of policies on land-use systems. Second, it considered physical and socio-economic factors, such as population growth and proximity to markets and roads, which drive human decisions related to use of land. Third, it incorporated human decision-making in the simulation of land-use changes through the integration of CA and MCDM techniques. In Chapter 4, I described how the use of these techniques serves to recover and integrate user preferences regarding land-use development, through the transition rules of CA and the suitability evaluation procedure. However, the CA-MCDM approach, while useful for
addressing human decision-making through transition rules in the model, does not capture the full complexity, as it does not address the heterogeneity of decision-making over space. Multi-agent systems that consider heterogeneity in actors and interactions between them can better represent the realistic situations of land-use change (Parker et al., 2000).

Another objective was to develop methods for comparing scenarios for their impacts on sustainability. Towards this, AgFutures provided a scientific method for quantitative evaluation of alternative scenarios. Different indicators and indices were developed and used in the model, as described in Chapter 7. These included indicators of food security, water quality, wildlife habitats and economic outputs. Alternative scenarios were assessed against these indicators to identify what land-use choices and policies meet different criteria. A related sub-objective was to address issues related to the aggregation of indices and presentation of multi-dimensional information for sustainability assessment in a flexible and transparent framework to the user. The sustainability assessment method used in the model allows users to use different indicators or aggregate them at different levels. The framework used for presentation of multi-dimensional information caters to both novice users as well as to expert users. The model provides results in a variety of ways that allows users to select information to suit their needs. It also presents results for the various levels in the hierarchy defined for sustainability assessment. The results presented for the lowest level in the hierarchy cater to the needs of experts who wish to examine outcomes with respect to specific issues, while the results presented in an aggregated form at the highest level satisfy those users who wish to explore the outcomes through a single index. Generation of a single index also allows the model to be easily used by non-experts who may not have enough understanding of the specific issues to carry out a detailed trade-off analysis of the different indicators. Moreover, multiple indicators presented in the form of sustainability cobwebs allow easy visualization of impacts with respect to several issues at the same time, while also allowing for their comparisons with the target values.

7.2 Application of the Model

Eight scenarios were generated that were based on different land-use policy, diet, agricultural intensification, and agricultural management practices. Results indicated some important concerns related to impacts on future agricultural sustainability. Significant consequences of urban development on agriculture are expected if the ALR is not preserved. Almost 18% of the
ALR was lost to urban growth in the ‘b’ type scenarios, 43% of which were high capability prime agricultural land. In order to protect the small food land base and land productivity in the region, it appears necessary to continue to preserve the ALR in future.

One of the strengths of the model lies in its spatial forecasting of land-use changes, which reveals hot-spots of land-use changes. Simulation results showed that certain census subdivisions, such as Richmond, Delta, and Surrey are expected to experience more urban growth, resulting in the loss of prime agricultural land situated there. This suggests that in order to save agricultural lands more policies at the local/municipality level need to be formulated, which direct urban growth to non-prime lands in these areas, or regional policies may be required that encourage multi-nodal urban growth (development around regional town centres rather than core-centred which is presently assumed in the model).

Delta is expected to experience most of the greenhouse growth in future. Under the BL scenario nearly 60% of the total greenhouse area is situated in Delta in 2040. This again suggests that some policies or regulations may be required in this area to constrain greenhouse growth, if there is a desire to preserve the bird habitat there.

It was described in Chapter 7 how different choices and management interventions, represented by different scenarios, are expected to affect agricultural sustainability in the Lower Mainland. Results suggest that the N-surplus will increase by 50% over the 2000 value under agricultural intensification (agribusiness scenario). This is a result of increases in the livestock density, which cannot be left unregulated. On the other hand, societal shifts in diet, such as a 20% decrease in meat diets (vegebusiness scenario) would result in decreasing the N-surplus by 30%. Improved management practices, such as reducing fertilizer inputs by 25 percent and controlling the livestock density to maintain present levels, resulted in a decrease in the nitrogen surplus to 30 percent of the levels in 2000. However, this was associated with lower economic benefits.

Overall impacts on sustainability were minimum in the protectionist scenario, followed by the vege-business scenario. These results were obtained under specific assumptions in the model. In actual implementation of the model (i.e., in a community setting), the preferences and weights defined may alter the results significantly. Thus, defining which scenario is ‘sustainable’ is a subjective issue which is more a function of the perceptions and values of the
different stakeholder groups using the model. Also, it is worthwhile noting here that the results of the model should not be relied upon for predicting land-use changes on a cell by cell basis. Rather, the scenarios show regional patterns of land-use change and their impacts and should be viewed as a means of identifying policies and choices leading to non-sustainable patterns of development resulting from explicit choices made regarding future developments.

7.3 Final Words

The AgFutures model represents an initial step in the integrated assessment of future land-use options. It not only is useful for simulating the spatial patterns of land-use change, and quantifying and comparing the potential effects under different scenarios, but has several other uses in making a transition to sustainable development.

Policy support

As explained in the preceding section, the model can be used for understanding policy implications related to the preservation of the ALR. As well, it can help in development of land-use strategies and formulation of policy objectives.

Community engagement

The AgFutures model can be used by a wide range of users for exploring alternative futures of agriculture. The model provides a means for users to explore a wide range of futures based on different choices, in order to identify the choices and trade-offs that they are willing to accept. It helps users to understand what compromises need to be made between the desired goals of sustainability and the consequences assessed under a particular scenario. A large gap between the desired goals and the consequences will encourage users to rethink the choices made and the kind of future that is acceptable to them. It is explicitly built to support group decision-making and goal setting, by encouraging the creation of future scenarios that are desirable and acceptable to stakeholders. It also will help users to understand the impossibility of creating a scenario that addresses equally all of the values of different groups.

Transparency

It is necessary that the broader community participate in policy development. While formulation of policies is helpful to achieving sustainability in the area, real progress in this
direction can only be achieved in an environment where agricultural and non-agricultural communities work together. To this end, AgFutures can act as a tool that helps different communities to work together towards a common goal of sustainability. It can help consensus-building in the policy process, as it helps build an open and transparent relationship between the different stakeholder groups of these communities and raises awareness of issues that are relevant to different communities (e.g., economic viability of the sector, dependence on imported food, stewardship of resources).

Sustainability tool

When integrated with other sub-models in GB-QUEST, AgFutures will help to contribute to an integrated assessment of sustainability in the region, reflecting trans-disciplinary interactions and synergies with other sectors and issues like water quality and air pollution. The sustainability assessment of scenarios, based on selected indicators, could be part of a larger and holistic framework for sustainability measurement.

While AgFutures represents only a part of the complexity of land-use systems, it nevertheless provides the possibility of generating fruitful debates on sustainability in the community. Finally, it is recognized that priorities and policies recommended on the basis of AgFutures need a social and political will to turn this knowledge and know-how into actions for making the transition to a sustainable agriculture future.

7.4 Future Directions

AgFutures is a prototype model and there is much scope for improvement. In its present form, it considers only food production systems. In addition to food production, floriculture, nurseries and sod farms are important components of the agriculture in the Lower Mainland, which the model could address. The indicators suite can be expanded to include more social impacts such as employment, and wider impacts on the environment such as greenhouse gas emissions. There is a need to include an economic modeling component that examines how global factors such as commodity prices may impinge on land-use decisions.

An important future research area will be to address the biophysical feedbacks to land-use changes, which can affect sustainability significantly. For example, agricultural intensification may result in land degradation, which in turn would affect crop yields. This would affect
agricultural output and undermine its sustainability. Such feedback would help address complex two-sided interactions between the driving forces and outcomes of agriculture and, hopefully, would mean a more robust and reliable tool for assessing sustainability.

The analytical capability of the model can benefit from recent approaches in land-use modeling, such as agent-based approaches, which capture human decision-making complexities in a better way. Spatially-aware, agent-based CA models will help in addressing the spatial heterogeneity of transition rules (e.g., municipality by-laws, tenure conditions). More robust methods are required for defining the transition rules in the CA model that are presently based on experts’ opinions. Methods that integrate artificial intelligence approaches, such as neural networks which search for patterns in, and learn from, past land-use changes, may prove quite useful in this direction. Also, new techniques need to be developed that address efficiently the problems of calibration of CA models.
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Appendix I  Description of Spatial Data Sets

A description of different spatial layers (primary and derived) used in the study is presented in this appendix.

Land-cover

Source: Ministry of Environment, Land and Parks; Surveys and Resource Mapping Branch, Baseline Thematic Mapping

Original map scale/resolution: 1:250,000; 50m pixel (resampled from 30m pixel of Landsat data)

Year of creation: 1996

This layer describes different land-use/land-cover categories in the area as mapped from Landsat image data. Different categories represented are: agriculture, alpine, barren surfaces, estuaries, freshwater, glaciers and snow, mining, old forest, rangelands, recently burned, recently logged, recreation activities, residential and agriculture mixtures, saltwater, shrubs, urban, wetlands, young forest.

Land Capability

Source: Canada Land Inventory

Original map scale: 1:50,000

Year of creation: 1965-1980

This layer describes the land capability classification for agriculture (Table A1). The classification is based on climate, soil and landscape limitations with regard to the agricultural use and productivity for common field crops.

Digital Elevation Model

Source: Base Mapping and Geomatic Services, Ministry of Sustainable Resource Management, BC; LandData BC - TRIM

Original scale/resolution: 1:20,000 / 25 m cell size; Accuracy: 5m – vertical, 10m - horizontal

Year of creation: 1997

This layer contains elevation values for cells of size 25 m.
Census SubDivisions (CSD)

Source: Statistics Canada

Original scale/resolution: 1:50,000

Year of creation: 1996

This layer contains the census sub-division (CSD) boundaries. A CSD is defined, by Statistics Canada, as the municipality as determined by provincial legislation (such as city, town, village), or its equivalent (e.g. Indian reserve, Indian Settlement and unorganized territory). CSDs in the study area are shown in Figure 3.3.

Agricultural Land Reserve (ALR)

Source: Agricultural Land Commission, BC

Original scale: 1:50,000

Year of creation: N/A

This layer shows the ALR area.

0 - represents areas outside ALR

1 – Areas within ALR

Roads

Source: National Topographic Data Base, Geomatics Canada

Original map scale: 1:50,000

Year of creation: 1980 – 1994

This layer represents different types of roads including highways and paved roads

Towns/Cities

Source: National Topographic Data Base, Geomatics Canada

Original map scale: 1:250,000

Year of creation: 1980 – 1994

This layer represents location of major towns and cities.
Slope

This layer (grid) was generated from the DEM (25 m). Slope in degrees was calculated, and the grid was resampled to 100 meter resolution and classified into 7 slope categories as follows: 0-1; 1-2; 2-5; 5-10; 10-15; 15-30; > 30

Proximity to markets

A grid with distances from major towns (towns/cities layer) was generated with a cell size of 100m. The distance grid was then reclassified into 5 categories as follows: 0-10; 10-20; 20-30; 30-40; >40 km.

Proximity to Roads

Class 1 and 2 roads were selected from the National Topographic Database 1:50K coverage. A grid with distances from these roads was generated and then reclassified as follows: 0-5; 5-10; 10-20; 20-40; >40 km.

Land price

Land prices were not available for all CSDs. So this information was supplemented by considering distance of a cell from Vancouver. Land prices are assumed to decrease with increasing distance from Vancouver city. A grid was generated consisting of 5 land price zones based on these two datasets: Very high; high; moderate; low; very low.

Relative proportion of land-use

This factor was used as surrogate for climate factor. It is assumed that higher areas for any operation represent higher climatic suitability for that operation. The area of CSD under a particular operation (e.g. greenhouse), obtained from 2001 census of agriculture, is normalized with respect to the maximum area of any CSD under that operation (i.e. greenhouse) and percent values are represented in the grid. As a result, all the cells in a CSD have the same value.
Table A1: Land capability classes for agriculture in BC

<table>
<thead>
<tr>
<th>Attribute value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Class 1</strong>&lt;br&gt;Class 1 land is capable of producing the very widest range of crops. Soil and climate conditions are optimum, resulting in easy management.</td>
</tr>
<tr>
<td>2</td>
<td><strong>Class 2</strong>&lt;br&gt;Class 2 land is capable of producing a wide range of crops. Minor restrictions of soil or climate may reduce capability but pose no major difficulties in management.</td>
</tr>
<tr>
<td>3</td>
<td><strong>Class 3</strong>&lt;br&gt;Class 3 land is capable of producing a fairly wide range of crops under good management practices. Soil and/or climate limitations are somewhat restrictive.</td>
</tr>
<tr>
<td>4</td>
<td><strong>Class 4</strong>&lt;br&gt;Class 4 land is capable of a restricted range of crops. Soil and climate conditions require special management considerations.</td>
</tr>
<tr>
<td>5</td>
<td><strong>Class 5</strong>&lt;br&gt;Class 5 land is capable of production of cultivated perennial forage crops and specially adapted crops. Soil and/or climate conditions severely limit capability.</td>
</tr>
<tr>
<td>6</td>
<td><strong>Class 6</strong>&lt;br&gt;Class 6 land is important in its natural state as grazing land. These lands cannot be cultivated due to soil and/or climate limitations.</td>
</tr>
<tr>
<td>7</td>
<td><strong>Class 7</strong>&lt;br&gt;Class 7 land has no capability for soil bound agriculture.</td>
</tr>
<tr>
<td>8</td>
<td><strong>Class 8</strong>&lt;br&gt;Class 8 represents unclassified areas (e.g., water, forest reserves, urban areas, national parks)</td>
</tr>
<tr>
<td>9</td>
<td><strong>Class 0</strong>&lt;br&gt;Class 0 represents organic soils (not placed in capability classes)</td>
</tr>
</tbody>
</table>

Source: Provincial Agricultural Land Commission
(http://www.alc.gov.bc.ca/alr/Ag_Capability.htm)
Appendix II  Scores of Suitability and Rules for Transition

In this appendix, scores of suitability assigned to different factors and translation of neighbourhood rules to scores are presented for urban and agricultural uses.

A. Urban Use

1. Land price

<table>
<thead>
<tr>
<th>Value</th>
<th>Price Zone</th>
<th>Score</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Very high</td>
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</tr>
<tr>
<td>2</td>
<td>Moderately High</td>
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</tr>
<tr>
<td>3</td>
<td>High</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>10</td>
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</table>

2. Proximity to core centre

<table>
<thead>
<tr>
<th>Value</th>
<th>Distance (km)</th>
<th>Score</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>2</td>
<td>20-40</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>40-60</td>
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</tr>
<tr>
<td>4</td>
<td>60-80</td>
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<tr>
<td>5</td>
<td>&gt; 80</td>
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3. Proximity to towns

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<th>Value</th>
<th>Distance (km)</th>
<th>Score</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0-5</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>5-10</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>10-15</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>15-20</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>20-30</td>
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</tr>
<tr>
<td>6</td>
<td>&gt; 30</td>
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</table>
4. Proximity to major roads

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</thead>
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<tr>
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<td>10</td>
</tr>
<tr>
<td>2</td>
<td>5-10</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>10-20</td>
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</tr>
<tr>
<td>4</td>
<td>20-40</td>
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</table>

5. Slope

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<td>-10</td>
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<tr>
<td>7</td>
<td>-10</td>
</tr>
</tbody>
</table>

6. Neighbouring land-use effects

<table>
<thead>
<tr>
<th>Neighbouring land-use</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>10</td>
</tr>
<tr>
<td>Built-up</td>
<td>5</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
</tr>
</tbody>
</table>
B. Agricultural uses

1. Land capability

<table>
<thead>
<tr>
<th>Land Capability</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Food crops</td>
</tr>
<tr>
<td>1</td>
<td>+10</td>
</tr>
<tr>
<td>2</td>
<td>+9</td>
</tr>
<tr>
<td>3</td>
<td>+8</td>
</tr>
<tr>
<td>4</td>
<td>+5</td>
</tr>
<tr>
<td>5</td>
<td>-5</td>
</tr>
<tr>
<td>6</td>
<td>-10</td>
</tr>
<tr>
<td>7</td>
<td>-10</td>
</tr>
<tr>
<td>8</td>
<td>-10</td>
</tr>
<tr>
<td>9</td>
<td>+10</td>
</tr>
</tbody>
</table>

2. Slope

<table>
<thead>
<tr>
<th>Slope Category</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Food crops</td>
</tr>
<tr>
<td>1</td>
<td>+10</td>
</tr>
<tr>
<td>2</td>
<td>+8</td>
</tr>
<tr>
<td>3</td>
<td>+5</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-10</td>
</tr>
<tr>
<td>6</td>
<td>-10</td>
</tr>
<tr>
<td>7</td>
<td>-10</td>
</tr>
</tbody>
</table>

3. Climate suitability

<table>
<thead>
<tr>
<th>CSD Name</th>
<th>Food crops</th>
<th>Greenhouses</th>
<th>Livestock crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>FVRD - Subd. A</td>
<td>4</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>FVRD - Subd. B</td>
<td>4</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Abbotsford</td>
<td>5</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Mission</td>
<td>5</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>FVRD - Subd. E</td>
<td>5</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>Langley</td>
<td>7</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Surrey</td>
<td>6</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Delta</td>
<td>10</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Richmond</td>
<td>10</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Vancouver</td>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Burnaby</td>
<td>9</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>GVRD Subd. A</td>
<td>6</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Pitt Meadows</td>
<td>8</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Maple Ridge</td>
<td>6</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>
4. Land price

<table>
<thead>
<tr>
<th>Value</th>
<th>Price Zone</th>
<th>Score – agri use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Very high</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Moderately High</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>Moderate</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>10</td>
</tr>
</tbody>
</table>

5. Proximity to markets

<table>
<thead>
<tr>
<th>Value</th>
<th>Distance (km)</th>
<th>Score – agri use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>10-20</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>20-30</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>30-40</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 40</td>
<td>0</td>
</tr>
</tbody>
</table>

6. Proximity to Roads

<table>
<thead>
<tr>
<th>Value</th>
<th>Distance (km)</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-5</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>5-10</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>10-20</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>20-40</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 40</td>
<td>0</td>
</tr>
</tbody>
</table>

7. Land-use conversion costs

<table>
<thead>
<tr>
<th>Land-use Class</th>
<th>Score</th>
<th>Food crops</th>
<th>Greenhouses</th>
<th>Livestock crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food Crops</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hay/Forage crops</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Pasture</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Greenhouse</td>
<td>-10</td>
<td>10</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Idle farms</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Natural pasture</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Urban</td>
<td>-10</td>
<td>-10</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Forest/Natural</td>
<td>-5</td>
<td>-5</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>Other (water, snow, rocky areas)</td>
<td>-10</td>
<td>-10</td>
<td>-10</td>
<td></td>
</tr>
</tbody>
</table>
8. Neighbouring land-use effect

<table>
<thead>
<tr>
<th>Land-use of neighbouring cell</th>
<th>Food crops</th>
<th>Greenhouses</th>
<th>Livestock crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food Crops</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Hay/Forage crops</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Pasture</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Greenhouse</td>
<td>7</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>Idle farms</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Natural pasture</td>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Urban</td>
<td>-5</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>Forest/Natural</td>
<td>-5</td>
<td>-5</td>
<td>0</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Appendix III AML for CA-MCDM Based Spatial Simulation of Land-use Changes

/***************************************************************************/
/* AML for spatial allocation using CA-MCDM approach*/
/***************************************************************************/

/* Set Workspace */
&setvar ws = [response 'Enter workspace']
workspace %ws%
/* Initial land-use info for 2000 */
&setvar FCNumPre = [response 'Enter No. of foodcrop cells in previous decade ']
&setvar GHNumPre = [response 'Enter No. of gh cells in previous decade ']
&setvar LSNumPre = [response 'Enter No. of livestock cells in previous decade ']

/* Grid operations */
grid
/* Initialize */
FCInit = scalar(0)
GHInit = scalar(0)
LSInit = scalar(0)
FCNum = scalar(0)
GHNum = scalar(0)
LSNum = scalar(0)
FCChng = scalar(0)
GHChng = scalar(0)
LSChng = scalar(0)

FCInit = scalar(%FCNumPre%)
ghInit = scalar(%ghNumPre%)
lsInit = scalar(%lsNumPre%)

/* Set up a loop for four decades */
&setvar index = 0
&do &until %index% eq 3
   &setvar index = %index% + 1

/* Get Input and output Grids for GB - Urban conversions are modelled for Georgia Basin */
&setvar GBingrid = [response 'Enter input GB Grid name for decade %index% ']
&setvar GBOutgrid = [response 'enter output GB grid name for decade %index% ']
&setvar NI = [response 'Enter No. of additional cells to be converted to urban in decade %index% ']
&setvar pres = [response 'Preserve ALR? 1 - yes; 0 - No']

/* Get Input and output Grids for Lower Mainland - Ag conversions */
&setvar ingrid = [response 'Enter LM land-use input Grid name for decade %index% ']
&setvar Outgrid = [response 'enter LM output grid name for decade %index% ']

/* Get number of cells in each category for this decade and previous decade */
&setvar FCNumDec = [response 'Enter No. of cells to be converted to Food crops in decade %index% ']

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&setvar GHNumDec = [response 'Enter No. of cells to be converted to Greenhouse in decade '%index%'']
&setvar LSNumDec = [response 'Enter No. of cells to be converted to ALL Livestock in decade '%index%'']

setwindow %GBingrid%
setcell 100
&if [exists %GBoutgrid% -grid] &then
  kill %GBoutgrid% all
&if [exists gbin -grid] &then
  kill gbin all
&if [exists lmin -grid] &then
  kill lmin all

&if [exists %outgrid% -grid] &then
  kill %outgrid% all
&if [exists lunew -grid] &then
  kill lunew all

copy %GBingrid% gbin
copy %ingrid% lmin

/* Calculate yearly change
FCChng = scalar(int((%FCNumDec% - FCInit) div 10))
GHChng = scalar(int((%GHNumDec% - GHInit) div 10))
LSChng = scalar(int((%LSNumDec% - LSInit) div 10))

&if [exists gbouturb -grid] &then
  kill gbouturb all
&if [exists urbscrl -grid] &then
  kill urbscrl all
&if [exists urnbmeanl -grid] &then
  kill urnbmeanl all
&if [exists urbsuit_l -grid] &then

/*@@@@@@@@@@@@@@@@@@@@@@@@@@@Model Conversions@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
kill urbsuit_l all
&if [exists urbprob_l -grid] &then
  kill urbprob_l all
&if [exists urbprob_l -grid] &then
  kill urbprob_l all
&if [exists urbproclasl -grid] &then
  kill urbproclasl all
&if [exists urbsuit_d1 -grid] &then
  kill urbsuit_d1 all
&if [exists urbsuitclsl -grid] &then
  kill urbsuitclsl all
&if [exists urbconst-1 -grid] &then
  kill urbconst-1 all
&if [exists urblandcon -grid] &then
  kill urblandcon all
&if [exists urbdec -grid] &then
  kill urbdec all
&if [exists UrbLuscrl -grid] &then
  kill UrbLuscrl all

/* Determine land-use constraints for urban growth (all built-up (also contains rec), water, snow = 0; rest = 1)
/*Multiply this by slope constraint (>4 class), and protected areas (green)
urblandcon = reclass (gbin.value, landconstn.txt)
If(%pres% eq 1) urbconst-1 = urblandcon.value * urbslpcon.value *
green_rcls.value * alr-rcls.value
else urbconst-1 = urblandcon.value * urbslpcon.value * green_rcls.value

/* Assign Neighbourhood scores */
urbnbclsl = focalmean(urbscrl, rectangle, 3, 3, data)
/*UrbLuscrl = reclass (%InGrid%.value, UrbLuscr.txt)

/ * Determine Urban composite suitability for decade 1
urbsuit_l = urbnbmeanl.value * 0.173 + slpcls7.urbscore * 0.147 +
coreprox.urbscore * 0.234 + townrecls.urbscore * 0.187 +
roadsprox.agriscore * 0.087 + coreprox.price * 0.173

/* Determine probability of conversion to urban use
suitmax = scalar(0)
TotCells = scalar(0)
Numclasses = scalar(0)
docell
if (not isnull(gbin))
{
  suitmax }= urbsuit_l
Totcells += 1
}
end
urbprob_l = exp(l * ((urbsuit_l div suitmax) - 1))
urbprob_l = urbprob_l * urbconst-1

/*
/*Check if probability is greater than a random number
&if [exists urbprob -grid] &then
  kill urbprob all
&if [exists random -grid] &then
  kill random all

random = rand()
if (urbprob_l gt random) urbprob = urbprob_l
else urbprob = 0
endif

/* Determine number of classes to reclassify probability values */
/* (based on number of cells that need to be converted to urban for the decade, */
/* quantile, equal area) */
Numtemp = scalar(\%N1\% / (10 * Totcells))
NumClasses = scalar(int(1 / Numtemp))
urbprclasl = slice(urbprob.value, eqarea, [show scalar Numclasses],1, #, #)

/* Assign the topmost probability class to converted-to-urban for the decade */
if (urbprclasl eq [show scalar Numclasses]) urbdec = 1
else urbdec = 2
endif

/* Create NEW Land-use for the Decade */
if (urbdec eq 1) gbouturb = 13
else gbouturb = gbin
endif

&type 'Urban conversion completed.................................'

 /***************************************************************************/
/* Agricultural Conversions */
/***************************************************************************/

/* Grid operations */
setwindow lmin

/* Calculate number of fc cells for this iteration */
FCNum = scalar(FCInit + FCchng)
GHNum = scalar(GHInit + GHChng)
LSNum = scalar(LSInit + LSChng)

show fcnum
show ghnum
show lsnnum

&if [exists Agrilccon -grid] &then
  kill Agrilccon all
&if [exists Agriconst -grid] &then
  kill Agriconst all
&if [exists Agriconst-1 -grid] &then
  kill Agriconst-1 all
&if [exists FCLuscr -grid] &then
  kill FCLuscr all
&if [exists LSLuscr -grid] &then
  kill LSLuscr all
&if [exists ghluscr -grid] &then
kill ghluscr all

@if [exists FCscr -grid] &then
    kill FCscr all
@if [exists LSscr -grid] &then
    kill LSscr all
@if [exists ghscr -grid] &then
    kill ghscr all
@if [exists fcnbmeanl -grid] &then
    kill fcnbmeanl all
@if [exists lsnbmeanl -grid] &then
    kill lsnbmeanl all
@if [exists ghnbmeanl -grid] &then
    kill ghnbmeanl all
@if [exists fcsuit -grid] &then
    kill fcsuit all
@if [exists ghsuit -grid] &then
    kill ghsuit all
@if [exists lssuit -grid] &then
    kill lssuit all
@if [exists lunew -grid] &then
    kill lunew all

if (not isnull(lmin))
    if (gbouturb eq 13) lunew = 13
    else lunew = lmin
endif

@if [exists ghtt -grid] &then
    kill ghtt all

/* Retain original gh cells */
if(lunew eq 4) ghtt = 1
else ghtt = 0

countghtt = scalar(0)
docell
    countghtt += ghtt
end.
show countghtt

/* Determine landcover(lc) constraints for Agri growth (all built up, water, snow = 0; rest = 1; new urban class 13 = 0) */
/* Multiply this by slope constraint (>5 class), and protected areas (green) */
Agrilccon = reclass(lunew.value, landconstn.txt)
Agriconst = Agrilccon.value * Agslpcon.value * green_rcls.value * aoi

/* Assign Land-use conversion cost rules - scores from respective ascii files */
FCLuscr = reclass(lunew.value, FCLuscrn.txt)
LSLuscr = reclass(lunew.value, LSLuscrn.txt)
GhLuscr = reclass(lunew.value, GhLuscrn.txt)

/* Assign Neighbourhood scores */
FCscr = reclass (lunew.value, FCscrn.txt)
LSscr = reclass (lunew.value, LSscrn.txt)
Ghscr = reclass (lunew.value, Ghscrn.txt)
FCnbmeanl = focalmean(FCscr, rectangle, 3, 3, data)
LSnbmeanl = focalmean(LSscr, rectangle, 3, 3, data)
GHnbmeanl = focalmean(GHscr, rectangle, 3, 3, data)

/* Determine Agricultural composite suitability for three categories */
FCsuit = (FCLuscr.value * 0.170 + FCnbmeanl.value * 0.065 + slpcls7.crpscore * 0.126 + soill_cap.crpscore * 0.162 +
urbprox.agriscore * 0.117 + coreprox.cropscore * 0.123 + roadsprox.agriscore * 0.083 + csd.crpscrnew * 0.152)
GHSuit = (GHLuscr.value * 0.164 + GHnbmeanl.value * 0.050 + slpcls7.ghscore * 0.163 + soill_cap.ghscore * 0.061 +
urbprox.agriscore * 0.138 + coreprox.cropscore * 0.108 + roadsprox.agriscore * 0.095 + csd.ghscore * 0.220)
LSSuit = (LSLuscr.value * 0.158 + LSnbnmeanl.value * 0.102 + slpcls7.lvscore * 0.133 + soill_cap.lvscore * 0.145 +
urbprox.agriscore * 0.079 + coreprox.cropscore * 0.184 + roadsprox.agriscore * 0.079 + csd.lvscrnw * 0.119)

/* Determine probability of conversion */

/* Determine max suitability */

fcsuitmax = scalar(0)
ghsuitmax = scalar(0)
lssuitmax = scalar(0)
fcsuitmin = scalar(0)
ghsuitmin = scalar(0)
lssuitmin = scalar(0)

TotCells = scalar(0)
&if [exists newgrid -grid] &then
   kill newgrid all
newgrid = lunew * aoi
docell
   if (not isnull(newgrid))
      { fcsuitmax = fcsuit
ghsuitmax = ghsuit
lssuitmax = lssuit
fcsuitmin = fcsuit
ghsuitmin = ghsuit
lssuitmin = lssuit }
   Totcells += 1
end

show totcells
show fcsuitmax
show ghsuitmax
show lssuitmax

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/* Compute probability and add stochasticity */
Sif [exists FCrand -grid] Sthen
kill FCrand all
Sif [exists ghrand -grid] Sthen
kill ghrand all
Sif [exists lsrand -grid] Sthen
kill lsrand all
fcrand = rand()
ghrand = rand()
lsrand = .rand()
Sif [exists FCstsuit -grid] Sthen
kill FCstsuit all
Sif [exists ghstsuit -grid] Sthen
kill ghstsuit all
Sif [exists lsstsuit -grid] Sthen
kill lsstsuit all
Sif [exists fcprob -grid] Sthen
kill fcprob all
Sif [exists ghprob -grid] Sthen
kill ghprob all
Sif [exists lsprob -grid] Sthen
kill lsprob all
/* Exclude gh cells (lmin or lunew = 4) from conversion */
fcsuit = (exp( 1 * ((fcsuit div fcsuitmax) -1))) * agriconst
if (lunew ne 4 and fcsuit gt fcrand ) fcprob = fcstsuit
else fcprob = 0
endif
ghsuit = (exp( 1 * ((ghsuit div ghsuitmax) -1))) * agriconst
if (lunew ne 4 and ghsuit gt ghrand ) ghprob = ghstsuit + (ghrand / 10)
else ghprob = 0
endif
lssuit = (exp( 1 * ( (lssuit div lssuitmax) - 1))) * agriconst
if (lunew ne 4 and lssuit gt lsrand ) lsprob = lsstsuit
else lsprob = 0
endif
/* Compare probabilities and determine areas suitable for fc, gh and ls conversions. */
/* Determine number of classes to reclassify the probability values */
/* (based on number of cells that need to be converted to diff uses for */
/* the decade, quantile, equal area) */
NumFccls = scalar(0)
NumGhcls = scalar(0)
NumLscls = scalar(0)
lstemp = scalar((lsnum) / Totcells)
ghtemp = scalar((ghnum - countghtt) / Totcells)
fctemp = scalar((fcnum) / Totcells)
Numlscls = scalar(int(1 / lstemp) + 1)
Numghcls = scalar(int(1 / ghtemp))
Numfccls = scalar(int(1 / fctemp))
show totcells
show numfcccls
show numghcls
show numlscls
@if [exists lsprclasl -grid] &then
  kill lsprclasl all
@if [exists ghprclasl -grid] &then
  kill ghprclasl all
@if [exists fcprclasl -grid] &then
  kill fcprclasl all
lsprclasl = slice(lsprob.value, eqarea, [show scalar Numlscls],1, #, #)
ghprclasl = slice(ghprob.value, eqarea, [show scalar Numghcls],1, #, #)
fprclasl = slice(fcprob.value, eqarea, [show scalar Numfccls],1, #, #)

/* Assign the topmost probability class to the use for the decade */
@if [exists lsdecl -grid] &then
  kill lsdecl all
@if [exists ghdecl -grid] &then
  kill ghdecl all
@if [exists fcdecl -grid] &then
  kill fcdecl all
if ((fcprclasl eq [show scalar Numfccls]) and (fcprob gt 0.6)) fcdecl = 1
else fcdecl = 0
endif
if ((ghprclasl eq [show scalar Numghcls]) and (ghprob gt 0.77)) ghdecl = 1
else ghdecl = 0
endif
if ((lsprclasl eq [show scalar Numlscls]) and (lsprob gt 0.6)) lsdecl = 1
else lsdecl = 0
endif

 /*************************************************************************************/
/** Find cells that are converted to more than one use; Resolve conflict */
/*************************************************************************************/
@if [exists temp -grid] &then
  kill temp all
@if [exists ls -grid] &then
  kill ls all
@if [exists gh -grid] &then
  kill gh all
@if [exists fc -grid] &then
  kill fc all
@if [exists lst -grid] &then
  kill lst all
@if [exists ght -grid] &then
  kill ght all
@if [exists fct -grid] &then
  kill fct all
@if [exists confarea -grid] &then
  kill confarea all

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/ * Allocate remaining gh change  
  ght = ghdecl  
  if (ght eq 0) temp = fcdecl + lsdecl  
  else temp = 0  
    if (temp gt 1) confarea = 1  
    else confarea = 0  
  /* Allocation of non-conflict areas  
  if (confarea eq 0 and ght eq 0 )  
  
  /*ght = ghdecl  
  1st = lsdecl  
  }  
  else  
  
  fct = 0  
  /*ght = 0  
  lst = 0  
  
  temp0 = fct + ght + lst  
  countfct = scalar(0)  
  countght = scalar(0)  
  countlst = scalar(0)  
  
  docell  
  countfct += fct  
  countght += ght  
  countlst += lst  
  end  
  show countfct  
  show countght  
  show countlst  
  
  /*///******* Conflict Resolving************///*/  
  /* upos returns the ingrid position (number) which has the max value of the  
  3 grids.  
  /* Grids are then generated for Areas suitable for conversion to a use  
  (value = 1)  
  
  &if [exists srank -grid] &then  
    kill srank all  
  &if [exists fcrarea -grid] &then  
    kill fcrarea all  
  &if [exists gharea -grid] &then  
    kill gharea all  
  &if [exists lsarea -grid] &then  
    kill lsarea all  
  &if [exists tempprob -grid] &then  
    kill tempprob all  
  tempprob = fcprob + ghprob + lsprob  
  if(agriconst ne 0 and tempprob ne 0) srank = upos(fcprob, ghprob, lsprob)  
  else srank = 0
/*fcrarea = test(srank, 'value eq 1')
/*gharea = test(srank, 'value eq 2')
/*lsarea = test(srank, 'value eq 3')

@if [exists allocfc -grid] &then
  kill allocfc all
@if [exists allocgh -grid] &then
  kill allocgh all
@if [exists allocls -grid] &then
  kill allocls all
@if [exists allocfc2 -grid] &then
  kill allocfc2 all
@if [exists allocgh2 -grid] &then
  kill allocgh2 all
@if [exists allocls2 -grid] &then
  kill allocls2 all
@if [exists allocfc3 -grid] &then
  kill allocfc3 all
@if [exists allocgh3 -grid] &then
  kill allocgh3 all
@if [exists allocls3 -grid] &then
  kill allocls3 all
@if [exists allocfc4 -grid] &then
  kill allocfc4 all
@if [exists allocgh4 -grid] &then
  kill allocgh4 all
@if [exists allocls4 -grid] &then
  kill allocls4 all
@if [exists allocfc5 -grid] &then
  kill allocfc5 all
@if [exists allocgh5 -grid] &then
  kill allocgh5 all
@if [exists allocls5 -grid] &then
  kill allocls5 all

docell
  if ((countfct lt fcnum) and (confarea eq 1 & srank eq 1))
  {
    allocfc = 1
    countfct += 1
  }
  else allocfc = 0

  /*if ((countght lt (ghnum - countghtt)) and (confarea eq 1 & srank eq 2))
/*{
/*  allocgh = 1
/*  countght += 1
/*}
/*else allocgh = 0

  if ((countlst lt lsnum) and (confarea eq 1 & srank eq 3))
  {
    allocls = 1
    countlst += 1
  }
  else allocls = 0
end

templ = temp0 + allocfc + allocls
/***** Allocation of remaining cells****************************

/* Iteration 1 ..........................

docell
if ((countfct lt fcnum) and (temp1 eq 0 and fcprob gt 0.78 and srank eq 1 ))
{
allocfc2 = 1
countfct += 1
}
else allocfc2 = 0

if ((countght lt (ghnum - countghtt)) and (temp1 eq 0 and ghprob gt 0.85 and srank eq 2 ))
{
allocgh2 = 1
countght += 1
}
else allocgh2 = 0

if ((countlst lt lstnum) and (temp1 eq 0 and lsprob gt 0.75 and srank eq 3 ))
{
alloccls2 = 1
countlst += 1
}
else alloccls2 = 0
end
temp2 = temp1 + allocfc2 + allocgh2 + alloccls2

/* Iteration 2..........................

docell

if ((countght lt (ghnum - countghtt)) and (temp2 eq 0 and ghprob gt .842 ))
{
allocgh3 = 1
countght += 1
}
else allocgh3 = 0

if ((countlst lt lstnum) and (temp2 eq 0 and allocgh3 eq 0 and lsprob gt .68 ))
{
alloccls3 = 1
countlst += 1
}
else alloccls3 = 0

if ((countfct lt fcnum) and (temp2 eq 0 and allocgh3 eq 0 and alloccls3 eq 0 and fcprob gt .7 ))
{
allocfc3 = 1
countfct += 1
}
else allocfc3 = 0
end
temp3 = temp2 + allocfc3 + allocgh3 + allocls3

/* Iteration 3.................................

docell

if (((countght lt (ghnum - countghtt)) and (temp3 eq 0 and ghprob gt .8 ))
{
    allocgh4 = 1
    countght += 1
}
else allocgh4 = 0

if (((countfct lt fcnum) and (temp3 eq 0 and allocgh4 eq 0 and fcprob gt .7
and srank eq 1 ))
{
    allocfc4 = 1
    countfct += 1
}
else allocfc4 = 0

if (((countlst lt lsnum) and (temp3 eq 0 and allocgh4 eq 0 and lsprob gt .6
and srank eq 3 ))
{
    allocls4 = 1
    countlst += 1
}
else allocls4 = 0
end

/* Iteration 4.................................

docell

if (((countght lt (ghnum - countghtt)) and (temp4 eq 0 and ghprob gt 0.77))
{
    allocgh5 = 1
    countght += 1
}
else allocgh5 = 0
if (((countlst lt lsnum) and (temp4 eq 0 and allocgh5 eq 0 and lsprob gt 0.6 ))
{
    allocls5 = 1
    countlst += 1
}
else allocls5 = 0
if (((countfct lt fcnum) and (temp4 eq 0 and allocgh5 eq 0 and allocls5 eq 0
and fcprob gt 0.6 ))
{
    allocfc5 = 1
    countfct += 1
}
else allocfc5 = 0
end
kill temp all
kill temp0 all
kill temp1 all
kill temp2 all
kill temp3 all
kill temp4 all

show countfct
show countght
show countlst

fc = fct + allocfc + allocfc2 + allocfc3 + allocfc4 + allocfc5
gh = ghtt + ght + allocgh2 + allocgh3 + allocgh4 + allocgh5
ls = lst + allocls + allocls2 + allocls3 + allocls4 + allocls5

/*****************************************************************/
/************************* update land
-use tnap********************

/* Update new allocations for fc, gh, and ls***************
Sif [exists lutemp -grid] Sthen
kill lutemp all
if (fc eq 1) lutemp = 1
else if (gh eq 1) lutemp = 4
else if (ls eq 1) lutemp = 2
else if (ls eq 0 and lunew eq 6) lutemp = 8
else lutemp = lunew
endif

/* Convert all remaining previous uses to fallow or appropriate category:*/
/* If land-use was fc, ls or pasture it converts to idle/fallow*/
/* category; if gh then it converts to Other category; if Natural PAsture/Shrub then it converts to Natural (trees)*/

Sif [exists tst -grid] Sthen
kill tst all
Sif [exists luse -grid] sthen
kill luse all

tst = fc + gh + ls
if(tst eq 0 and (lunew ge 1 and lunew le 3)) luse = 5
else if (tst eq 0 and lunew eq 6) luse = 5
else if (tst eq 0 and (lunew eq 4)) luse = 12
/* Following statement was used for allocations for 2000 only*/
/*else if (tst eq 0 and %ingrid% eq 6) luse = 8*/
else luse = lutemp
endif

Sif [exists agluse -grid] &then
kill agluse all

if(aoi-rcls eq 1) agluse = luse
else agluse = lunew
endif

kill lmin all
lmin = agluse
FCInit = scalar(countfct)
GHInit = scalar(countght + countghtt)
LSInit = scalar(countlst)
show fcinit
show ghinit
show lsinit

setwindow gbin
kill gbin all
gbin = gbouturb

&end

/**************************Outputs for the decade**************************
/* Save output grids for the decade
%GBoutgrid% = gbin

setwindow lmin
&if [exists lmout -grid] &then
    kill lmout all
/* Update categories within ls crops i.e hay, pasture and
/* natural pasture from original input grid; category 20 = new ls cells
if (lmin eq 2 and %ingrid% eq 2) lmout = 2
else if (lmin eq 2 and %ingrid% eq 3) lmout = 3
else if (lmin eq 2 and %ingrid% eq 6) lmout = 6
else if (lmin eq 2) lmout = 20
else lmout = lmin
endif
%outgrid% = lmout

&end
&return