Integrated modeling for exploring sustainable agriculture futures

Tara Sharmaa,*, Jeff Carmichaelb, Brian Klinkenberga

aDepartment of Geography, University of British Columbia, 1984 West Mall, Vancouver, BC, Canada V6T 1Z2
bSustainable Development Research Initiative, University of British Columbia, 1924 West Mall,
Vancouver, BC, Canada V6T 1Z2
Available online 10 August 2005

Abstract

Sustainable agriculture meets human needs for food, enhances the quality of life of people, protects the integrity of natural systems, and is economically profitable. Making a transition to agricultural sustainability involves difficult choices and an understanding of the complex trade-offs associated with different agricultural pathways. In this paper, we describe the development and application of a decision support tool—AgFutures—for exploring alternative futures for agricultural sustainability in the Lower Mainland of British Columbia. The main core of the model is simulation of future land-use changes in different scenarios and assessment of social, economic and environmental consequences under these scenarios. Evolution of land-use is simulated as a result of not only biophysical conditions but also as a result of human behaviour and choices, specifically related to lifestyle, agricultural management practices and institutional policies. Eight different scenarios are generated and compared for their impacts on sustainability in the Lower Mainland.

AgFutures helps users to identify desirable future scenarios and the set of choices and trade-offs that they are willing to accept. Identification of these allows decision-makers to formulate policies that would lead to achieving the goals of sustainable agriculture. The novel aspect of this model lies in its design and methods, which represent a balance between the need for rigour and the need for a tool that can be used by a wide array of users.

© 2005 Elsevier Ltd. All rights reserved.
1. Introduction

1.1. Agriculture and sustainability in the Lower Mainland

The Lower Mainland of British Columbia (Fig. 1), comprising two regional districts—the Greater Vancouver and the Fraser Valley—covers an area of almost 17,000 km², 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. It is one of the most agriculturally productive areas in Canada, with excellent soil and climate conditions for agriculture and it is the province’s most concentrated farming region, having over 5500 farms covering an area of 88,405 ha. Around 128,000 ha of land are protected as provincially designated agricultural land reserve (ALR) in the Lower Mainland, which represents less than 3% of the total provincial ALR. The ALR Act ensures that the best land suited to agriculture is not developed or used for other purposes and, therefore, provides some guarantee that it is available for food production for future generations [12]. Despite occupying a relatively small proportion of farmland in BC, the Lower Mainland accounted for about 62% of BC’s gross farm receipts in 2001, amounting to over 1.4 billion Canadian dollars [13].

Agriculture here is distinguished by its diversity; more than 80 different commodities are produced. Berries, vegetables, floriculture, nursery, and livestock such as cattle, hogs and poultry are some of the major agricultural products of the region. Dairy products produce the greatest revenue of agriculture production and account for nearly one-quarter
of farm cash receipts. There is also increasingly significant greenhouse production of vegetables and flowers. The majority of farmland is used for pasture and hay crops, primarily to feed the large dairy herds in the region. In 2001, about 55,000 ha of the region’s farmland were under cultivation with the chief crops being hay, corn for silage, berries, and grapes and vegetables.

Over the last decade, agriculture in the Lower Mainland has undergone changes in response to social, economic and environmental conditions in the region. Rapidly increasing population and changing demographics have resulted in not only increased demands but also preference for different types of food, such as fresh food and vegetables, and a shift from red meat to chicken meat. In addition, many consumers now 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.

Pressure of urban growth on farmland and environmental problems due to the intensification of agriculture have been identified as significant challenges to agricultural sustainability in the Fraser basin [5]. Most of the agricultural area is situated in the Fraser valley around the lower Fraser river in proximity to the growing metropolitan Vancouver and other urban centres. Agricultural lands are threatened as population grows and developers lobby for the removal of lands from the ALR.

Globally competitive markets have led to changes in agricultural land-use, and agricultural intensification has shifted production, for example, from dairy and vegetables to berries and livestock (mainly chickens and hogs). Besides the shift in land-use, there has also been an increase in the size of farms, presumably to benefit from economies of scale. For example, the number of cattle and calves per farm increased by 1.5 times from 1981 to 2001, while the number of chicken and hens per farm increased more than three times during the same period [13]. These changes in agricultural practices have affected environmental and socio-economic systems in different ways. One of the major environmental concerns is water pollution from nitrogen in animal manure because of the concentration of animals and a limited land base for disposal. Zebarth et al. [20] found that there was a large increase in nitrogen surplus in an aquifer in this region resulting from changes in land-use. 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 [4].

In order to make a transition to sustainability in the region, it has become ever more important to understand the dynamics of land-use changes and their future evolution, and to assess their impacts on the ecosystem.

1.2. Land-use models and decision-making

Understanding the dynamics of land-use changes is critical in the context of sustainability. However, it is not by itself a means to achieve sustainability. To make
progress towards sustainability also requires understanding the means of creating or influencing these changes through effective policies and through making informed and sustainable choices. Various stakeholders, including policy makers, farmers, and other involved public groups, need to have information on the performance and behaviour of the system, the driving forces involved, and likely future outcomes in response to potential changes in policies and other driving forces such as consumption practices. If people have a clear understanding of the links between choices and consequences, they are more likely to make informed and sustainable choices. Decision support tools and techniques can assist a wide range of users in making these informed decisions based on sound technical information, while also increasing public involvement in the process.

There have been extensive efforts in the field of land-use analysis aimed at understanding past, current and future land-use changes. However, crucial deficiencies exist in this research area. Land-use models are often 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. The technical details and complexity of the models restrict their interpretation and use to a small community of experts. Moreover, most land-use studies have 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.

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 alternative 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 therefore has to be a collective, uncertain and adaptive endeavour by society. In the context of agriculture, various scenarios of agricultural development, based on different choices, need to be explored and examined for their effects and trade-offs with respect to sustainability objectives as defined by different stakeholder groups.

In this study, we use land-use modeling as a tool to aid decision-making for sustainable development. We develop an integrated model called ‘AgFutures’ that is capable of generating a wide range of possible agricultural futures based on different choices and assessing the associated land-use changes and their impacts under various scenarios, in order to explore alternative futures of agricultural sustainability.

1.3. Context of research

AgFutures was developed as a module within an integrated assessment model called ‘Georgia Basin Quest’, or ‘GB-QUEST’ that has been developed to explore future
scenarios of the Georgia Basin (GB) in British Columbia, Canada, through the lens of environmental, economic, and social sustainability [14]. 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. A user or group of users choose among several potential paths from a variety of topics including urban growth, transportation, and economic growth, with the goal of creating their most desirable future, 40 years from now. GB-QUEST fosters an understanding of sustainability by placing the user or group in the position of making decisions that impinge upon regional development, and allowing them to reflect upon the consequences and trade-offs associated with those decisions. The tool includes several integrated sub-models including agriculture, urban growth, demography, transportation, macro economy, energy and forestry. Methods and algorithms developed in this research have been implemented in the Agriculture sub-model of GB-QUEST. The outputs from the agriculture sub-model are linked to other sub-models in GB-QUEST, such as water quality and air pollution, to give an integrated assessment of sustainability.

2. Model design criteria

The design of the AgFutures model was governed by the overall goals defined for GB-QUEST. GB-QUEST seeks to achieve two potentially contradictory goals—to build realistic scenarios of the future and to engage stakeholders in a debate about desirable futures [2]. This implies quite different design criteria for this model than for traditional land-use models. Various design criteria implemented in the model are discussed below:

(i) User-friendly, simple interface. The model is built with a primary purpose of engaging the community in the debate of sustainability. In order for the model to be valuable to a wide range of persons and groups, it was important that a broad range of issues be represented, and that the issues be displayed in the interface in a way that easily engages users. It was thus necessary to develop a user-friendly, easy-to-understand interface. Through this interface, key issues are presented to the user as questions, which are easy to understand by the general public, avoiding technical terms. Answers to the questions dictate model parameters which then generate future outcomes under the chosen conditions.

(ii) Involvement of stakeholders. Models for policy support should address real issues and choices faced by the community or that are of interest to the community. Policy makers and other stakeholders were included in the process of issue identification as a precursor to model development. This approach is a marked contrast to the typical approach of stakeholder involvement, which often includes stakeholders in decision-making only at the last stage of choosing among a specific set of policies that have been chosen and analyzed by ‘experts’. Stakeholders made a substantive contribution to the process of defining key agricultural issues and outcomes to be addressed. This makes the use of AgFutures more relevant and acceptable by the community, and also allows policy makers to address issues that are of interest to the community. The policies formulated on the basis of this approach will thus be more socially acceptable.
(iii) **Integrated approach.** The complexity of land-use systems and the associated sustainability analysis demand a need for the integration of physical and social sciences. While the disciplinary models are complex, have a sound theoretical basis and address specific issues (e.g. groundwater contamination) in depth, the integrated models are designed to be easy to use and implement, and therefore 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 [3]. Most previous land-use models have been disciplinary in nature, addressing either human or physical dimensions of land-use change, or addressing only one part of the complexity of land-use systems [17]. In contrast, in AgFutures we integrate human and natural dimensions of a land-use system at multiple scales, and examine the impacts on social, economic and environmental outcomes and the trade-offs among these, through selected indicators of sustainability. Inclusion of variables related to all three components of sustainability provides a balanced perspective, in contrast to analyses that emphasize only economic or environmental aspects of a system.

(iv) **Complex, invisible, quick back-end model.** To facilitate the integration of AgFutures with GB-QUEST, a back-end model design is adopted where the actual model or algorithm works in the background to generate user-desired scenarios, and only the final relevant outputs are presented to the users. Although the issues and consequences are presented in a broad manner, the underlying model is based on a complex web of interactions that describe the relationships between choices and consequences. It uses sophisticated techniques for generation of ‘what-if’ scenarios of land-use changes and impact assessment related to social, economic and environmental consequences. Much of the modeling work was done in the ‘pre-model’ stage (e.g. statistical equations, decisions on weights used for land suitability, coefficients in indicator models) in order to reduce the need for run-time calculations, allowing for the rapid generation of future scenarios in a real-time setting. User choices change the value of key variables in these algorithms to allow for the generation of ‘desired’ scenarios quickly.

(v) **Scenarios approach.** Predictive models focus on predicting futures based on past trends. These fail to recognize that the future is in many ways a result of the consequence of present and future choices. The use of scenarios, which often relates to a backcasting approach to decision making [10], 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 used in the model also allows users to explore different assumptions concerning human behaviours and values, institutions and technology, which are seldom jointly considered in predictive models.

(vi) **Address uncertainty.** Models for exploring alternative futures need to address the uncertainty surrounding the behaviour of systems in a manner that is transparent to the user. The need to address uncertainty is especially relevant in scenario generation models that include uncertainties from many different disciplines and that wish to consider time frames far into the future. The scenario-based approach used includes the explicit ability to examine how scenarios vary under different assumptions regarding specific aspects of uncertainty, including human behaviours and values, institutions and technological
innovation. Using scenarios also provides a means to test the sensitivity of variables, such as prices.

3. Development of the model

3.1. Conceptual framework

AgFutures describes the impacts of human choices on future land-use changes and the social, economic and environmental consequences of different choices related to land-use policies, diet patterns, agricultural intensification and management practices.

The model was built with a strong emphasis on the integrated nature of the systems in question. Fig. 2 illustrates the modeling framework, including main components of the model along with required inputs and the methods used in the research. Model inputs represent 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. The model consists of two major components: land-use evolution and impact assessment. The land-use evolution component simulates plausible changes/conversions in land-use up to the year 2040 and predicts how much, 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 the regional level (macro-scale) from 2000 to 2040 at decadal intervals. These projections are based on analyses of historical regional land-use trends, statistical relationships of driving factors with changes, or exogenous models of demand for a particular category. The dynamic simulation of land-use is then carried out at a micro-scale and uses a spatially explicit multi-scale approach that integrates social and biophysical driving forces in the generation of future land-use patterns. It is achieved through a relatively new technique of integrating cellular automata and multi-criteria decision-making within a geographic information system (GIS), and is based on competition among different uses. The simulation model uses land-use information that is derived from remote sensing data. 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 and calves, pigs, and hens and chicken. While micro-scale spatial modeling is done only for the major land-use categories, the regional level projections are made for all land-use types including different crops in the ‘food-crops’ category. The spatial simulation methodology is explained in detail in a later section.

The second component of the model provides a regional-level assessment of the impacts of these land-use changes on environmental and socio-economic systems. Indicators related to food security (represented by agricultural land base availability and land production potential), water quality, wildlife habitat and economic production and costs are developed and used for the assessment of different scenarios. The micro-scale and regional-scale land-use results from the land-use evolution component, as well as from the environmental and economic analysis are used in the calculation of these sustainability indicator values. An aggregated sustainability index is also developed and used for comparison of different scenarios with respect to their overall impacts on sustainability.

3.2. Methods

3.2.1. Development of scenario space

One of the major steps in the development of the AgFutures model is to design the scenario space. This involves the identification of issues of concern related to agricultural sustainability in the region, and their driving forces, followed by an analysis of the range of input parameters under future conditions that may be associated with the user group’s choices regarding each of these issues. This is necessary to determine what type of scenarios should be constructed in the model, or what key variables should be provided in the model for generation of scenarios, and what outcomes need to be considered in impact assessment.

The process of identification of issues took place in consultation with local communities and key stakeholders in the region, rather than being based on objectives that are solely economy-oriented. Several workshops were organized by the GBFP project to engage in discussions with concerned people 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, and were attended by farmers, researchers, local people and government
officials responsible for making policy decisions. VanWynsberghe et al. [16] describe in detail the workshop process for community engagement in the design of archetypes or potential alternatives for future scenarios. A preliminary list of sustainability concerns or objectives as identified in the community workshops is given in Table 1.

In addition to community workshops, literature review and analysis of past agricultural trends were also carried out to enhance the list of potential issues and outcomes, as well as to understand the causes of change.

Some of the issues identified through community participation and through literature review that directly affect agricultural land-use decisions, such as preservation of ALR and intensity factors, were considered for inclusion in the set of questions that user groups could explore in developing their future scenarios. The issues were translated to questions and possible responses in ways that were easily understandable by users. The set of questions and responses that were implemented in AgFutures are listed in Table 2. The choices are mainly related to local agricultural development issues. The responses chosen

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Sustainability objectives listed in the food system sector workshop of GBFP-October 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe food</td>
<td>Living wage—global</td>
</tr>
<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>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Scenario generation: implemented questions and possible responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Ag land preservation’—‘Will ag lands be preserved or developed?’</td>
<td></td>
</tr>
<tr>
<td>Don’t preserve ALR or other ag land</td>
<td></td>
</tr>
<tr>
<td>Preserve ALR but not other ag land (default)</td>
<td></td>
</tr>
<tr>
<td>Preserve ALR and other ag land</td>
<td></td>
</tr>
<tr>
<td>‘Farm size’—‘How big will farms be?’</td>
<td></td>
</tr>
<tr>
<td>Small farms—xx–xx (default)—xx—agribusiness</td>
<td></td>
</tr>
<tr>
<td>‘Local markets’—‘Where will local farmers sell their products?’</td>
<td></td>
</tr>
<tr>
<td>Less locally—xx–xx (default)—xx—more locally</td>
<td></td>
</tr>
<tr>
<td>‘Crop and livestock intensity’—‘How intensive will farm and livestock operations be?’</td>
<td></td>
</tr>
<tr>
<td>Less—xx–xx (default)—xx—more</td>
<td></td>
</tr>
<tr>
<td>‘Management practices’—‘How efficiently will farms be managed?’</td>
<td></td>
</tr>
<tr>
<td>Less—xx–xx (default)—xx—more</td>
<td></td>
</tr>
<tr>
<td>‘Diet’—‘What kind of diet will people have?’</td>
<td></td>
</tr>
<tr>
<td>More vegetarian—xx–xx (default)—xx—more meat</td>
<td></td>
</tr>
</tbody>
</table>
by a user group determine which scenario will be generated (for example, traditional agribusiness scenario or environmentalist scenario). Each of the choices affects specific model parameters. Model variables and/or parameters are also affected by user-determined choices from other sub-models within GB-QUEST concerning future global development, as well as the user group’s ‘worldview’ of how well people will adapt, how well technology helps society, and how well natural systems cope with human activities. The ‘worldview’ choices represent scientific and behavioural uncertainty, which may significantly influence how easily policies may accomplish intended outcomes.

Some issues (e.g. environmental concerns) were included as outcomes. Concerns of the 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 concern process rather than outcomes.

3.2.2. Spatial land-use simulation

Land-use related decisions are based on opportunities and constraints affected by both biophysical and socio-economic factors operating at different scales. Integration of multi-criteria decision making (MCDM) approaches with GIS has proved useful in various studies related to land-use analysis and planning [6,9], as these are able to integrate multiple, disparate, socio-economic and environmental factors that affect land-use changes. However, 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. Dynamic modeling approaches such as cellular automata (CA) and Markov chains are efficient in representing spatial dynamics. The approach used here integrates the functionality of MCDM and CA techniques in order to simulate the land-use conversions.

The land-use simulation procedure is spatially explicit, operating on cells of 100×100 m² size, wherein conversion probabilities of a cell are computed for different uses. In a CA model, the state of a cell at time \( t+1 \) is decided by the state of its neighbouring cells at time \( t \) according to pre-defined transition rules [15,18]. In the CA-MCDM approach adopted here, the future state of a cell is determined based on the transition probability of a cell for a given use. This transition probability in turn is determined as a function of not only the neighbourhood effects but also other important determinants of land-use changes such as land characteristics (e.g. soil, topography), current land-use, proximity factors (such as distance to markets) as well as human factors including user preferences for evaluating criteria and the user responses to questions concerning preservation of agricultural land, agricultural intensification and management practices, and diet preferences. The responses related to intensification of agriculture and diet preferences change the area requirements for different land-use types and affect land-use transitions in an indirect way by assigning competitive advantage in the spatial allocation process to the land-use types that are in greater demand.

The list of factors affecting transition probabilities for urban and agricultural use is given in Table 3. Data corresponding to each factor were assigned standardized scores on a [0,10] interval for all the uses. A value of 0 represents the least preferred score of the factor for a particular land-use while the value of 10 represents the most preferred score of
the factor. Integration of these scores into a probability value was based on the composite suitability score determined through weighted linear combination as follows

$$CS_{tk} = \sum W_{ik}X_{ik}IC_i$$

where $CS_{tk}$ is the composite suitability score of a cell with respect to all factors, $W_{ik}$ are weights associated with each factor for use $k$ and $X_{ik}$ are scores of factors with respect to use $k$ and $C_i$ are Boolean scores of restrictive factors, meaning that scores are set to zero for lands that cannot be used for agriculture, such as urban areas and lakes. Regional policy regulations are introduced in this step as constraints. For example, policy choices related to preservation of ALR were considered as constraints for urban development. The weights in this equation were determined using the MCDM technique—Analytical Hierarchy Process (AHP) [11]—that is based on decision-maker’s preferences or judgments with respect to evaluation criteria. 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.

The composite 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 ($CS_{Max_{tk}}$) changes in each iteration and relative suitability in each iteration was used to determine the probability of conversion ($P_{tk}$) of a cell to use $k$ at time $t$

$$P_{tk} = \exp[\alpha(CS_{tk}/CS_{Max_{tk}}) - 1]$$

where $\alpha$ is the dispersion parameter that is determined on the basis of transition rules. It is the strength of a cell for a particular use. 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. The probability function assigns a transition probability value of 1 to the highest score in the iteration and assigns a value of 0 when the score is 0. This approach has been used earlier by Wu [19] to study urban development in Guangzhou, China. However, Wu and many other researchers used CA models for allocations to one use only. The present approach can be considered as an extension of the approach used by Wu 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.

Land-use transitions were then determined by assigning uses to the cells in the order of cell’s probability for conversion for that use, with the cell being assigned to the use for which its probability of conversion was highest. This rule ensures that the assignment process maximizes composite suitability over all uses. The number of cells assigned to each use is based on the demands for each use that are computed by the macro-scale module and are affected by the scenario-driving variables. 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. At the end of the allocation process, the cell states were updated and the new land-use patterns generated were used as the initial state of the cells for the next iteration. The stochastic process prevented a ‘checkerboard’ effect of different uses. Ten iterations were carried out for modeling land-use conversions taking place in one decade. In each time step of the CA model, the constraints and the transition rules related to neighbouring effects are updated to reflect the land dynamics in the previous step. The final land-use patterns are thus a result of not only the initial land-use of the cell but also the evolution of land-uses in its neighbouring cells and other local and regional factors that affect the development process.

3.2.3. Model calibration

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 required finding the appropriate weights and finding the value of parameter $\alpha$. In order to do this, it was necessary to compare the simulation results with actual data. 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.

Detailed land-use data of years prior to 2000 were unfortunately not available for whole study area to check the model’s ability to simulate. Therefore, model calibration was carried out using data for the base year 2000 and simulating changes for the year 2002 for which data were available for parts of the study area. Furthermore, calibration was done only for $\alpha$. As the weights were derived using the pair-wise comparisons of criteria [11] based on judgments of experts in this field and/or literature sources, the calibration process involved only 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 2002. Simulations were carried out for just two time steps representing 2-year span. A goodness-of-fit between the predicted and observed land-use was used to select the appropriate value of $\alpha$ for different uses. Weights were only fine-tuned in the iterative process which resulted in a slight improvement in the goodness of fit.
3.2.4. Impact assessment

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. This is done through development of sustainability indicators and indices that have been used to assess and compare scenarios. The evaluation of alternative scenarios for their impacts on sustainability was done with respect to six issues that were identified as chief concerns for agricultural sustainability in the region. These are availability of land base, land productivity potential, economic outputs, economic costs, water quality and availability of wildlife habitat. Indicators developed for these social, economic and environmental concerns are presented in Fig. 3. These indicators are described below.

3.2.4.1. Agricultural land loss. A decrease in availability of land for agricultural purposes may result in eroding the food base in the valley. This indicator is defined as the amount of agricultural land lost to urban growth and was determined from the outputs of the spatial simulation model.

3.2.4.2. Land marginality index. This is an indicator of land production potential and, together with the previous indicator, it addresses food security concerns. 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 input costs.

This indicator was calculated as:

\[ \text{LMI} = 1 - L_p \]

where LMI is land marginality index and \( L_p \) is the proportion of agricultural land of prime capability class. The classification map of \( L_p \) was achieved by overlaying a land capability

![Fig. 3. Indicators for sustainability assessment of scenarios.](image-url)
map with the land-use map from the simulation model to find the percent of cultivated area on prime agricultural land.

3.2.4.3. Natural land conversion. 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. This indicator assesses the potential risk of land-use conversions to the wildlife habitats. It is defined as the 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.

3.2.4.4. Nitrogen surplus. This indicator was developed for assessing risk to water quality and was calculated 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 is measured in kilogram per hectare of cropland

\[
N_{\text{sur}} = (N_{\text{fert}} + N_{\text{man}} - N_{\text{rem}})/A
\]

where \(N_{\text{sur}}\) is the nitrogen surplus; \(N_{\text{fert}}\) is the nitrogen from fertilizer application (kg); \(N_{\text{man}}\) is the nitrogen from manure; \(N_{\text{rem}}\) is the nitrogen removal by crops; and \(A\) is an area of cropland.

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

To compute the nitrogen from manure, projected livestock numbers for three categories are further categorized into different types, for example, cattle were further categorized as beef and dairy cows. Coefficients for nitrogen from manure of each animal per year were then used to compute the total manure nitrogen. Atmospheric deposition of nitrogen was not considered in these calculations.

3.2.4.5. Agricultural output. This is defined as total output of all agricultural activities in monetary units. It was calculated in real year 2000 dollars and was based on total economic output from various agricultural products of a land-use or livestock. It used information on yields and prices of different commodities. Yields of commodities are affected by scenario assumptions.

3.2.4.6. Costs. This indicator calculates total operating costs of various agricultural activities. Coefficients of costs per hectare for different types of crops and livestock were taken from published sources for the region and were used in these calculations.

Wherever possible and applicable, detailed sub-categories of land-use and livestock products were considered in these calculations. For example, eggs and poultry meat production were considered for computing economic agricultural output of chicken.
4. Application of the model

4.1. Scenario definitions

Scenario analysis is an appropriate and valuable use of AgFutures, because many of the factors that influence agricultural production and the use of agricultural lands are within the control of local policy makers. For this paper, the model was used to develop four different scenarios of agriculture for the Lower Mainland:

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

(ii) **Agribusiness scenario (Agbus).** This scenario examines the effects of agricultural intensification practices, specifically related to livestock production and greenhouse production. 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 development in food crops. Yields are expected to reach the potential levels determined by current technology.

(iii) **Protectionist scenario (Prot).** This scenario assumes low-intensity agricultural development oriented towards protection of the environment. It assumes that ill effects of current intensification on environment will be recognized and there would be a move to maintain current livestock densities.

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

Livestock numbers and land-use demands were computed for each of these scenarios. Each of the four scenarios above was also examined under two sets of conditions concerning urban growth. One option, labelled ‘a’, preserves the ALR so that no urban development can take place in the ALR. The other option, labelled ‘b’, considers effects of not preserving the ALR and allowing urban development to take place within the ALR. Thus, in all, eight scenarios were examined for their effects on environmental and economic systems.

4.2. Results and discussions

Simulated land-use maps for 2040, showing spatial patterns of all land-use categories were generated for all eight scenarios. 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. These maps can be used to study the hot spots of land-use changes under different scenario assumptions.
As expected, spatial simulation results show that in scenarios, which preserve the ALR, urban expansion takes place in a manner that does not affect ALR (Fig. 4a). Higher concentrated growth is observed nearer to the 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. Under scenario b, which does not preserve the ALR, most of the urban growth takes place as a result of conversion of existing agricultural lands (Fig. 4b). Fig. 5 shows the quantitative loss of agricultural land under scenarios ‘a’ and ‘b’. In ‘a’ scenarios that preserve ALR, only 3653 ha of agricultural land (currently not under ALR) are lost, in contrast to ‘b’ scenarios where more than 25,000 ha of agricultural
land are lost. In the former case, no land is lost from the ALR, but in the latter case most of it comes from the ALR. Fig. 6 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.

Indicator values for different scenarios are presented in Table 4. The land marginality index (LMI) is higher for all scenarios as compared to year 2000, except for the Prot-a scenario. In general, ‘b’ scenarios have a higher LMI, implying that in these scenarios most of the prime agricultural land is lost to urban conversion, causing agricultural production to shift to marginal lands.

It is observed that the highest increase in agricultural output is obtained for the Agbus-a scenario, whereas the least increase is obtained under the protectionist scenario. There is a nearly 150% increase in agricultural output in Agbus-a scenario. The agricultural intensification in this scenario results in a five-fold increase in greenhouse vegetable production, which accounts for more than 50% of the total agricultural value in 2040 (Fig. 7), as compared to 25% in year 2000. Agricultural output related to chicken and hens’ products (meat and eggs) increases by 150% over the value in year 2000. However, the increase in agricultural output in the Agbus-a scenario is at the expense of economic and environmental costs that are higher than in all other scenarios. The agricultural operation costs increase by 100%, nitrogen surplus increases by 60%, and there is a maximum loss of natural lands amounting to more than 38,000 ha. Fig. 8 clearly indicates the trade-offs between agricultural production and its costs. Table 4 can be used to carry out a similar trade-off analysis between production and environmental costs.

A variety of multi-criteria decision methods can be used to analyze multi-dimensional information in Table 4 for evaluating trade-offs in alternative scenarios and for generating a sustainability index to aid consensus-based decision-making for sustainability. In the simplest form, all indicator values were converted to standardize scores and combined as a weighted sum to obtain the Outcomes Index (OI) for assessment of overall impacts or outcomes of a scenario. As the model is AHP-enabled, paired comparison of evaluation

Fig. 6. ALR area lost by land-use classes.
Table 4
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></td>
<td>BL-a</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>31,953</td>
</tr>
<tr>
<td>N surplus (kg/ha)</td>
<td>99</td>
<td>89</td>
</tr>
<tr>
<td>Ag output ('000' $$)</td>
<td>641,173</td>
<td>1,112,579</td>
</tr>
</tbody>
</table>

Ag land loss, agricultural land loss; BL, baseline scenario; LMI, land marginality index; AgBus, agri-business scenario; Nat land conv, natural land conversion; Prot, protectionist scenario; N surplus, nitrogen surplus; Vege, vege-business scenario; Op. Costs, operation costs; a, ‘a’ type scenario (Preserve ALR); Ag output, agricultural output value; b, ‘b’ type scenario (do not preserve ALR).
criteria could be used to derive user-specified preferences (weights) for aggregation in the real-time use of the model in public settings. However, for this paper, equal weights were considered for all indicators.

A high OI indicates relatively higher adverse impacts on sustainability. This is because all the indicators, except agricultural output, were designed to represent unsustainability. For aggregating in the OI, the Agricultural output indicator value was taken as 1 (standardized score of Ag output). Fig. 9 shows the OI values for all scenarios. Maximum adverse impacts on sustainability are observed for the Agbus-b scenario. Prot-a scenario results in the least unsustainability followed by the Vege-a scenario. It should, however, be noted that these summary results have been obtained by assigning equal weights to all of the indicators. Different stakeholder groups may place different importance on various issues, which will result in different values of the index.

5. Conclusions

The AgFutures model described in this paper serves as a decision support tool that can be used by a wide range of users for exploring alternative futures of agriculture. Using this
A tool, a range of future scenarios can be generated and various possibilities evaluated based on different human choices and behaviours, such as those related to diet or agricultural management practices. The model allows systematic comparison of consequences of alternative futures through different indicators that helps the user 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 allows users to reconsider their choices.

While in this paper we have presented only eight structured scenarios, it is obviously possible to generate many random scenarios through its use in real-time in public settings. It has been integrated with GB-QUEST model and has been played in various interactive settings such as workshops to collect information on what kinds of futures do people prefer and what kinds of trade-offs are they prepared to make to attain them. These data will provide valuable information to policy and decision-makers that would lead to achieving the goals of sustainable development.

AgFutures is a prototype model and there is much scope for improvement in it. Different ‘values’ of agriculture, such as local jobs, need to be addressed and included as ‘outcomes’ in the model. The analytical capability of the model can benefit from recent approaches in land-use modeling, such as agent-based approaches [7], which capture human decision-making complexities in a better way. An important future research area will be to address other ‘values’ of agriculture such as local jobs and the biophysical feedbacks to the land-use changes, which can affect the sustainability significantly. For example, agricultural intensification may result in land degradation that in turn would affect the yields of the crop. This would affect agricultural output and undermine its sustainability. Other relevant connections for future research include climate change impacts on crop yields and nutrient loading implications on local water quality. Such models would help address complex two-sided interactions between the driving forces and outcomes of agriculture and hopefully serve as more robust and reliable tools for sustainability.
Acknowledgements

We would like to thank anonymous reviewers for their useful comments on this paper. One of the authors (Sharma) gratefully acknowledges the financial support received for this work from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

References