Integrating socio-economic and land-use models to support urban and regional planning

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ABSTRACT

In the past decades several attempts have been made to integrate socio-economic models with land use change (LUC) models. In most cases, however, there is a uni-directional relation from the socio-economic model(s) to the LUC model by providing land use demands based on demographic and economic developments. In this paper we present a model that allows for a more dynamic integration between both processes by including a bi-directional interaction that enables a feedback from the land use model to the economic model in addition to the above-mentioned traditional link. To facilitate its use in a planning and policy-making context the integrated model is provided in the form of an Integrated Spatial Decision Support System (ISDSS) that allows policy analysts to assess the impact of various policy options (related to spatial planning, infrastructure development and economic incentives) on a set of social, economic and environmental indicators and to test the robustness of those policy alternatives under various external conditions (mainly demographic and macro-economic developments). This paper will present an application of the ISDSS to the Wellington region in New Zealand. We will describe the individual models incorporated in the ISDSS, the integration between the individual models and the impact of the feedback mechanisms. The latter will be demonstrated through the results of the Wellington application. One of the main findings of the approach is that the feedbacks incorporated in the system show that socio-economic development is an important driver for land use change, but that limited (land) resources also have an impact on economic development and restrict the economic growth that most (demand-driven) economic models would project.

KEYWORDS: Integrated Spatial Decision Support System, Model integration, Policy support, Urban and rural dynamics, Land use modelling

INTRODUCTION

The proposition that land use dynamics are complex and exhibit self-organising behaviour may seem at odds with the prima facie assumption that planners and policy-makers have a decisive influence on future land use. In reality this is not a contradiction, but rather a challenge for modellers to recognize disparate types of drivers and look at autonomous behaviour, exogenous drivers and (spatial) planning as an integral part of the land use system.

A closer look at the drivers of land use makes it apparent that dynamics are driven by processes operating at various spatial scales. When focusing on urban and rural environments there is interaction between cities, between a city and its hinterland, between neighbourhoods of the same city and at local level, although none of these processes operate in isolation. Bottom-up as well as top-down interactions play a crucial role in the overall dynamics. Socio-economic developments at macro level impact on the demand for residential, industrial and commercial locations, while the availability of suitable locations and the actual spatial configuration in turn impact on the overall socio-economic developments.

The notion that economic and land use change processes interact, is common knowledge (Castells, 1977; Harvey, 1985; Lefebvre, 1991). How to simulate this interaction in (integrated) models is not that straightforward. Both disciplines have co-existed for decennia and each has developed its own concepts and (modelling) paradigms. When integrating models from these different disciplines, underlying assumptions and limitations of the existing individual models are passed on to the integrated model. A proper integration therefore requires a thorough understanding of the underlying theories of both types of models. Over the past decade, several attempts have been made to integrate socio-economic models with land-use change models (Van Delden et al., 2010; Britz et al., in press). In most cases, however, there is a uni-directional relation from the socio-economic model(s) to the LUC model by providing land use demands based on demographic and economic developments (e.g. Eururalis, Verburg et al., 2008 and Xplorah, Van Delden et al., 2008).

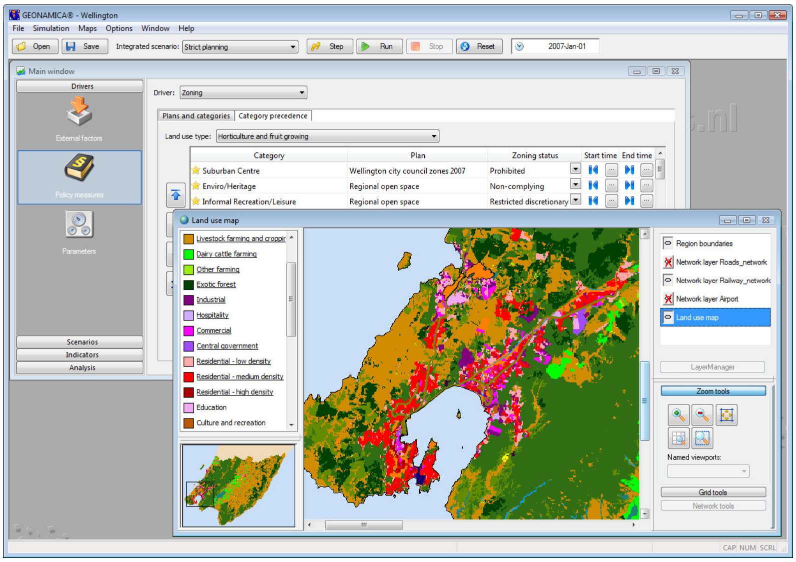

Figure 1: Screenshot of the ISDSS presenting the main window and the land use map of Wellington.

This paper presents an integrated spatial decision support system (ISDSS) for simulating urban and regional dynamics, for which early prototypes (developed in the first two years of a six year programme) have been applied to the Auckland and Wellington regions in New Zealand (Figure 1). The aim of this ISDSS is to support long-term integrated policy development and planning by taking into account social, cultural, environmental and economic developments. An important aim of the approach is to show the trade-offs that need to be made when deciding about future development directions and therefore simulating the impact of alternative scenarios on the economy as well as the environment was found crucial.

The structure of the paper is organised as follows: first the components of the integrated model and their interlinkages are described, followed by a practical application of the SDSS to the Wellington region showing the impact of the feedback loops in the model. Based on the theory and the results of the practical application, we will discuss the approach, draw conclusions on provide some ideas for future work.

THE INTEGRATED MODEL

The ISDSS includes an ecological economic model to represent macro-economic developments, an age-cohort model for demographic changes and a cellular automata based land-use change (LUC) model for simulating the competition for space at local level and hence the spatial allocation. Details on each individual component and their underlying concepts are provided below. The integrated model has a temporal resolution of one year and a time horizon of 40-50 years into the future. The spatial resolution is 100 m and its extent is the size of the districts that together make up the metropolitan area and its outskirts; in both cases an area of roughly 150 x 150 km.

The land use model

The ISDSS incorporates the Metronamica land use model, a cellular automaton based (CA-based) LUC model that has the objective to simulate spatially explicit dynamics and is based on complexity theory (White and Engelen, 1993; RIKS, 2010). CA-based land use models generate an organized but unpredictable behaviour of the land use system. This behaviour is represented by a large set of simple equations or rules that together create a complex behaviour that includes non-linear dynamics and emergent properties. They are simulation models that start with a land use map of the initial year and use a set of drivers (behavioural, institutional and physical) to calculate future developments (see Figure 2). These models are exploratory and show what could happen, rather than what should happen. There is no ideal future, nor is there an assumption that the world reaches equilibrium at any point in time. CA-based land use models are grid-based applications in which each cell is in a possible state, i.e. occupied by a specific land use. Time progresses in discrete time steps and at each time step all cells update state (land use) simultaneously, based on the state of the previously time step, the neighbourhood of the cell and the transition rules that state under which conditions cell states change.

Similar to most LUC models currently in practice, Metronamica makes use of a special form of CA, called constrained CA. In this type of model, area demands for each land use are determined exogenously, after which these demands are allocated by the model. Furthermore, in most applications land use transitions are not purely based on the cell states in the neighbourhood, but on local characteristics as well, such as accessibility to infrastructure, the inherent suitability of the location for a specific land use and the spatial planning applied to various locations. With these additional behavioural components the systems have been named ‘relaxed’ CA (Couclelis, 1985). An overview of the main drivers of the Metronamica model is provided in figure 2.

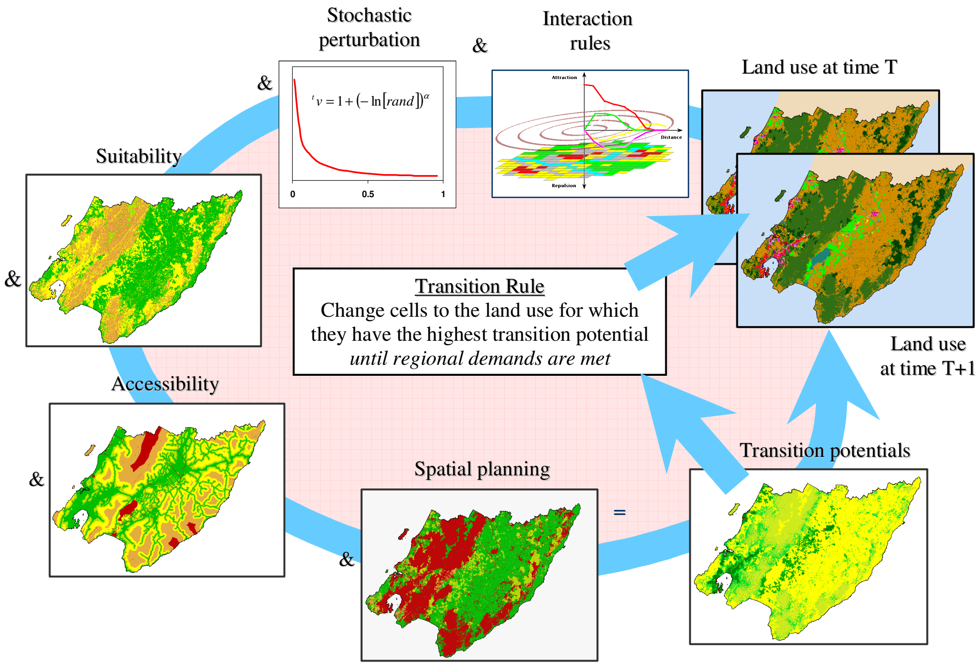

Figure 2: Main drivers of the Metronamica land use model include interaction rules simulating the preferences of the various actors for certain locations based on their surroundings as well as their power to actually occupy the most desirable locations, physical suitability, accessibility and spatial planning. A stochastic perturbation is included to account for individual preferences not accounted for in these main drivers.

The macro-economic model

For representing macro-economic developments, the Region Dynamic Economy Environment Model (RDEEM) input-output model has been selected (McDonald and Patterson, 2008; McDonald, 2010). Input-output (IO) models provide a snapshot of the structural interdependencies between industries (e.g. agriculture, manufacturing, and services), primary inputs (e.g. wages and salaries, profit, imports, depreciation) and final demands (household consumption, government consumption and exports) for a given financial year within an economy (Miller and Blair, 2009) and as such do not include a temporal component. For different years different IO tables can be constructed. Input-output tables are presented in matrix format with row entries representing sales and column entries purchases. Using simple matrix algebra IO tables may be used as an analytical tool to study the short-to-medium implications of comparative static changes in demand (i.e. consumption, exports, and environmental emissions), or supply (e.g. wages and salaries, imports, and environment factors such land, energy, water etc), on an economy. Importantly, IO models capture not only direct, but also indirect (through supply chain purchases) and induced (through consumer spending) impacts associated with economic change.

The demographic model

The demographic model used in the ISDSS is an age-cohort model that calculates population projections for the entire modelled region according to birth, mortality and migration figures. Each year of the simulation, it calculates how many man and woman are present in each one-year age cohort and by doing so an age pyramid can be created for the entire population of the region. Baseline figures for birth rates, mortality rates and migration rates come from historic data, but for alternative scenarios the user is able to alter these rates and can in this way simulate alternatives for e.g. immigration and the aging of the population.

Integration between model components

The integration between the economic model and the land use change (LUC) model is presented in Figure 3. The macro-economic model (shown in the figure by both its demand and supply side) is an important driver for land use change in providing land use demand for a range of economic activities such as industry, commercial activities, dairying, cropping, and beef & sheep farming. The LUC model subsequently tries to allocate these demands at the local level. Only suitable and available locations are taken into account during the allocation. This avoids e.g. allocation of dairying land and industrial locations on steep slopes or urban development in conservation areas. When not all demands can be met, the competition for space between different actors is simulated by the land use allocation algorithm, and the final allocation is fed back to the economic model. The supply side of the economy is affected by this information and hence economic growth is less than what would be expected by a purely demand-driven approach. Because the IO approach captures the interdependencies between industries, the availability of suitable land can restrict growth for different economic sectors.

The demographic model is linked to the economic model through the consumption of goods and services. It furthermore provides the land use demands for the residential land uses in the land use model. No feedback from the land use model or the economic model to the demographic model is included; it is not assumed that land scarcity will have an impact on the growth of the population and evidence of changes in the regional economy on the regional population is too little to be included as a feedback process.

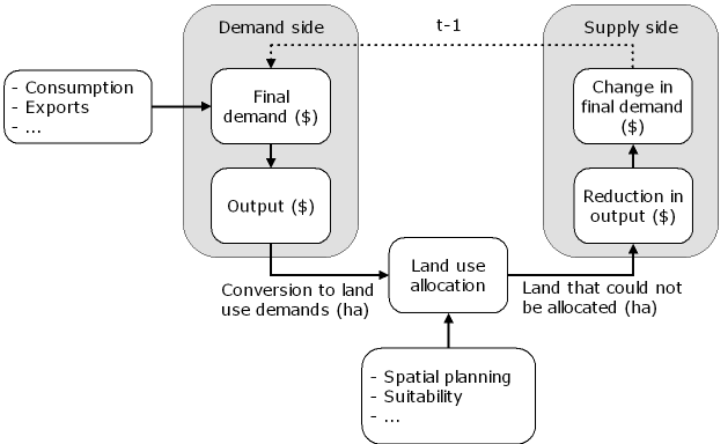

Figure 3: Schematic representation of the integration between the economic model and the land use change model.

RESULTS OF THE APPLICATION FOR WELLINGTON

A first application of the ISDSS has been set up for the Wellington region. Looking at the baseline scenario for this region we see that due to the socio-economic growth, urban and agricultural land uses take over a large part of the (unprotected) natural areas (Figures 4 and 5). Furthermore we notice that over time not all land use demands that are calculated based on the economic projections can be fulfilled. The strong economic functions, such as industrial, commercial and other urban activities, will occupy the locations that they desire (Figure 6a), while some of the agricultural land uses will not be able to meet their demands. As a result of the competition for land in the agricultural sector we see that the stronger agricultural land uses, such as dairying, take over those with less (economic) power, such as livestock farming and cropping and that the total area of the latter even decreases over time (Figure 6b).

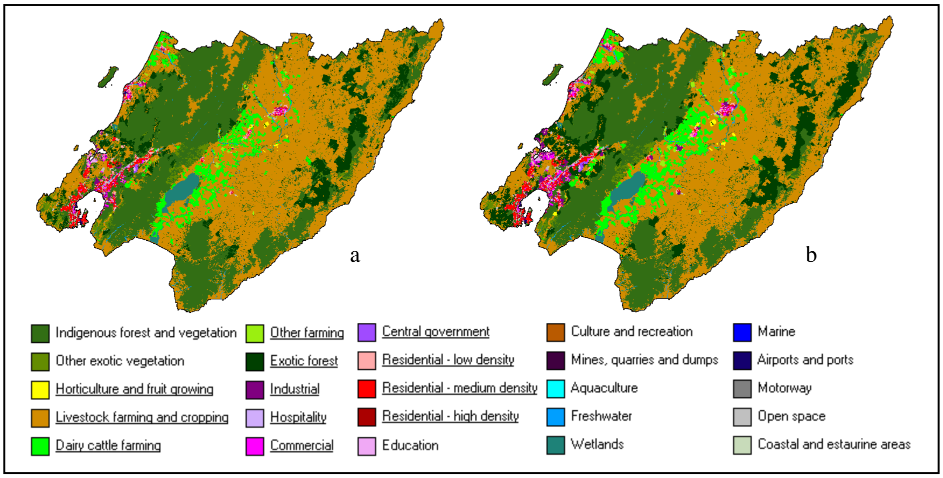

Figure 4: Land use map of 2007 (a) and 2051 (b) according to the baseline scenario.

When we compare the baseline scenario to a scenario that is not taking into account any land limitations, a so-called unconstrained scenario, we find that the limited resources (in the baseline scenario) have a small impact on the overall economic growth (less than 0.1%), but the impact on the affected sector -livestock farming and cropping- is more than 10% (Table 1). Because we use an IO model to calculate the economic developments we also calculate the impact of the limited land resources for livestock farming and cropping on the related economic sectors. Here we find for example that the growth in meat and meat product manufacturing over the period 2007-2051 is a little over 1% less in the baseline scenario than in an unconstrained scenario

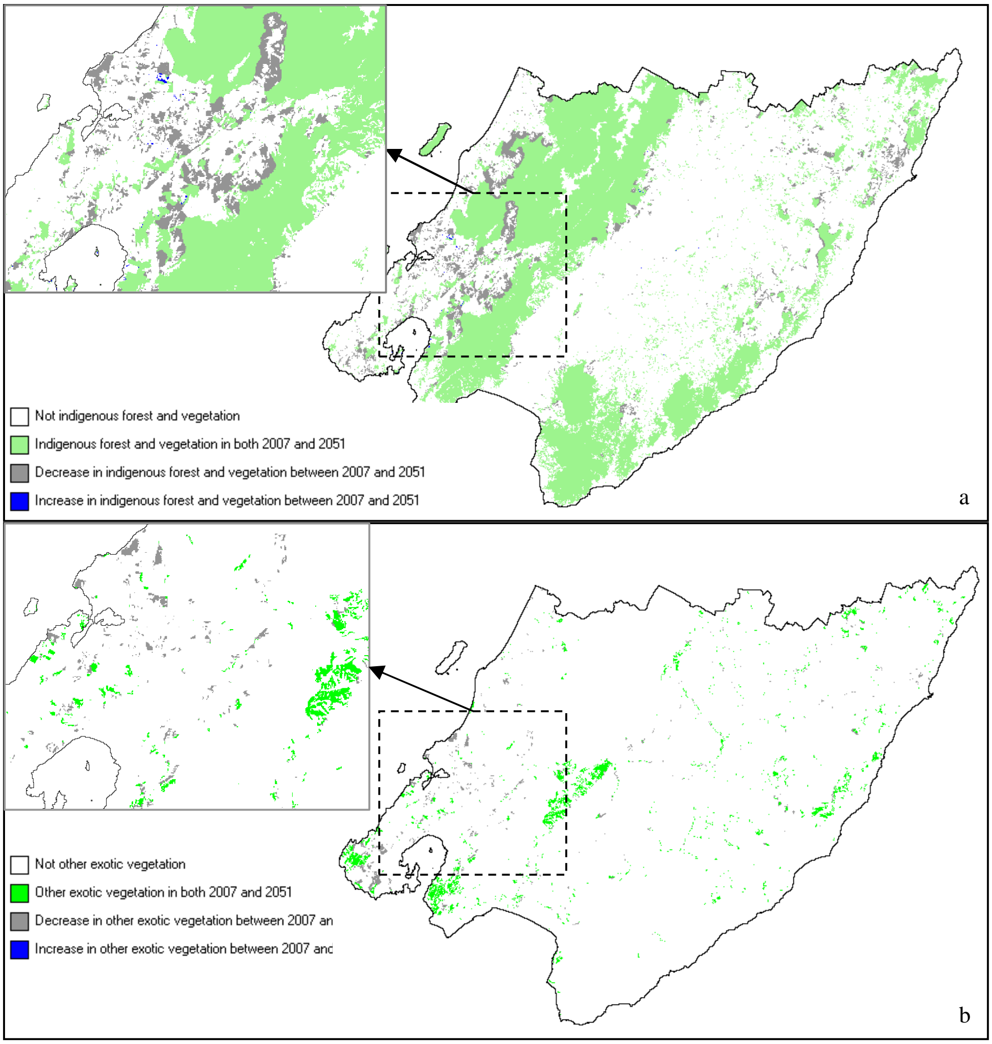

Figure 5: Decrease in indigenous forest and vegetation (a) and other exotic vegetation (b) in the period 2007-2051 according to the baseline scenario.

Scenarios → Results from the economic model ↓	2007	Baseline 2051	Unconstrained 2051	Stricter zoning 2051
Total economic output (mln $2004)	37604	64872	64897	64837
Output in Livestock and cropping farming in 2051 (mln $2004)	184	189	208	188
Output in Meat and meat product manufacturing in 2051 (mln $2004)	278	413	417	413
Overall economic growth over the period 2007-2051 (%)		72.51	72.58	72.42
Growth in Livestock and cropping farming over the period 2007-2051 (%)		2.44	12.63	1.77
Growth in Meat and meat product manufacturing over the period 2007-2051 (%)		48.55	49.83	48.41

Table 1: Economic impact of the various scenarios.

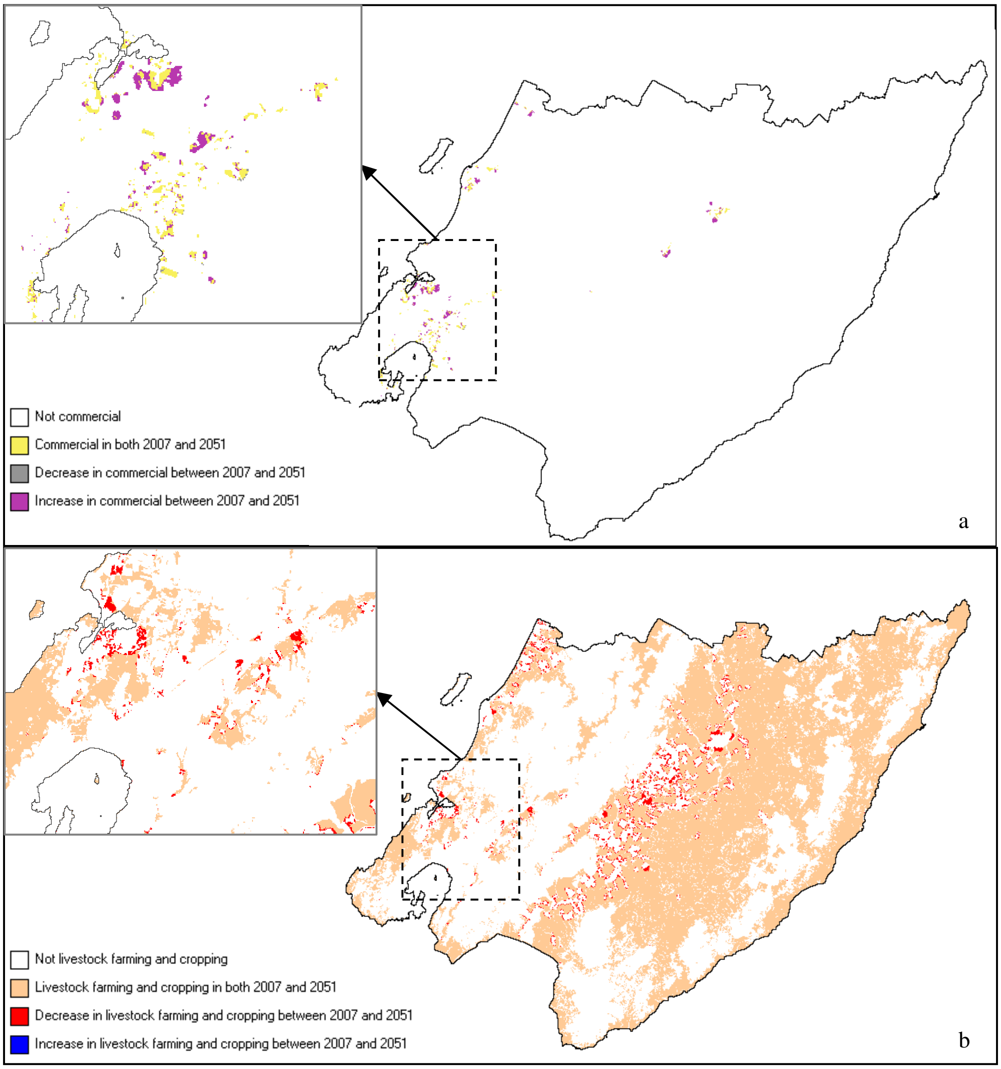

Figure 6: Increase in commercial areas (a) and decrease in livestock farming and cropping (b) in the period 2007-2051 according to the baseline scenario.

Because the protection of the indigenous forest and vegetation is highly valued in New Zealand we also run an alternative scenario in which all indigenous forest and vegetation was protected, the so-called stricter zoning scenario. As expected this scenario will result in a larger area of indigenous forest and vegetation in 2051 compared to the baseline scenario (Figure 7), but also in a slightly smaller economic growth (around 0.1% for the total economy and 1% for the livestock and cropping sector) because of the additional land resource limitations. Figure 7b shows an additional decline in livestock farming and cropping in the stricter zoning scenario compared to the baseline scenario.

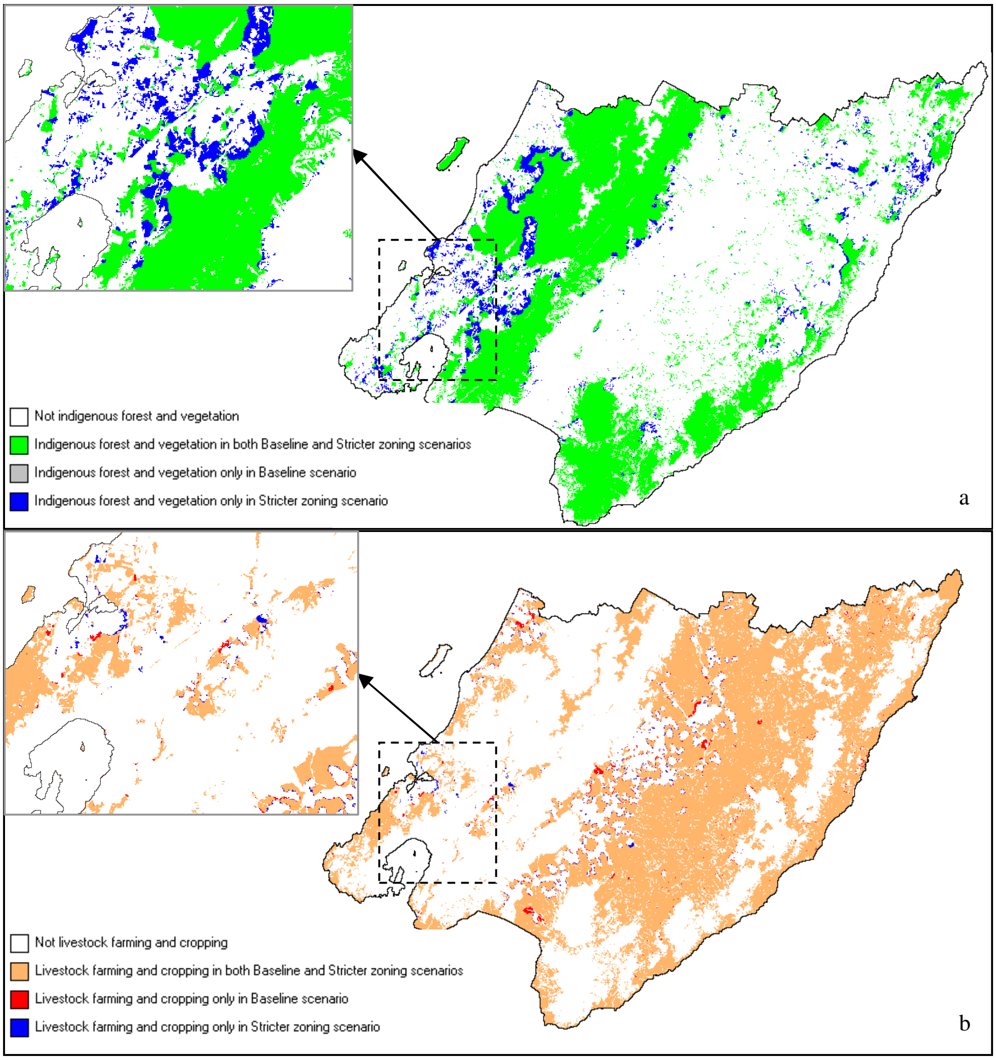

Figure 7: Difference in indigenous forest and vegetation (a) and livestock farming and cropping (b) in 2051 when comparing the baseline scenario with the stricter zoning scenario.

DISCUSSION AND CONCLUSIONS

The ISDSS that is being developed demonstrates that a dynamic coupling between socio-economic and land use change models is able to simulate the feedback between both processes. First results of an application for Wellington show a realistic behaviour of all model components. Because the integrated model is provided as an ISDSS that allows entering various policy options, calculating their impact on both the environment and the economy, and elucidating trade-offs, the system has a high potential to support policy analysis and impact assessment.

The chosen approach brings conceptual strengths and weaknesses associated with the incorporation and integration of the economic, demographic and land use models. The key strength of this approach is the integration of available resources in the supply side of the economic model, simulating how physical and institutional restrictions on land resources are limiting the land supply and hence economic growth. This offers a unique way of creating a feedback not only from the economy on the land use, but also from the land resources on the economy. Furthermore, this approach has the ability to capture the interdependencies (i.e. supply chain linkages) between industries, and in turn, changes in land use requirements across all industries.

A drawback of the IO model is that this is a linear model and interdependence between industries is assumed to be constant with no technological change. This makes the model less suitable for more creative and long-term scenarios. Furthermore, when implementing the interactions between the land use and economic components a main difficulty was experienced. For the macro-economic model to operate correctly, the demand and supply side should be in equilibrium for a single year. Because the demand side impacts on the LUC model and the supply side is affected by the LUC model, equilibrium could only be obtained through an iterative procedure between the LUC and the economic component, which would have to be carried out during each time step. Such a procedure would however not match the simulation approach of the LUC model in which action and reaction are modelled over time. After reviewing several alternatives and investigating their results, it was decided to divide the demand and supply calculations over two time steps. This solution is conceptually not ideal (nor is the other solution of iterating between the economic model and the LUC model in the same time step), but was favoured because of its shorter execution time (which was important for the use value of the ISDSS) and its fit with the overall dynamic nature of the integrated model, which is related to its ability to support scenario studies.

As already mentioned in the introduction a key challenge in model integration lies in integrating models that have been developed in different disciplines. Our experience is that the equilibrium approach of economic models often poses conceptual conflicts with the simulation approach of dynamic land use change models. While sometimes the integration seems to be there when we provide both types of models in an integrated model, special care is required regarding the conceptual validity of this integration. Being able to couple models technically doesn't mean the coupling makes sense! For future research we therefore recommended to focus first on the integration of the processes and next on the model implementation.

The presented ISDSS is being developed as part of a larger project that aims to provide support to policy makers in developing sustainable pathways for the future development of their city or region. Besides the ISDSS development, the project also includes a series of meditated modelling workshops. Both streams are intended to strengthen each other and to provide policy support by themselves as well as in conjunction. The project is carried out in close collaboration with the intended end users, the planners and policy makers from Auckland and Wellington. In the remaining four years of the project we aim to improve the integration between the land use and the economic model by making the economic model more dynamic and by incorporating agents into the land use model to make its behavioural component more realistic. Furthermore we aim to improve the current set of policy options and indicators to better connect to the policy practice in both regions. Finally, as a collaborative effort, an interpretation will be made of the current policy documents to set some of the model's parameters more realistically. The aim of this exercise is to both improve the model's behaviour as well as its implementation in the user organisations.

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