Modeling Feedback Mechanisms Between Land Use and Climate Change

T. K. BenDor[1], J. M. Bielicki[2], B. S. Powell[3], and D. T. Robinson[4]

We investigate the coupling between land use and climate change via a simple feedback mechanism. To explore the feedback, we develop a basic REPAST model in which agents choose a land use to maximize their local utility. Agent's utility functions determine whether to convert undeveloped land to farmland or urban land. Farmlands may subsequently be converted to urban land when the utility of the land serves an urban purpose. When changing land use, there is a pollution penalty based upon the conversion type. The agent's utility depends upon the need for food, proximity to population, proximity to similar land, and pollution. The dual use of the utility functions was found to be inadequate and gave similar results to a random utility.

Introduction

Human land use activity, such as terracing rice fields, forming cities in the middle of deserts, and removing vegetation to make room for strip malls and housing tracks, has fundamentally altered the natural character of the Earth's surface. Land use induced changes in the surface energy budget can affect climate across all scales: local, regional, and global [14]. Additionally, the combined impacts of land use and climate change are likely to dramatically affect natural resources and ecosystems [23].

Recently, scientists have estimated that as much as fifty percent of global climate change can be causally linked to patterns and change in land use [9]. While some debate this percentage [22,24], it is agreed that the effects of land use on climate are substantial. Activities such as replacing rainforests with less transpirant crops, irrigating farmland, and harvesting and replanting forests substantially effect temperatures, cloud cover, and levels of atmospheric water vapor in ways more deleterious than altering the global carbon cycle [17].

This paper presents a model that couples land use decisions with their environmental implications. We present and analyze a model in which land use decisions depend upon and effect environmental variables over time. The environmental variables feedback and

[1] Department of Urban and Regional Planning, University of Illinois at Urbana-Champaign, Champaign, IL 61820. bendor@uiuc.edu
[2] Belfer Center for Science and International Affairs, Harvard University, Cambridge, MA 02138, Jeffrey_Bielicki@ksgphd.harvard.edu
[3] Colorado Center for Astrodynamics Research, University of Colorado at Boulder, Boulder, CO 80309-0431. brian.powell@colorado.edu
[4] School of Natural Resources, and Center for the Study of Complex Systems, University of Michigan at Ann Arbor, Ann Arbor, MI 48109. dt_robins@yahoo.ca

influence the viability of the land for varying land use. We first briefly summarize major characteristics of land use and climate change. We then present our model that couples land use decisions and climate change and analyze the results of simulations. We close with a discussion of future directions for the model and subsequent analyses.

Land Use

Understanding land use change over time plays a major role in determining the structure and function of governance in areas as diverse as public finance, quality of life, and environmental protection. Changes in land use patterns can profoundly affect basic processes driving both human and natural systems [1]. Research has shown that the provision of public services (and the costs associated with these services) is a function of the development patterns and development rates [4,11]. Ecological impacts stemming from development can include the fragmentation or loss of habitat as well as the alteration of a region's hydrologic behavior such as reductions in water quality and increases in urban runoff. Changes in land use patterns can change community attributes such as mix of residents, aesthetics, and community social dynamics that lead to inefficiencies in the pattern of land development. The ability to understand land-use changes is important for policies designed to manage growth and maintain the social and environmental welfare of a community [19].

Alterations in land-use patterns result from complex interactions between many factors, including public policy, local culture, management, economics, environmental, and human behavioral factors [18]. As such, the drivers of land-use patterns can be extremely diverse. Location decision models have suggested that individual agents consider a variety of attributes when making decisions regarding their use of land [18]. Over the last several decades, examinations of the demand for residential development in exurban areas (urban fringe and edge cities) focus on the trade-off between lower land prices and increased travel costs to an urban or suburban employment and commercial centers.

While this trade off (some research views it as a market failure associated with artificially low transportation costs [3]) may help to explain the allocation properties associated with growth in exurban areas, it does not explain the spatial distribution of development in these areas. Rather, we see that the distribution of land-uses tend to cluster in certain areas due to spatially heterogeneous variables that change across a region, making some locations more desirable relative to others.

These spatial factors include:

- Proximity to employment and other desirable activities;
- The spatial distribution of the provision of public services (e.g. sewer and water); Natural features (e.g. rivers, mountains, slope);
- Surrounding land uses of an area, and;
- Growth management policies regulating density of development [1]

Different spatial patterns can result in widely varying social, economic, and ecological impacts. Understanding spatial land-use patterns is important and often requires modeling techniques that explicitly represent spatially extended geographical areas (spatial

heterogeneity and the resulting landscape patterning are usually not accounted for in studies of land use change that use large and highly aggregated areas as their observational units). The ability to study land-use change as it occurs in a realistic, spatially explicit manner facilitates an improved understanding of environmental, social, and economic impacts while enabling planners and policymakers to assess how individual decisions drive changes in land-use.

Land use change models have been useful tools for exploring common land-use change mechanisms, projecting possible future environmental, social, and economic impacts of land use change, and evaluating the influence of alternative policy and management scenario structures on development patterns [1]. Although some approaches focus on modeling aggregate land use within large observational units [6], models that predict spatial patterns can provide more detailed and functional information with which planners and policymakers can evaluate the impacts of development.

Climate Change

The evidence for the warming of the Earth over the past 60 years is substantial. The average ground temperature has been increasing [8], major reductions in glaciers are reported [2], the oceans are heating up [12], there is an increasing variability in sea surface height as correlated with sea surface temperature [15], and an increase in the Earth's oblateness with the steric height of the ocean [16]. Each of these factors helps show the complete picture of increasing warming of the Earth.

Using borehole samples taken globally from the mid-latitudes, [8] have shown that the average rise in ground temperature from the pre-industrial age until 1990 has been 0.7±0.1°C. From 1990 until 2001, an additional increase of 0.4° is shown for a total increase of ~1.1°C of average ground temperatures. These temperatures are having a dramatic effect on the retreat of ancient ice caps around the globe. The Qori Kalis, Quelccaya, and Cordillera Blanca ice caps in Peru have been decreasing dramatically. During the period of 1983 through 1991, the amount of volume decrease at Qori Kalis has increased 165% such that 2.155×10^6 m^3/yr is lost [2]. Similarly, ice caps on Ruwenzori Mountain and Mount Kenya in Africa have decreased as have high latitude glaciers in Austria and Iceland.

Warming trends of surface land heating is prevalent, as is evidence of oceanic heating. Studying the heat content of the ocean, [12] has shown that until the mid-1970s, the ocean was in a cool state (as measured by heat content anomalies). Since then, the ocean has been in a warm state with increased warmth accelerating. Quite recently, 1998 was the warmest year on record for the North Atlantic ocean with heat content anomalies reaching 4×10^{22} J (equivalent to 0.37°C of warming). Late 1997 into 1998 was the warmest and most variable year in the Pacific as related to the massive El Niño of 1997 [15]. Over the past fifty years, coherent changes with a cumulative net warming have occurred in the oceanic heat content. This increase in heat content shows a heat budget surplus of 0.5 to 0.7 W/m^2 from 1979 through 1996 [7].

Modeling Land Use/Climate Interaction

An agent-based model (ABM) serves as a pedagogical tool to explore the following questions: 1) how do coupled environmental and human systems interact (i.e., how do local area climate and anthropogenic land uses interact)? 2) What factors are instrumental to the choice of land use types among humans? 3) How can these processes be modeled in a disaggregated ABM framework to provide insight and further learning into both the issues of climate change and anthropogenic land use as well as the conceptual and applied constructs of an ABM?

It is important to note the tension of purpose and prediction versus explanation, which often accompany modeling projects. Given the time constraints, we have made certain assumptions in constructing the model, particularly with regards to calibration and parameterization. We acknowledge this as a fundamental limitation to the use of the model for predictive purposes. Regardless, "thought process" models of the type described often provide a "proof of concept" or help derive new questions that may be later used to inform theory, empirical investigation, or further modeling. The remainder of this section first outlines the conceptual ideas on which the model is based, and second, provides a detailed description of the model.

The Model

The model conceptually represents three systems: climatic, terrestrial, and human. Humans have limited direct influence on climate; interaction often occurs through an intermediary, in this case land use and land cover change. Figure 1 demonstrates the flow of interaction whereby humans change the land use and land cover, which also affects the future decisions of humans, and land use influences and is influenced by local area climate.

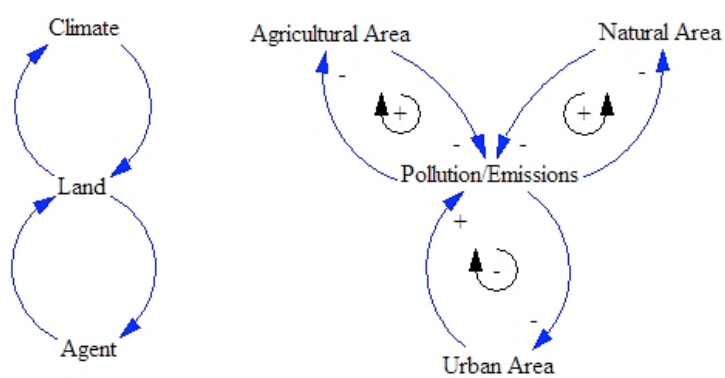

Figure 1: (left) the feedback behavior in the described model: agents affect the land directly and the climate indirectly with a complete feedback. (right) The feedback (positive or negative) feedback between the climate and three types of land use.

While one may make the assumption that the climate influences human choices of land use, thus creating a larger feedback loop, real-world examples prove that often this is not

the case (i.e. despite unfavorable climatic conditions in the southwestern United States, populations persist due to available technologies that improve living conditions in otherwise near inhospitable locations). Instead, we allow utility from land use to govern human choice.

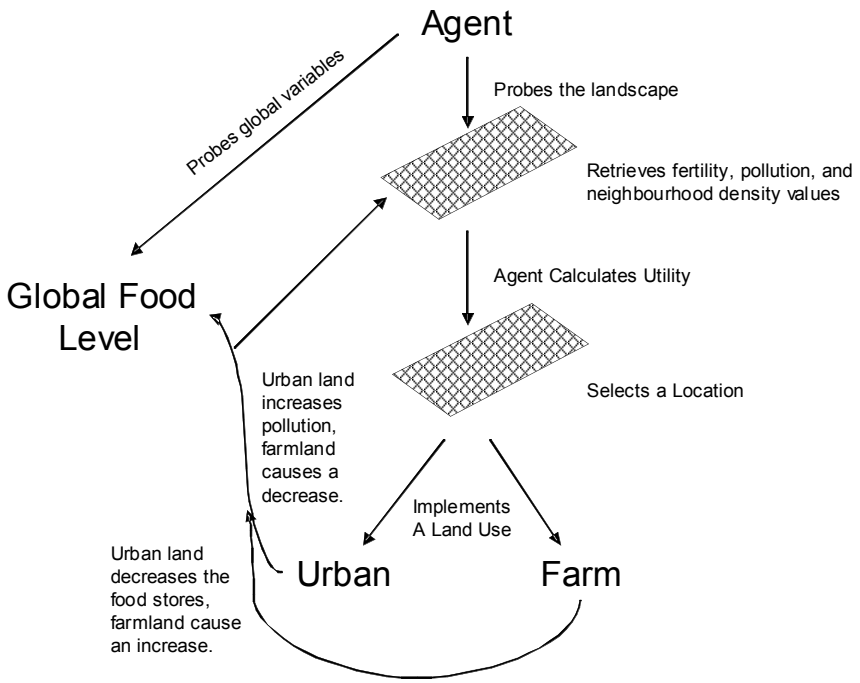

Figure 2: Outline of agent behavior and land use change process.

The process flow of the model is displayed in Figure 2 and a screen capture of the model is shown in Figure 3. An agent evaluates several locations in the landscape based on proximity to other features, fertility, amount of food available, and the level of pollution at those locations. The agent decides to convert the land at a specific location to either farm or urban based on a maximum utility calculation from its bounded site selection. Conversion of natural areas to farmland depreciates the ecosystems ability to absorb pollutants, which is a function of utility. Conversion of natural areas to urban causes an increase in local pollutants. Pollution diffuses throughout the landscape affecting future agent decisions and dissipates into the atmosphere at a specified rate.

The Landscape

The model consists of three grids: the agent grid, the land cover grid, and the pollution grid. Since the focus of this paper and the model is on land use and climate, the agent grid remains hidden and acts as a container. Agents cause a change of state in the land cover grid by converting natural land. The initial population is comprised of objects representing natural land cover assigned a random fertility value between 0-1. The

pollution grid begins empty but at each iteration pollution is added by urban land use areas. The pollution diffuses across the landscape at a constant rate and also is dissipated by the global environment at a constant rate.

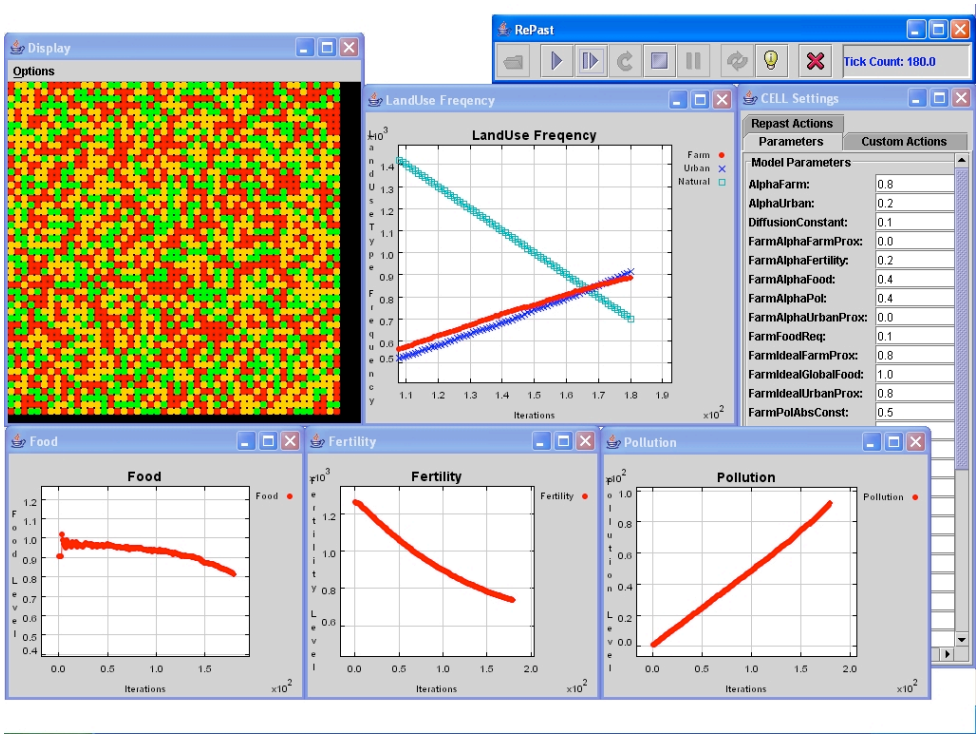

Figure 3: Screen capture of the model (from left to right, top to bottom): landcover space, land use frequency chart, RePast toolbar, model parameters, and charts plotting global food, fertility, and pollution levels.

Land Use and Land Cover Objects

As noted above, agents convert natural areas to farm or urban objects. Pollution absorption by natural and farm land uses occurs as a function of the fertility of that location.

$$P_{i,j}^{t+1} = \text{Max}\ (\ 0,\ P_{i,j}^{t} - f_{abs} * \ln(\text{fertility}_{i,j} * 100 + 1) / \ln(101)\ )\ ) \qquad (1)$$

Where $P_{i,j}^{t}$ is the pollution at cell row i, column j, time t. The farm absorption constant, f_{abs}, is then multiplied by a scaled natural log function of the fertility at that location, $fertility_{i,j}$ to ensure that the result is between 0-1. Since all values in the model are scaled between 0-1, and ln(1) = 0, and ln(anything < 1) is negative, we scaled the equation such that the log function gives us a value between 0-1.

Similarly, natural areas absorb pollution using (1) except the natural area pollution absorption constant n_{abs} replaces the farm absorption constant f_{abs}. The creation of

pollution by urban areas follows a much simpler equation whereby the existing pollution at a location $P_{i,j}$ is multiplied by an urban pollution creation constant Urb_{pol}.

$$P_{i,j}^{t+1} = P_{i,j}^{t} + Urb_{pol} \quad (2)$$

Agent Strategy

A constant number of agents enter the simulation at each iteration. Each agent evaluates a number of random locations for both farm and urban land use types. The location with the highest utility is selected for land use conversion and the land use associated with that utility is implemented at that location. Agents have a Cobb-Douglas utility function that incorporates proximity to other farm and urban land use types, fertility, level of pollution, and quantity of food in the total system. Food is used as a universal measurement supporting supply and demand calculations that influence agent utility calculations and their choice of which land use type to implement.

Agents interact indirectly by converting land to new types at earlier time steps. Proximity calculations and pollution diffusion based on previous agent behavior enhance the effects of local interaction while global food quantities act as a top-down constraint on agent decision-making.

Verification and Validation

The process of verification ensures that aspects of the model have been implemented in correspondence to its conceptual design. Testing specific components with known input and output values is ideal but can be difficult as the scope and extent of the tested components increase. Since the purpose of the presented model has been to foster conceptual formulation and ideas related to the linkages between land use and land cover with local area climate, no verification or validation methods have been implemented. The reader is referred to the following literature for detailed descriptions and techniques on verification and validation ([10],[13],[20]).

Results

Preliminary analysis of the presented ABM involved the comparison of model results to that of a 'null model' [5]. To implement a null model, agent utility functions, which determine the type of land use and land cover created (agent behavior), were replaced with random number generators. Face value validation [21] and qualitative comparisons between the model and null model results showed that the utility functions described earlier performed identically.

After analysis of the disappointing results, it is believed that the utility functions are incapable of making two decisions in a single metric. The current utility functions determine both function and location. The choice of function (whether to convert to urban or farm land type) should be based upon a simple decision: is there enough food production for the number of agents already in the state space? If there is enough food, a farm is not needed. The utility function should be used to determine the most ideal

location for the decision made. By implementing this two-step decision process (function, then location) the model would create structure (urban areas grow together, farms around the edges). This structure is important for accurately modeling human development activities.

As the purpose of the model is to serve as a pedagogical exercise, we feel that the failure of the original model to provide the results predicted at the outset provides a great deal of understanding into the problems encountered with such model development. As stated, if the utility functions are organized slightly differently, we feel the model will provide a reasonable framework from which the study of human land use and climate interact.

Future Directions

As described above, the most beneficial future direction is to simplify the utility functions. At this point in time, we believe that the most promising utility function for location decisions is

$$U(i) = (\text{Fertility})^{\alpha}(\text{Proximity to Urban})^{1-\alpha} \qquad (3)$$

where *i* is the location being considered and α is high when a farm is to be built and low when an urban area is to be built.

In addition to the restructuring of the utility functions, a number of enhancements to the model could be made. Currently, urban land types are identical; however, allowing for urban density growth (allowing new agents to join a particular urban sector such that population is a state variable) would provide a more accurate reflection on the effect of urban pollution. With three land types available, adding a water land type would help understand the spread of pollution as water acts as a sink of CO_2 and other pollutants (the water land type would not be available for conversion to other land types). In future work we plan to represent our agent-based model with a Markov Model and determine the ranges of transition probabilities, if any, that result in the aggregate proportions of the three transferable land types (natural, farm, and urban) for the parameters within our agent-based model.

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