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Integrating land markets, land management, and ecosystem function in a model of land change

Derek T. Robinson[a], **Tatiana Filatova**[b], **Shipeng Sun**[c], **Rick L. Riolo**[d], **Daniel G. Brown**[a], **Dawn C. Parker**[c], **Meghan Hutchins**[a], **William S. Currie**[a], **Joan I. Nassauer**[a]
[a]School of Natural Resources & Environment, University of Michigan, Ann Arbor, MI 48109, United States (dtrobins/danbrown/@umich.edu)
[b]Centre for Studies in Technology and Sustainable Development, University of Twente, 7500 AE Enschede, The Netherlands (t.filatova@utwente.nl)
[c]School of Planning, University of Waterloo, Waterloo, ON, N2L 3G1, Canada (sunsp.gis@gmail.com, dcparker@uwaterloo.ca)
[d]Center for the Study of Complex Systems, University of Michigan, Ann Arbor, MI 48109, United States (rlriolo@umich.edu)

Abstract: We present the conceptual design of a new land-change modelling framework that builds on previous land-change research and models (i.e. ALMA, SOME, DEED). The design integrates agents of land change, land-market mechanisms, land-management behaviour and its ecosystem impacts, and land-policy scenarios into a single framework that can be used to address questions about land-change processes in exurban environments. The framework is implemented in Java, built using the Repast Simphony agent-based libraries within the Eclipse integrated development environment. The framework serves as a platform for integrating human and natural processes, as well as data that include social surveys of residential landscape and neighbourhood preferences as well as land-management behaviours, ecological field measurements of biomass in residential property parcels, interpretations of historical air photographs, and economic and household data acquired from local governments in Southeastern Michigan. The purpose of the framework is to provide an overarching design that can be extended into specific model implementations that evaluate, among other questions, how policy, land-management preferences, and land-market dynamics affect land-use and land-cover change patterns and subsequent carbon storage and flux.

Keywords*: land-use and land-cover change; carbon storage and flux; policy; agent-based modelling; exurban development*

1. INTRODUCTION

The extent and types of land-use and land-cover change have become critical issues of global concern. Land-cover changes account for ~30% of historical anthropogenic efflux of CO_2, making it the second largest driver of anthropogenic CO_2 efflux behind only fossil fuel burning (Sarmiento and Sundquist 1992, Sundquist 1993). Recent decades have seen rates of conversion of natural and agricultural land to residential development in industrialized nations that exceed rates of growth in population size and number of households (Theobald 2005). Much of this growth is due to the low-density nature of the development, occurring in suburban and exurban densities and, therefore, covering large geographic areas. The processes and implications of these development patterns on the overall contribution of land to the carbon cycle is not well known.

The emerging field of land-change science addresses these and other important issues associated with coupled natural-human land systems (Rindfuss et al. 2004). Turner et al. (2007) identify four goals under which land-change scientists seek to improve our understanding: "(*i*) observation and monitoring of land changes underway throughout the world, (*ii*) understanding of these changes as a coupled human–environment system, (*iii*) spatially explicit modeling of land change, and (*iv*) assessments of system outcomes, such as vulnerability, resilience, or sustainability." This paper focuses on (ii) and (iii) by developing a new agent-based modeling (ABM) framework that is designed to integrate and understand biophysical, geographic, cultural (i.e., social norms), and economic processes associated with land use and land management decision-making.

Few modeling efforts have explicitly incorporated the dynamic behavior and effects of land markets, land management, or their combination on land-use and land-cover change (LUCC) patterns, especially in residential landscapes. The purpose of our modeling framework is to evaluate how policy, land-management practices, and land-market dynamics affect LUCC and subsequent storage and flux of carbon in ex-urban residential landscapes (Figure 1). We will use this modeling framework to explore a range of research questions, such as what the relative influences of land-use vs. land management on ecosystem function are; what is the relative effectiveness of planning vs. market-based policies in encouraging carbon storage in ex-urban landscapes; how do land-management policies interact with social (neighborhood/ network), demographic, and economic factors to encourage land management changes that increase carbon storage; and how do the initial landscaping decisions of developers influence the range of possible carbon outcomes over time in these landscapes.

Protocols have been developed for describing agent-based models (e.g. ODD - Grimm et al. 2006), and have been applied to the legacy models used to design this framework (Polhill et al. 2008, Parker et al. 2008). Rather than further documenting existing models, we provide an overview and description of the design concepts for the framework components, how they interact, specific types of questions they have been designed to address, and reserve the use of these protocols for specific model implementations. Results of model outcomes and detailed descriptions of specific implemented versions are beyond the scope of this paper and reported elsewhere (see for example Parker et al. in review).

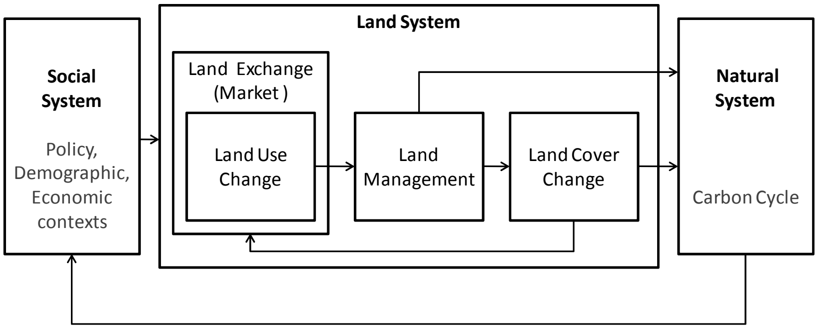

Figure 1: Conceptual outline of the presented framework. While we reserve the ability to turn on and off mechanisms in specific implementations of the framework, land-use change is shown as a component of land exchange because parcel exchange may occur without a change in land use, but land use change is always associated with land exchange. Market is placed in parentheses because land exchange may also occur in the presence or absence of market mechanisms.

2. THE FRAMEWORK

The empirical context we used while developing this framework is the land system of exurban residential development in Southeastern Michigan. The framework is implemented as a collection of libraries created to represent specific components of the larger land system, which include but are not limited to the landscape, agents, land-use change, the land market, land management and land-cover change, and the ecosystem impacts of development as measured through changes in carbon storage and flux. We model the exogenous social system through specific model settings that represent policy, demographic, and economic contexts. The structure of the framework is grounded in previous modeling efforts that have produced the following models: SOME and DEED (Brown et al. 2008), ALMA (Filatova et al. 2009a), and Biome-BGC (Running and Hunt 1993).

The framework is implemented in Java, built using the Repast Simphony agent-based libraries within the Eclipse integrated development environment (Howe 2006). Within the framework, actors and their behaviors are represented as individual agents (see 2.2). Agents create land-use-change dynamics across the landscape as a result of their individual and collective land exchange actions (see 2.3), while their specific characteristics, preferences, and decisions about land cover and land management (see 2.4) subsequently affect ecosystem function(s) and the provision of ecosystem services in the exurban land system modeled. To estimate the ecosystem impacts of exurban development, the framework links to the ecosystem process model BIOME-BGC (Running and Hunt 1993). While BIOME-BGC estimates a variety of daily and annual ecosystem function variables, we focus our work on the storage and flux of carbon in the exurban land system (see 2.5).

2.1 The landscape

The landscape is defined as a collection of land-unit objects, where each object implements a land-cover interface[1] and an ecosystem-model interface. The land-cover interface is designed to track the proportion of land-cover types (e.g. tree cover, impervious, grass, shrubs) within the boundary of the land-unit object. The ecosystem-model interface is designed to gather the necessary input variables for integrating the land-unit with an ecosystem process model (in our case we use BIOME-BGC).

We instantiate three types of land-unit objects (cells, parcels, and subdivisions) that each implement the land-cover and ecosystem-model interfaces, which allows us to integrate the ecosystem model at all possible scales of a model run. Each land-unit acts as a container for geographic and biophysical location-based state variables as well as the natural processes that it may undergo. Effectively this allows each land unit to be an independent automaton.

In an effort to create a framework that could incorporate a variety of natural and human systems processes we use a hybrid raster-vector approach to represent the landscape. Similar to Box (2002), our landscape is initialized as a grid composed of cell objects. Parcels are then created as a collection of cell objects, which may be used to represent an individual residential land parcel, farm property, or, among other land-uses, area used for conservation and preservation of open space. Similar to the way a collection of cells forms a parcel, a collection of parcels can be combined to form a residential subdivision or farm.

The three land-unit objects (cells, parcels, and subdivisions) have a hierarchical relationship to allow information to be passed among them - either through a top-down or bottom-up process. In the former, a developer may implement a land-management strategy at the subdivision level that is carried down to a specific parcel and then to specific cells within a parcel. In the latter situation a residential household may evaluate the biophysical or geographic characteristics of a parcel, which would require summarizing values from the collection of cells that form a parcel (e.g. nearest cell to a road or average aesthetic quality).

2.2 Agents

The framework includes agents that represent rural landowners (i.e. farmers), developers, land brokers, and residential households. What follows is a general description of the framework of these agents barring specific implementation characteristics and behaviours.

Rural landowners. A rural landowner agent continues using the land as it has historically (to support its livelihood) until an offer is made for its parcel that exceeds its

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[1] Here we are referring to a Java interface. When an object implements an interface it is forced to provide the methods and type of output specified by the interface. By standardizing this relationship, we ensure the necessary data is available for input to the ecosystem model and other model components.

willingness to accept price (WTA). When this occurs the landowner will sell the parcel and exit the model.

Developers. Developer agents acquire land parcels for the purpose of subdividing into smaller parcels, or aggregating into larger parcels, for sale and profit. Each developer agent has its own preferences for the biophysical and geographical characteristics of a parcel or set of parcels. Developers establish land management strategies on the parcels they create by initializing the proportion of land-covers within each parcel.

Land Brokers. Land broker agents facilitate the exchange of land between two agents by 1) providing additional information to agents concerning available parcels, 2) transferring property ownership, 3) posting sale opportunities and closures to the market institution, and 4) implementing negotiation mechanisms to determine the sale price.

Residential households. Residential household agents participate in land-use change, through the process of land exchange, and land management. Entering the model based on an exogenously defined in-migration rate, each residential household agent seeks to find a settlement location that optimizes its utility under several constraints (i.e. degree of information, budget). If the agent is successful in acquiring a parcel then it begins to manage the land cover within the parcel boundary (see Section 2.4). Residential household agents may also offer their properties up for land exchange. When a residential household agent sells its parcel it may, depending on model settings, 1) search out an alternative location that provides a higher utility and attempt to purchase that location before selling the current location, 2) sells its parcel to the highest bidder and either a) exit the model or b) look for an alternative location in the landscape. Land management strategies and sale prices formed by residential households may be a function of spatial neighbourhood or social factors (e.g., networks of family and friends).

2.3 Land-use change

In this framework, we differentiate land-use change from land management such that land-use change refers to the exchange of land between two agents performing different land use activities (e.g. urban or rural land use) and land management refers to agent actions that change the proportion or quality of land-cover types and ecosystem functions within a parcel or unit. Land exchange does not necessarily change land use (e.g. a property is transferred from one residential household to another). The exchange may occur in the absence (see 2.3.1) or presence (see 2.3.2) of a land market, as influenced by exogenous policy, economic, and demographic contexts (see 2.6). Land is supplied by rural land owners (e.g. farmers), subdivision developers, or existing residential land owners intending to move. Land can be acquired by developers and residential households.

2.3.1 The non-market approach

We model the exchange of land with and without the inclusion of land-market processes. In the non-market approach land policies provide the only constraints to land acquisition. The focus of non-market implementations of the presented framework is on evaluating the effects of residential household agent preferences for geographical (e.g. nearness to water or roads) and biophysical (e.g. soil conditions, elevation, percent tree cover) characteristics on development patterns.

2.3.2 The land market

The land market model borrows from the previously developed ALMA model (Filatova et al. 2009a, 2009b) and utilizes concepts from urban economics (e.g. spatial structure, location decisions under budget constraints, and competition) to represent interactions between the demand and supply of land. When implemented within a model run, the land market is formed by bilateral trades amongst agents that buy and sell parcels. The collective outcome of these decentralized trades replaces traditional equilibrium price determination mechanisms (Arthur 1997, Tesfatsion and Judd 2006).

Demand and supply side of a land market. The supply of land (i.e. parcels) by an agent for purchase or acquisition by another is determined as a function of policy constraints (e.g. zoning), subdivision sales, and each agent's motivation for supply, WTA and ask price. The rate of in-migration and existing agents desire to relocate within or outside the region determine aggregate demand. At the individual level, agent willingness to pay (WTP) is determined as a function of transportation costs, parcel characteristics, location preferences, and budget constraints.

Market Transactions. Market transactions take place when two agents negotiate an exchange of land through a land-broker agent. Buyers form a WTP and then either submit a bid to a broker agent or directly to the seller. The bid price is a function of WTP, excess supply and demand, and the seller's ask price. The seller, having already formed a WTA and posted an ask price, determines which bid (if any) to accept and may conduct a price negotiation strategy. The inclusion of bid and ask prices that serve as reservation prices and the WTP and WTA prices, which depend on various market factors, allow us to model strategic behaviour.

Following a sale, the seller submits transaction information to the broker agent, which then posts the sale to a market-institution object. This object tracks market information (e.g. number of buyers and sellers; recent transactions). It also maintains a list of available parcels and their characteristics that enable broker agents to efficiently search the list for a specific property, type of property, or create a sublist of properties. The market institution acts like a multiple listing service and facilitates the expansion of the framework to include new agent implementations (e.g. realtor agents).

Land market based research questions. The inclusion of a land market in a land-use model allows us to ask questions related to the effect of market factors (e.g. credit availability, interest rates, strength of demand relative to supply, competition) and heterogeneous individual characteristics (e.g. budget constraints, strategic behavior) on the allocation of land uses, land covers, and subsequent ecosystem function. As a first step to addressing these types of questions Parker et al. (in review), we incrementally included additional land market mechanisms to first answer the question: How do spatial patterns of development differ with the inclusion of a land market? To answer this question we start with a simple initial model of residential location and step-wise include additional market mechanisms to evaluate the role of land markets in spatial development. For example, we explore the patterns of residential development in the absence of a land market, when the market is present and agents face budget constraints, then we add competitive bidding, and then strategic behavior.

2.4 Land management and land-cover change

In addition to the location search and market interactions, each agent also implements a land management strategy that alters the biophysical characteristics of the land cover within its parcel boundary. The land management behaviour is based on the existing land management of a parcel, management behaviour of neighbours or other social contacts, expectations of land market valuation, and agent characteristics and preferences. We define a land management strategy as the collection of land-management actions conducted by a land owner. The ecosystem impacts of land-use changes and land management are then estimated using BIOME-BGC (see 2.5).

In the framework, we separate land management into two types of actions performed by landowners. The first is an alteration to the biogeochemical state variables within a land unit (e.g. changes in litter carbon pool). In this case, land management actions are implemented by removing, adding, or transferring carbon and nitrogen values from one land cover to another (or out of the model). For example, a residential household may rake and remove leaf litter (e.g. burning it) or rake and transfer leave litter from one location to another.

The second action involves a change in resource inputs (e.g. increased irrigation for lawn maintenance) and is a direct driver of ecosystem function (Figure 1). These alterations affect the abiotic growing conditions or alter the physiological behaviour of the biome or land cover represented. For example, a residential land owner that implements an irrigation land management action would alter the precipitation inputs that are typically specified as a meteorological input. Greater flexibility exists for the implementation of land management practices that alter the meteorological input variables because they may be represented at a finer resolution, since in BIOME-BGC these variables are read on a daily time step. For example, irrigation could be implemented 1) at a fixed interval, or 2) triggered under conditions of low precipitation.

We set up the land unit and management strategy components in such a way that the land management strategy can be imposed from the top down on all land units (i.e.

subdivision, parcel, and cell) or it may be specified for any specific land unit. This was done to represent the case in which a developer creates a subdivision and implements a management plan at the subdivision level that is carried out on all parcels within the subdivision and all cells within each parcel. We will use the framework to address the hypothesis that the top-down assignment of land management practices creates a form of lock in that is difficult to reverse. Alternatively, we also allow a residential household to perform one type of management strategy on its parcel or a set of specific cells within its parcel.

2.5 Impact on ecosystem functions

To estimate the ecosystem impact of exurban development and land management practices, the SLUCEII project team decided to use the widely published ecosystem process model BIOME-BGC (Running and Hunt 1993) to estimate changes in carbon storage and flux. With respect to the carbon cycle, the BIOME-BGC model simulates vegetation growth and changes in ecosystem C flux and storage in individual pools (e.g. root, stem, and canopy) as well other ecosystem functions such as gross and net primary production (Running and Hunt 1993). The model could be classified as a point-based model that estimates the output of a series of ecosystem functions for the site conditions at a specific point. The corollary assumption is that the point is representative of a homogenous region to which the output is multiplied by the area of that region to provide an estimate of regional level ecosystem function output.

To estimate the ecosystem impact of exurban development and land management practices, each land unit is first initialized with a number of biogeochemical state variables. The state variables are initialized by running BIOME-BGC through a spin-up phase that establishes a dynamic equilibrium among vegetation ecophysiology, soil organic matter, nutrient pools, and climate (Thornton et al. 2002). To incorporate the effects of land-use histories and land management practices on ecosystem function we alter these state variables to approximate the changes in carbon and nitrogen pools above and below ground, similar to Robinson et al. (2009).

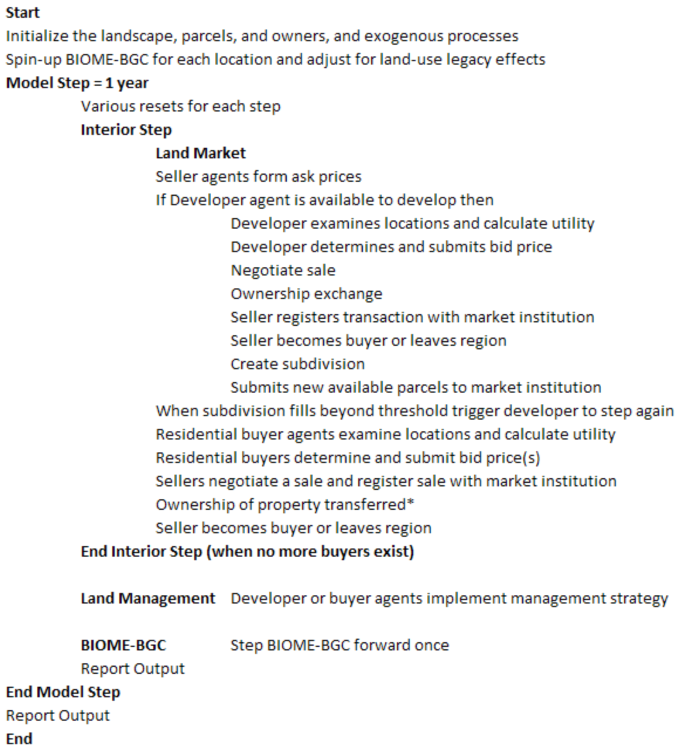
Figure 2 demonstrates the schedule of agent and component actions that occur in a typical implementation of the presented framework, which includes the initiation of BIOME-BGC following LUCC decisions and actions.

2.6 Land policy, demographic, and economic contexts

One goal of extending LUCC models to include land market and land management behaviour is to evaluate a number of land-use and land-management policies that could be enacted to help keep highly fragmented and human dominated exurban landscapes acting as carbon sinks, essentially providing an ecosystem service and help mitigate the effects of climate change. Land policy scenarios are implemented exogenously in the presented framework by manipulating specific model implementation parameters. Policy options could include minimum lot-size zoning regulations, use of tax or transaction costs to promote regions of high versus low development, and inclusion of carbon-storage incentives such as carbon payments. Some parameters also allow us to investigate the influence of processes not explicitly represented within the framework, but are included as exogenous drivers. The effects of population size, rate of in-migration, the distribution of population characteristics and preferences on development patterns and subsequent ecological effects are some of the exogenous demographic factors we plan to investigate. Similarly, exogenous economic factors like credit availability, opportunity costs to moving outside the region, and changes in interest rates may also drive development patterns.

2.7 Limitations

While the framework could be extended to add additional focus on the influence of farmer decision making, local economic development, or collective action on LUCC and resource and ecosystem management, the current framework is designed to represent land systems where residential development and residential land-management behaviour are the dominant mechanisms driving LUCC. Given this orientation, the framework could be extended to serve as a template for other systems within the United States, Canada, or abroad.



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Start
Initialize the landscape, parcels, and owners, and exogenous processes
Spin-up BIOME-BGC for each location and adjust for land-use legacy effects
Model Step = 1 year
    Various resets for each step
    Interior Step
        Land Market
        Seller agents form ask prices
        If Developer agent is available to develop then
            Developer examines locations and calculate utility
            Developer determines and submits bid price
            Negotiate sale
            Ownership exchange
            Seller registers transaction with market institution
            Seller becomes buyer or leaves region
            Create subdivision
            Submits new available parcels to market institution
        When subdivision fills beyond threshold trigger developer to step again
        Residential buyer agents examine locations and calculate utility
        Residential buyers determine and submit bid price(s)
        Sellers negotiate a sale and register sale with market institution
        Ownership of property transferred*
        Seller becomes buyer or leaves region
    End Interior Step (when no more buyers exist)

    Land Management     Developer or buyer agents implement management strategy

    BIOME-BGC           Step BIOME-BGC forward once
    Report Output
End Model Step
Report Output
End
```

Figure 2: Order of actions in a typical implementation of the framework. Other implementations can replace various components, e.g., the Land Market could be replaced by a simpler Land Exchange or BIOME-BGC could be replaced by a simpler submodel.

3. CONCLUSIONS

The framework presented here extends traditional LUCC models to incorporate land-market mechanisms, land-management behaviour, and, by linking to an ecosystem process model (i.e. BIOME-BGC), estimates of ecosystem function. In combination, these components contribute a novel approach to the study of land-change science. For example, inclusion of the land-market mechanisms (e.g., budget constraints, competition, strategic behaviour, and neighborhood effects – all known to drive land change dynamics), allow us to explore how and what types of LUCC patterns and subsequent carbon storage and flux occur when 1) policy is used to exploit market mechanisms, 2) there are joint effects among market mechanisms and land management, and 3) heterogeneity in buyer preferences and their socio-economic characteristics influence land-market and land-management behavior.

Furthermore, by incorporating market mechanisms, we may improve the alignment of our model structure with the structure of the Southeastern Michigan land system. The benefit is twofold: first, by incorporating additional mechanisms driving land change our model results will become more comparable to the study system; second, the inclusion of additional mechanisms and variables deemed to drive LUCC provide additional patterns to which model results may be compared or validated against observations, and/or used to gain stakeholder or policy-maker confidence.

Land-use and land-management dynamics jointly determine land-cover change and ecosystem function. By developing a framework that can be tightly coupled to a variety of ecosystem process models, we create flexibility for not only providing ecologically based estimates of changes in ecosystem function and services, but we also create the opportunity to utilize different ecosystem process models. By better representing the natural system in coupled natural-human land systems, we answer research calls by international and national organizations (e.g. Global land project, U.S. National Science Foundation's Coupled Natural/Human System program) that aim to address questions such as: what conditions create lock-in or path dependence in the types and proportions of land-cover and subsequent carbon flux and storage when developers initialize subdivision landscapes; what management strategies have unintended effects on carbon flux and storage with and without the presence of land markets; and how does residential demand for properties depend on current and projected land management practices?

While contemporary land-change research has increased focus on better coupling natural and human system models (e.g. Yadav et al. 2008), we go one step further to include land management practices. By improving our understanding of what drives landowners to perform specific land management actions as well as how and to what degree land management can alter ecosystem function, we can understand the social, economic, policy conditions that may lead a property (and, collectively, a community and region) to be a source or sink of carbon. The combination of land market, land management, and estimates of ecosystem impacts provides a rich framework that allows us to ask policy questions that may help keep highly fragmented and human dominated exurban landscapes acting as carbon sinks, essentially providing an ecosystem service that could help mitigate the effects of climate change.

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