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Coupled simulation of human-driven and natural land cover change in the Front Range Corridor, CO

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Abstract: The Colorado Front Range Corridor is a mixture of urban, agricultural, grassland, and diverse forest types, making it an ideal natural laboratory to investigate feedbacks and interactions of coupled human and natural systems. We explored future scenarios of human-driven land use change and natural vegetation dynamics using the CHANGE model, which integrates a demand-allocation land use change module, a succession module for natural vegetation dynamics, and a spatially explicit fire initiation and spread module. We used the model to project landscape change over an approximately 48000 km² study area from 2005 through 2050 under A2 and B1 emission scenarios. The area of young forest and deciduous forest increased due to increased burned area. The degree of forest species and structure change depended on the fire regime, with more dramatic change simulated under the A2 emission scenario. Expansion of developed areas resulted in loss of natural vegetation, and most of the newly developed area was in the Great Plains. However, expansion of the wildland urban interface (WUI) mainly occurred in the forests of the Southern Rocky Mountains and was concentrated along roads. The results suggested that: (1) increase of young forest may lead to higher drought and fire susceptibility, further amplifying fire risks; (2) fire and fuel management in the WUI is already challenging and those challenges will be greater with continued expansion of the WUI and changes in fire regimes; (3) changing land cover and natural vegetation composition and structure in our study area may have significant effects on a variety of ecosystem services.

Keywords: coupled human and natural systems, wildland urban interface, land use and cover change, climate change, ecosystem disturbance, wildfire

1. INTRODUCTION:

Land cover and land use (LCLU) change increasingly has been recognized as a primary driver of global environmental change, and understanding its causes and consequences is critical in the study of both human societies and natural ecosystems. LCLU change is the result of reciprocal interactions and feedbacks between human activities (e.g., forest harvesting, urban expansion, agriculture intensification), natural processes (e.g., succession, wildfires) and environmental change (e.g., climate warming) that occur across multiple spatial and temporal scales. To better understand the causes and consequences of LCLU, there is strong appeal in using a conceptual framework of coupled human and natural systems, that incorporates nonlinearities, threshold behaviors, and emergence properties of the systems (Liu et al., 2007). These interacting factors can influence landscape change at different spatial and temporal scales, and their feedbacks and interactions are often difficult to measure empirically. In this context, integrated
simulation modeling has served as both a philosophical perspective and a technical tool for identifying the cause–effect relationships that couple natural and human systems, thus providing the basis for a more holistic understanding of landscapes as highly integrated systems.

In particular, the continued expansion of residential housing and other human infrastructure into wildland vegetation poses a challenge for fire and fuel management in the United States (Spyratos et al. 2007). In this study, we developed a spatially explicit land cover change model, CHANGE, which integrates a demand-allocation LCLU module, a state and transition succession module for natural vegetation dynamics, and a spatially explicit fire initiation and spread module. The model simulates the landscape as coupled human and natural system by explicitly considering human and natural processes that drive landscape change as well as their interactions. The objectives of this study are to demonstrate the ability of CHANGE to (1) simulate LCLU as a coupled human and natural systems, and (2) project landscape change from 2005 through 2050 under A2 and B1 emission scenarios, (3) simulate the dynamics of wildland urban interface and fire risk from 2005 through 2050 under A2 and B1 emission scenarios.

2. MATERIALS AND METHODS

2.1 The CHANGE model

The Coupled Human and Natural Geospatial Environments (CHANGE) model is a spatially explicit, stochastic, computer model designed to simulate regional land change dynamics resulting from multiple human and natural processes and their interactions. LCLU change is modeled in two separate stages: demand and allocation (Sohl et al., 2012). Demand indicates the total areas of different types of land changes that will occur during a given time step. The allocation algorithm distributes the transition pixels specified in the demand step to specific locations on the landscape based on a variety of spatial constraints, such as probability surface for each destination class, land ownership, or spatial distance lag from existing land cover class. Within vegetated LCLU classes, vegetation succession is modeled as pre-defined pathways which simulated changes in structural class and cover type, together called a successional stage. Fire can disrupt succession and can delay or advance the time spent in a successional stage, or cause an abrupt change to another successional stage. Wildfires are simulated using a spatially explicit fire spread algorithm that captures key interactions between the human and natural systems, such as the potential for fire spread from human-dominated areas into natural vegetation (Wimberly and Kennedy, 2008). In CHANGE, the simulated landscape is divided into a number of relatively homogeneous regions based on climate, vegetation, and physiography. Within each region, fire frequencies, sizes, and severities are assumed to be different. The user supplies the parameters of the fire regime, such as fire rotation and the mean and standard deviation of fire size. Fire occurrence is simulated based on topographic and vegetation characteristics and size is modeled as a lognormal distribution. Fire propagation is simulated using a cellular automata algorithm. Fire severity is conditioned by the vegetation type and successional stages. The spread and effects of individual fires can also be influenced by landtype. For example, southern slopes may promote fire spread and reduce fire severity due to low buildup of fuel.

Another unique feature of CHANGE model is that it can simulate the human-natural interface where human activities such as development and agriculture intermingle with natural ecosystems. For example, the wildland urban interface (WUI), which is defined as areas where low density human development abuts or intermingles with natural vegetation, is a special case of human-natural interface, and pose particular challenges for fire and natural resource management in the US. The WUI was simulated as an “overlay” class in which low-density human development is allowed to occur in naturally-vegetated land cover types. Therefore, the WUI can be considered as hybrid class, as it is a human-dominated LCLU type in which natural vegetation dynamics and disturbance still occurs.

2.2 Study area description
We selected an area of approximately 48000 km$^2$ at the intersections of three EPA level III ecoregions in Colorado: Southern Rockies, High Plains, and Southwestern Tablelands (Figure 1). The study area includes a mountainous forest region in the west, the Colorado Front Range urban corridor in the middle, and agriculture and grassland-dominated plains in the east. Thus, the study area contains a mixture of urban, agricultural, grassland, and diverse forest types, making it an ideal natural laboratory to investigate the feedbacks and interactions of coupled human and natural systems that drive the LCLU change.

2.3 Simulation scenarios and parameterization

The main parameters for the model were determined as explained below.

**Demand.** The demand for each scenario was provided by downscaling land cover change projections from the IPCC special report on emissions scenarios (SRES) to the EPA level III ecoregional scale. The downscaling processes incorporated modeling results from an integrated assessment model (IMAGE model), LCLU histories (1973 – 2000 land cover trends), and expert knowledge in USUS EROS center (Sleeter et al., 2012, Sohl et al., In press). The net results of the downscaling effort were quantitative proportions of each future LULC at 5-year increments from 2005 to 2100 for each of the four SRES storylines, for each of the 84 Level III ecoregions. We further downscaled the demand for each land cover class by an area-weighted approach for the ecoregions in our study area for A2 and B1 emission scenarios. The Demand for WUI was estimated by extrapolating historical trend (1980 - 2000) into future (2000-2050) using data from Theobald (2005). The demand for burned area under B1 and A2 emission scenarios was set as a relative increase of 15.3% and 38.5% in current time step compare to previous time step based on Litschert et al. (2012), and the historical burned area (1984 - 2010) was calculated from MTBS dataset (http://www.mtbs.gov/).

**Spatial constraints of land cover change.** Once the demand for each land cover class was determined, the spatial allocation of land cover change was controlled by probability of occurrence surface for each destination class, land ownership, or spatial distance lag from existing land cover class. We used logistic regressions to relate land cover type with a suite of predictors (see Sohl et al. 2008 Table 2 for variable lists) to get probability-of-occurrence surfaces for each land cover type. Land ownership was used to denote the constraints on certain land cover conversion designated by different management policy (e.g., urbanization was prohibited on public lands and other protected areas). New patches were constrained to be within a threshold distance of existing patches of the same LCLU type based on data from the Land Cover Trends project (Loveland et al., 2002).

**Sensitivity analysis.** To explore variability in the spatial pattern of land cover change in response to model inputs, we conducted a sensitivity analysis on each of the following parameters.

1. The degree of land cover change which was controlled by “demand” for land cover classes and burned area.

2. Land cover change pattern, which was controlled by spatial distance lag. New patches were allocated based on a spatial distance lag, under the assumption that land cover change was more likely to be occurred near to existing land cover types. Smaller lag values result in more compact land cover changes (e.g., edgy growth), whereas larger values result in more dispersed land cover change (e.g., leapfrog).

3. Patch complexity, which was controlled by a patch shape parameter. Smaller complexity values resulted in more compact and contiguous patches, while larger values resulted in more complex and irregular patches.

4. Probability threshold, which indicated the minimum probability surface value at which change occurred and interacted with lag distance to control the eligible cells for change. If there were not enough cells within the spatial distance lag to meet the demand, then the placement of new patch was only constrained by probability threshold. Lower values led to more dispersed change because more eligible cells are available to change, whereas larger value will result into more compact land cover change.
Simulation scenarios. We projected landscape change from 2005 through 2050 under the A2 and B1 emission scenarios. Specifically, we compared (1) what is the proportion of broad land cover classes and forest structure trajectory under A2 and B1 emission scenarios; (2) what is the future potential WUI fire risk in the study area.

![Figure 1: The location of study area, and the simulated landscape cover for 2050 under a) compact (Distance lag = 1; patch complexity value = 1; Prob = 0.95), and b) dispersed (Distance lag = 9; patch complexity value = 3; Prob = 0.50) development pattern for B1 emission scenarios.](image)

Figure 1. The location of study area, and the simulated landscape cover for 2050 under a) compact (Distance lag = 1; patch complexity value = 1; Prob = 0.95), and b) dispersed (Distance lag = 9; patch complexity value = 3; Prob = 0.50) development pattern for B1 emission scenarios.

![Figure 2: LCLU change under A2 and B1 emission scenarios (Distance lag = 5; patch complexity value = 1; Prob = 0.95). See Figure 1 for legend.](image)

Figure 2. LCLU change under A2 and B1 emission scenarios (Distance lag = 5; patch complexity value = 1; Prob = 0.95). See Figure 1 for legend.

3. RESULTS AND DISCUSSION
Sensitivity analysis showed that different parameter settings led to different land cover change patterns and patch complexity. Consistent with our expectation, shorter spatial distance lags, lower values of the patch shape parameter, and higher thresholds for probability-of-occurrence surfaces resulted into more compact land change patterns and more contiguous patches (Figure 1a). On the contrary, longer spatial distance lags, higher values of the patch shape parameter, and lower thresholds for probability-of-occurrence surfaces resulted in more dispersed land change patterns and more irregular patches (Figure 1b). Spatial distance lags had a relatively large influence on land cover change patterns. To enable both edge growth and leapfrog type development, we adopted 5 pixels (450 meters) as the spatial distance lag value. The land cover change was more dramatic under A2 emission scenario due to higher demand for urban and agriculture and more associated loss for natural land cover types than that under B1 emission scenarios (Figure 2). Generally, the model behaved as expected, and demonstrated its ability to simulate various patterns of land cover change and natural dynamics in a coupled human and natural systems framework.

Figure 3. Proportion of LCLU under A2 and B1 emission scenarios. A2 emission scenario was represented as circular and solid lines, and B1 emission scenario was represented as triangular and dashed lines.

There was a greater amount of area in human dominated land-cover types (e.g., developed, and wildland urban interface) due to higher demand under the A2 emission scenario. Correspondingly, there was a more dramatic decreasing trend of natural vegetation types (e.g., shrub, grass, evergreen forest) under the A2 emission scenarios (Figure 3). Because burned area increased over time, there was an increase
in the deciduous forests under A2 emission scenarios. A closer examination revealed that the increase of deciduous forests was mainly driven by increases in young deciduous forest, especially under the A2 emission scenario. Under the A2 emission scenarios, we simulated a larger proportion of young forest due to increase in burned area and higher severity fires (Figure 4). The increase of burned area, along with the expansion of WUI in the natural vegetated region greatly increased the WUI fire risk suggesting that more human properties may be at risk of loss to fires in the future (Figure 5).

Figure 4. Proportion of different forest structures under A2 and B1 emission scenarios. A2 emission scenario was represented as circular and solid lines, and B1 emission scenario was represented as triangular and dashed lines.

Our results suggested that future LCLU change and climate-driven increases in burned area will have significant influences on landscape structure, ecosystem function, and human society in the study area. In the Great Plains, human population growth drives the rapid expansion of urban areas, and could potentially increase carbon sequestration through tree and shrub planting in the urbanized area (Golubiewski, 2006). However, the loss of natural vegetation through urbanization and agriculture expansion may drive the local extinction of wildlife because of the loss and fragmentation of wildlife habitat. In the Southern Rocky Mountains, landscape change is driven by a combination of ecological and
human factors. For example, future climate-driven increases of wildfire occurrence will promote the development of deciduous forest and young forest. Therefore, the increase in burned area driven by climate change could potentially reduce the carbon stocks of forest regions.

Our analysis showed that WUI expansion will occur along major road corridors and near the boundaries of private and public lands due to accessibility and the preference for housing in areas with natural amenities. As the simulation progressed, we showed an increasing area burned in the WUI, suggesting that structures will be at higher risk to wildfires in the future (Figure 5). This may pose a particular challenge to fire and fuel management. However, we are likely underestimating the human property risk to wildfires, because (1) human presence and structures may increase the fire ignition and also create difficulty in protecting valued human properties during wildfire; and (2) future structures are likely to be built on parcels that, on average, have somewhat higher potential fire intensity and higher percentage of crown fire compared to currently developed parcels (Platt et al., 2011).

![Figure 5. Area burned for WUI under a) A2, and b) B1 emission scenario](image)

4. CONCLUSION

We demonstrated the ability of a newly developed regional land change model, CHANGE, to simulate land cover change, natural dynamics and disturbance, and wildland urban interface expansion in a coupled human and natural system in the Colorado Front Range area. Our results showed that human and natural process both contributed to landscape change, but in different geographic regions. The increase of young forest and deciduous forest resulted from climate-driven increases of burned area, and magnitude of forest species and structure change depended on the magnitude of fire regime alteration. Human-driven expansion of developed areas resulted in loss of natural vegetation in the Great Plains. The expansion of WUI mainly occurred in the forests of the Southern Rocky Mountains and was concentrated along roads. However, it should be emphasized that these simulations are a projection of the future under hypothetical conditions. They provide a structured way to think about possible future outcomes of current policies. Nonetheless, the results suggested that: (1) increase of young forest may occur, potentially leading to higher drought and fire susceptibility and further amplifying fire risks; (2) fire and fuel management in the WUI is already challenging and those challenges will be greater with continued expansion of the WUI and changes in fire regimes; and (3) changing land cover and natural vegetation composition and structure in our study area may have significant effects on a variety of ecosystem services.

5. ACKNOWLEDGMENTS

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6. REFERENCES