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A model of exurban land-use change and wildfire mitigation

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Abstract. As exurban development spreads throughout fire-prone areas of the western United States, the threat of wildfire to life and property grows. To address this threat, wildfire mitigation, such as mechanical thinning, often takes place in areas close to exurban development. This study demonstrates the utility of spatially explicit dynamic models to understand better where the wildland – urban interface is, how it might change in the future, and how this might affect which land would be prioritized for mechanical thinning. Specifically, a model (WHAMED) is presented that forecasts the prioritized locations for future mechanical thinning as a function of projected exurban development in the montane zone of Boulder County, CO. To predict exurban development, WHAMED uses a cellular automata model with rules derived from statistical models of historical exurban development. The study tests two general sets of criteria for prioritizing mechanical thinning, that of the Community Protection Zone and the Healthy Forests Restoration Act of 2003. The study shows that under any forecast of exurban development, and under either set of criteria, prioritized land for mechanical thinning is set to expand primarily on US Forest Service land. Methodologically, the study illustrates the importance of making variability transparent and of providing multiple methods of model validation.

1 Introduction

Wildland fire poses considerable risk to howeowners, governments, and land-management agencies across much of the western United States. To reduce the threat of wildfire, landholders have two primary options: suppress fires once they have started, or mitigate future fires with treatments such as prescribed fire or mechanical thinning (the reduction of ladder fuels and small-diameter trees in order to maintain persistent openings in the canopy). In 2003, federal agencies employed both suppression and mitigation: they spent a total of $1.3 billion on fire suppression activities and treated approximately 3 million acres.[(1)] Though fire suppression has long been a priority, it is also seen as a victim of its own success. In certain ecosystems, such as the ponderosa pine forests of the southwest United States, disruption of natural fire cycles has led to a buildup in fuel that increases the probability of catastrophic wildfires (Covington and Moore, 1994). Recent fire policy, such as the National Fire Plan (USDI, USDA, 2001a) and the *Healthy Forests Restoration Act* H.R. 1904 (hereafter the HFRA, see US House of Representatives, 2003), emphasizes mechanical thinning as a means to reduce the intensity of wildfire and to reverse the buildup of dense stands assumed to be caused by years of fire exclusion (USDI, USDA, 2001a).

Increasingly, wildfire mitigation such as mechanical thinning is focused at the wildland – urban interface (WUI), at which homes and other structures mix with or are adjacent to wildland vegetation (USDI, USDA, 2001a). Prioritization of the WUI has arisen because it is not feasible (or desirable) to thin all 200 million acres of fire-prone federal land and additional private land. According to one estimate, the WUI covers 9% of land area and contains 39% of all houses nationally, though not all of this is fire-prone (Radeloff et al, 2005). Two characteristics of the WUI remain ill defined:

[(1)] National Interagency Fire Center, http://www.nifc.gov.

precisely, where it is and how it might change in the future. Spatially explicit models of land-use change have great potential to illuminate these characteristics of the WUI, and thus to reveal where future mechanical thinning may take place.

Thus far, spatially explicit models of the WUI have generally followed two strands of research. First, many WUI models are designed to delineate the current extent of the WUI. For example, one study mapped the extent of the WUI by overlaying census and land-cover data (Radeloff et al, 2005). Another study mapped the WUI with the use of classified nighttime satellite imagery (Cova et al, 2004). A second strand of WUI research has focused on spatially explicit evaluations of wildfire hazard. Examples, include the Wildfire Hazard Identification and Mitigation System (Boulder County Wildfire Mitigation Group, 2001) and the risk-hazard-value map (Theobald, 2001). In both strands of WUI research, spatially explicit models have been used to delineate the past and present state of the WUI. WUI models also have the potential to illustrate probable *future* extent and *future* hazard. Spatially explicit dynamic models of land-use change have been successfully applied to resource-related issues such as watershed function (Jantz et al, 2004), sustainability in developing countries (Barredo et al, 2003), rapid urbanization (Cheng and Masser, 2004; Lopez et al, 2001), farmland conversion (Bradshaw and Muller, 1998; Wu, 2002), cropping patterns (Verburg and Veldkamp, 2001), and deforestation (Pontius et al, 2000). To date, however, they have not been applied to the pressing problem of wildfire mitigation in the expanding WUI.

This paper describes a model called WHAMED (Wildfire Hazard Mitigation and Exurban Development), which identifies and prioritizes land for mechanical thinning on the basis of the density of exurban development. The model has two main components. First, a cellular-automata (CA) model predicts where exurban development is likely to occur. Second, a site-sustainability model determines which land should be prioritized for mechanical thinning, according to two sets of criteria: the criteria for the community protection zone (CPZ) (Nowicki, 2002) and the criteria for the WUI as defined by the HFRA (US House of Representatives, 2003). The conceptual framework, construction, and validation of WHAMED are described in the paper, and initial output according to the two sets of criteria is presented. The study shows that, under any forecast of exurban development for the study area, prioritized land for mechanical thinning is set to expand primarily on US Forest Service (USFS) land.

2 The wildland – urban interface (WUI)

To be relevant to policy, a model of the WUI must have two elements. First, the model must incorporate the driving forces of land-use change specific to exurban environments. Second, the model must simulate the policy response to exurban development, in this case mechanical thinning. In the following section these two specific elements are described conceptually and in the methods section they are operationalized for the study area of Boulder County, CO.

2.1 Driving forces of exurban development

The proximate cause of the expansion of the WUI is exurban development in areas with extensive wildland vegetation. Exurban development is a function both of national-scale trends and of local characteristics. At the national scale, several trends have contributed to expanding exurban development. First, residential development has become more dispersed as employment centers have shifted from urban areas to suburbs and edge cities (Garreau, 1991)—thereby placing rural areas within commuting distance. Consequently, commuting time and housing costs in the 'exurbs' are similar or lower than for suburban or urban residents (Dueker et al, 1983). Second, the ability to telecommute makes it easier to live and work in more remote areas (Riebsame et al, 1996).

Local characteristics are also important drivers of exurban development. For example, access to amenities such as ski resorts (Duane, 1999), public lands (Riebsame et al, 1996), and space and seclusion (Davis et al, 1994; Nelson, 1992) have become important determinants of exurban development, especially in areas with a large number of second homes (Rudzitis, 1999). Scenic and ecologically valuable resources such as riparian areas and lakeshores also draw low-density development (McGranahan, 1999; Myers et al, 2000). In rural counties of the northern Rockies (Idaho, Montana, and Wyoming), population growth is associated with mountainous areas, forest cover, precipitation, and conserved land (Hansen et al, 2002; Rasker and Hansen, 2000). In addition, policy at the local level often encourages development at exurban densities in an effort to maintain rural character and environmental quality (Nelson et al, 1995).

2.2 Exurban development and mechanical thinning

The national-scale trends and local characteristics have led to an expansion of exurban development characterized by a high per capita footprint, conflicts with public land, and exposure to wildfire (Riebsame et al, 1996; Theobald, 2001). Within such areas a pressing challenge is to mitigate wildfire hazards in order to protect structures and other values at risk, while also meeting ecological goals. Toward this end, a common management practice is mechanical thinning, the reduction of ladder fuels and small-diameter trees to maintain persistent openings in the canopy. It is unrealistic and undesirable to treat all land; therefore areas must be prioritized by some set of objective criteria (Aplet and Wilmer, 2003). One way to prioritize mechanical thinning is simply to target areas closest to exurban development. Experimental studies and computer simulations have shown that the thinning of trees within 60 m of a structure will protect a structure from the heat of a torching and crowning wildfire (Cohen, 2000). Indeed, the creation of defensible space through a reduction of fuels immediately surrounding a structure is an effective way to improve structure survivability (Cohen, 2001). There is wide support for such treatments: organizations as diverse as the Sierra Club (2002), the Western Governors' Association (USDI, USDA, 2001a), the USFS (Cohen, 2000), the Bush Administration (US Government, 2003), and the Center for Biological Diversity (Nowicki, 2002) have advocated mechanical thinning of land close to structures or communities. Here, however, the consensus ends: these organizations disagree about how large an area around structures should be thinned and the extent to which treatments should occur on public lands, private lands, or both. Though the specifics may vary, the location of exurban development is an important criterion for siting mechanical thinning. Therefore, as exurban development expands, the areas prioritized for mechanical thinning will also change. A spatially explicit model has been developed to explore this dynamic.

2.3 Study area

The spatially explicit model described in this study has been calibrated, validated, and applied to the montane zone of Boulder County, CO. Located between 1830 m and 2740 m in elevation, the study area is characterized by ponderosa-pine-dominated ecosystems and is situated in rugged terrain. It spans approximately 20 km east to west and 38 km north to south. Approximately 42% of the study area is USFS land; 2% is Bureau of Land Management (BLM) land; 28% is managed by the Boulder County and City Open Space and Mountain Parks (henceforth called 'open space') or other public uses; and 28% is privately owned. Several high-profile wildfires have occurred in the study area, including the Black Tiger Fire, which burned 850 hectares (2100 acres) and destroyed forty-four homes on Sugarloaf Mountain in 1989 (National Fire Protection Association, 1989), Such events, combined with an increasing demand for wildfire mitigation, make the montane zone of Boulder County, CO, an ideal site for this research.

3 Methods

3.1 Conceptual model

The model described in this paper, WHAMED, simulates the effect of exurban development on the extent of land prioritized for mechanical thinning. It has two main components. First, WHAMED simulates possible future exurban development on the basis of driving forces related to local characteristics—distance to public lands, distance to streams, slope, distance to employment, neighborhood exurban density, and zoning (figure 1). Second, areas prioritized for mechanical thinning are identified as a function of the predicted location of exurban development. Two sets of criteria for prioritizing mechanical thinning are implemented: the criteria for the CPZ (Nowicki, 2002) and the criteria for the WUI as defined by the HFRA.

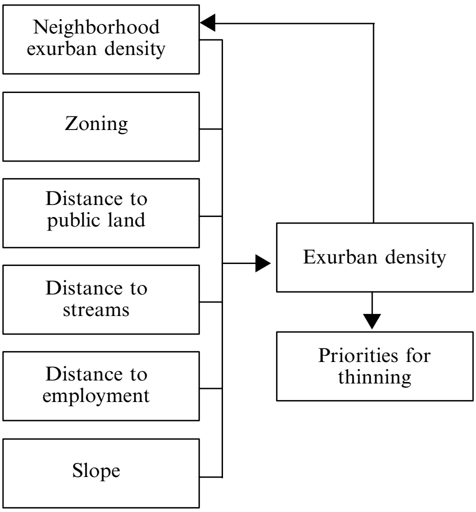

Figure 1. Conceptual model for WHAMED (Wildfire Hazard Mitigation and Exurban Development).

WHAMED is based on CA, a raster-based dynamic system that simulates local processes which result in large-scale patterns (Batty and Xie, 1994). Over several iterations, CA models demonstrate the probable evolution of landscape given a set of transition rules. CA models have a number of desirable properties (Batty and Xie, 1994; Couclelis, 1985; 1997; White and Engelen, 2000; Xie, 1996):

(1) Dynamic visualization—CA models directly and transparently show landscape change.

(2) Rule basis—CA models use either probabilistic or deterministic transition rules that give rise to complex self-organizing behavior.

(3) Flexibility—CA models can easily be modified for changing conditions, different scales, and new data. They are adaptable to a range of processes and contexts.

(4) Simplicity—CA models are computationally efficient, require only enough data to define the transition rules, yet can represent complex behavior.

As the process of exurban development and subsequent mechanical thinning is dynamic, partially self-organizing, and follows a logical sequence (Cheng and Masser, 2004), the CA framework is appropriate for this application.

At a minimum, all CA models comprise a raster gird, states of each grid cell, a definition of neighborhood, a set of transition rules, and discrete time steps (White and Engelen, 2000). In the case of this implementation of WHAMED, the raster grid represents the study area of the montane zone of Boulder County, Colorado; the states of each cell are five density categories of exurban development; the neighborhood is a three-cell lag; the transition rules (the probability of a cell becoming more densely developed) are calculated with statistical models; and the discrete time step is one year. Future exurban development predicted by WHAMED is constrained by historical development; the number of cells that change from 2000 to 2022 is dictated by the rate of change between 1978 and 2000.

WHAMED operates on a grid of 14 ha (35 acre) cells. This cell resolution was chosen for two reasons. First, exurban land-use change, though common across large areas, is a rare and difficult-to-predict event at fine scales. Therefore spatially explicit models of land-use change are generally more appropriate at coarse scales, at which the process is observable and more predictable. Second, much of the exurban development in the study area occurs on 14 ha (35 acre) plots, because Boulder County law does not allow new subdivisions smaller than this.

The model was implemented in SELES, the Spatially Explicit Landscape Event Simulator (Fall, 1998). SELES is a declarative modeling language specially designed for constructing spatial landscape models. All SELES models are composed of a set of raster layers that represent the initial conditions in the simulation. These layers are then modified at the cell level by a set of landscape events specified within the model. SELES allows sophisticated, explicitly defined models to be constructed within a high-level generalized modeling environment. SELES also helps to make the variability in model output fully transparent.

In the following section the construction, calibration, and validation of the model are described. The model is then used to predict exurban development and associated change in prioritized areas for mechanical thinning at one year intervals from 2000 to 2002.

3.2 Model construction

WHAMED predicts exurban land-use change by determining (1) which cells will develop in a given time step, and (2) how many new structures will be built in cells chosen for development. The study area comprises grids of 2527 cells, of which 400 cells were randomly selected for validation procedures. The remaining 2127 cells were used to calibrate the model on the basis of actual exurban development from 1978 to 2000.

To determine which cells will develop in a given time step, WHAMED uses a probability surface generated by logistic regression. Logistic regression predicts the probability of a binary event on the basis of one or more independent variables by fitting a logistic curve:

$$p = \frac{1}{1+\exp(-a-BX)} , \tag{1}$$

where p is the probability of a binary event, X is an independent variable, and a and B are the logistic intercept and slope, respectively.

As $(a-BX)$ approaches ∞ or $-\infty$, p approaches 1 or 0, respectively. In this study the logistic regression model estimates the probability that new structures will be built (CHANGE) on the basis of five independent grid-based variables: mean housing density of surrounding cells (NEIGMEAN), remaining number of houses that could be built according to zoning laws (REMAIN), Euclidean distance to open space (DISTSPACE), distance by road to Boulder (DISTBOUL), Euclidean distance to the closest stream (DISTSTREAM), and percentage slope (SLOPE) (table 1, over).

The independent variables described in table 1 are consistent with studies which suggest that the probability of development is influenced by zoning, accessibility,

Table 1. Variables and data sources.

Name	Description	Source data	Type
REMAIN	Remaining number of structures that can be built according to zoning laws.	Boulder County zoning	dynamic
NEIGMEAN	Neighborhood density of exurban development within three-cell lag.	Boulder County parcels	dynamic
DISTSPACE	Euclidean distance to the edge of the nearest public land (m).	Boulder Country land use, parcels	static
DISTBOUL	Distance to the edge of the City of Boulder along roads (m).	highways, local roads, USFS [a] roads	static
DISTSTREAM	Euclidean distance to nearest stream (m).	USGS [b] streams	static
SLOPE	Slope as a percentage.	30-meter DEM [c]	static

[a] US Forest Service.
[b] US Geological Survey.
[c] Digital elevation model.

topography, neighborhood, and amenities (Davis et al, 1994; Nelson, 1992; Riebsame et al, 1996; Rudzitis and Streatfield, 1993). The following relationships were hypothesized:
(a) REMAIN is expected to be positively related to CHANGE because the more structures that can be built in a given cell, the more likely it is that one will actually be built. CHANGE is not expected to be related to REMAIN in areas that are zoned for only a single structure.
(b) NEIGMEAN is expected to be positively related to CHANGE because a densely developed neighborhood suggests that an area has appropriate infrastructure for development. Clearly, NEIGMEAN is difficult to define and may be strongly scale dependent. The three-cell neighborhood was selected on the basis of a Moran's I correlogram, which revealed that spatial autocorrelation of housing density becomes insignificant ($p < 0.05$) beyond this threshold.
(c) DISTSPACE is expected to be negatively related to CHANGE; cells closer to open space should be more likely to develop because of the draw of scenic and recreational amenities. In areas zoned for only one structure, DISTSPACE is expected to be less important because these areas effectively contain their own open space.
(d) DISTBOUL is expected to be negatively related to CHANGE; cells that are a shorter drive from the employment center of Boulder are more likely to develop.
(e) DISTSTREAM is expected to be negatively related to CHANGE; cells closer to streams might be more likely to develop because water is an important natural amenity. Though development is forbidden immediately adjacent to streams, this is not expected to be reflected in the relationship between DISTSTREAM and CHANGE because of the coarseness of the grid cell (14 ha).
(f) SLOPE is expected to be negatively related to CHANGE because steep slopes are difficult or impossible to built up on. Even in areas with views, shallow slopes are preferred for development sites.

Most of the independent variables are assumed not to change over time; SLOPE is time invariant, DISTSPACE is largely fixed, and zoning in the study area changes minimally. NEIGMEAN and REMAIN both change over time and are dynamically updated in the simulation.

To determine the probability of development, two logistic regression models were calibrated: one for land with a maximum zoned density of more than one structure per 14 ha cell (called LR1 and calibrated on 927 observations) and one for land with a maximum zoned density of exactly one structure per 14 ha cell (called LR2 and calibrated on 1327 observations). Once the probability of development of a given cell was calculated, the model determined which cells will develop. In an average one-year time span from 1978 to 2000, six cells zoned for one structure developed, and thirty-six cells with a maximum zoned density above one structure developed. This historical average is the number of cells allowed to change in any one-year period in the simulation. A cell is selected to change if the cell is below its maximum zoned density and if a random number is below the probability of development generated by the logistic regression.

After choosing which cells will develop, WHAMED determines the number of new structures that will be built in each of these cells. Clearly only one structure can be built in cells zoned for one structure per 14 ha (35 acres). For cells zoned for more than one structure, an ordinary least squares (OLS) regression was used to predict the number of new structures with the same independent variables as the logistic regressions (927 observations). The predicted change in the number of structures was rounded to the nearest positive integer and was capped at the maximum allowed by zoning laws. Each cell was then classified into one of four density categories: (1) undeveloped, (2) low-density exurban (one structure per cell), (3) medium-density exurban (two to four structures per cell), and (4) high-density exurban (more than five structures per cell). Zoning imposes a strict limit on the maximum density of each cell, which will be reached if the model is run over a sufficient number of time steps.

3.3 Model calibration

Calibration is the process of fitting a model and evaluating the fit. For LR1 all variables were significant (table 2), but several of the relationships did not meet expectations. NEIGMEAN, SLOPE, and REMAIN all met the hypothesized relationship with CHANGE. DISTBOUL, DISTSTREAM, and DISTSPACE all had the opposite of the expected relationship. In the case of DISTSPACE, areas farther from open space are more likely to develop. This may be because land near open space is less accessible than land farther away from open space. In the case of DISTBOUL, though the coefficients are small, land farther away from the City of Boulder by road is more likely to be developed. This may be because much of the available land near Boulder has been built out or is too expensive, which leaves cells that are mostly father away. Also, though the coefficients are small, land farther from streams is more likely to develop.

Table 2. Regression results. Where values are not given, the variables were excluded from the model specification.

Regression type	Cells zoned for one structure Logistic—LR1	Cells zoned for more than one structure Logistic—LR2	Cells zoned for more than one structure that change state OLS [a]
Constant	0.685*	−0.556*	0.406*
REMAIN	–	0.167	0.263
NEIGMEAN	0.733	0.515	0.254
DISTSTREAM	0.001	0.001	0.0004
DISTSPACE	–	0.002	0.001
DISTBOUL	0.0004	0.0004	0.0004
Model fit	0.766 [b]	0.731 [b]	0.459 [c]

* Not significant at the $p = 0.05$ level.

[a] Ordinary least squares.

[b] Area under the receiver operating characteristic curve.

[c] Adjusted R^2.

Possible reasons for this are that cells close to streams have been occupied, that it is difficult to build near streams, or that people have developed a preference for locations with views, such as ridge tops, which are often farther from streams. The sign of the coefficients are the same for LR2 as for LR1 except that, as expected, REMAIN and DISTSPACE were not significant in the latter case and were therefore omitted from the analysis.

LR1 and LR2 were evaluated with a receiver operating characteristic curve (Metz, 1978). The curve shows the trade-off between sensitivity (the proportion of cells that have been correctly predicted to stay undeveloped) and specificity (the proportion of cells that were correctly predicted to develop) under all possible critical values. The area under the curve indicates how well the model performs. A model with no power to predict the outcome over and above chance has an area of 0.5, and a perfect model has an area of 1. In this study the logistic model of low-density exurban development has an area under the curve of 0.766, and the model of high-density exurban or suburban development has an area of 0.731 (table 2). This indicates that the logistic regression models perform well, relative to a model with no predictive power.

Logistic regression assumes that variables are not perfectly collinear and that the residuals are independent. It was found that the correlation between independent variables is 0.286 or less, and therefore multicollinearity is probably not an issue. The residuals, however, do not meet the assumption of independence (Moran's I of residuals in adjacent cells $= 0.33$, significant at $p < 0.01$). Consequently, the standard errors of the regression coefficients are underestimated, which may lead to incorrect hypothesis testing and type 2 errors (accepting an incorrect hypothesis). However, the violation of the assumption of independent residuals does not influence the predictive power of the model, nor does it bias the estimated regression coefficients.

The OLS regression was found to be significant with an adjusted R^2 of 0.459. The signs of the relationships were the same as those for LR1 (table 2). Linear regression is based on a number of statistical assumptions: residuals should be homoscedastic (constant variance of residuals), independent, and normally distributed. The residuals were found to be close to normal, but the other two assumptions were violated. The Moran's I of adjacent cells was 0.45 (significant at $p < 0.01$), which indicates that residuals were spatially autocorrelated. In addition, the residuals were heteroscedastic—the variance of the residuals increased as the predicted change in structures increased. The violation of these regression assumptions indicates that hypothesis testing may be prone to type 2 errors (falsely accepting that the coefficient is significantly different from zero). However, again, these violations do not bias the estimated coefficients or reduce the predictive power of the model.

3.4 Model validation

Validation is the process of determining whether the model results are reasonably accurate and realistic. To validate this model the predicted density categories of exurban development in 2000, based on data from 1978, were compared with observed categories through the following methods: (1) percentage accuracy and sources of successes and errors, (2) a confusion map, (3) Moran's I, and (4) a persistence map. Each validation method has a separate purpose. The percentage accuracy and sources of successes and errors method indicates the overall performance of the model as well as whether a model performs well owing to chance or to predictive ability. This is based on 400 observations (cells) that were randomly excluded from the calibration process. The confusion map shows where density categories were correctly and incorrectly predicted. Moran's I indicates whether the predicted density categories display a similar degree of clustering to the observed density categories, on the basis of 400 observations excluded from calibration. The persistence map indicates the cell-by-cell frequency with which the model correctly predicts the density category over the course of 100 model iterations. All methods except for the persistence map validate a single representative model iteration. The representative iteration is defined as the single run, from the 100 runs, which is closest to the cell-by-cell median outcome, as selected by a least-squares criterion. Because it is not smoothed, this single model run is more representative than the cell-by-cell median result. The combination of validation strategies paints a complete picture of model performance.

3.4.1 *Percentage accuracy and sources of successes and errors*

The model predicted the observed density category 72% of the time for the 400 validation points. Only 7.5% of the predicted observations were more than one category removed from the actual category. Predictions of category 1 (undeveloped) and category 4 (high-density development) were highly accurate at 80% and 84%, respectively (table 3). Predictions of middle-density categories were less accurate: 51% for category 2 and 60% for category 3. These two categories are similar to each other and are therefore more difficult to predict.

Table 3. Confusion matrix of exurban-development-density classification. The diagonal of this table shows the number of validation points correctly classified in each density category. The off-diagonal shows the number of validation points incorrectly classified.

Predicted category	Observed category				Percentage correct
	1. undeveloped	2. low-density exurban	3. medium-density exurban	4. high-density exurban	
1. Undeveloped	130	18	12	3	80
2. Low-density exurban	33	47	11	1	51
3. Medium-density exurban	12	17	53	7	60
4. High-density exurban	0	2	9	58	84

Percentage accuracy is an important means of validation, but does not indicate the sources of success or error in model predictions. In this case, the kappa variations (Pontius, 2000) reveal that 28% of predictions are correct by chance, and 44% are correct either because the location or the quantity were correctly predicted. This shows that the model does, indeed, have predictive power over and above what would be expected by change.

3.4.2 *Confusion map*

The confusion map shows the predicted category and whether the prediction is correct or incorrect (figure 2, over). It reveals the spatial patterns of the success and error described in table 3. To the west of the northwestern end of the City of Boulder, the model falsely predicts that a number of cells remain undeveloped. This may be due to a missing explanatory variable that is unknown, yet important for predicting development in this area. Elsewhere, errors appear to be evenly distributed across the study area.

3.4.3 *Moran's I*

Kappa and the percentage correct are important forms of validation, but they do not indicate whether the spatial structure has been properly modeled. Moran's I measures the spatial autocorrelation between an observation and neighboring observations at given distance intervals. In this context, it can be interpreted as the degree of clustering of cells of similar density. Moran's I is defined as the slope of a regression line showing

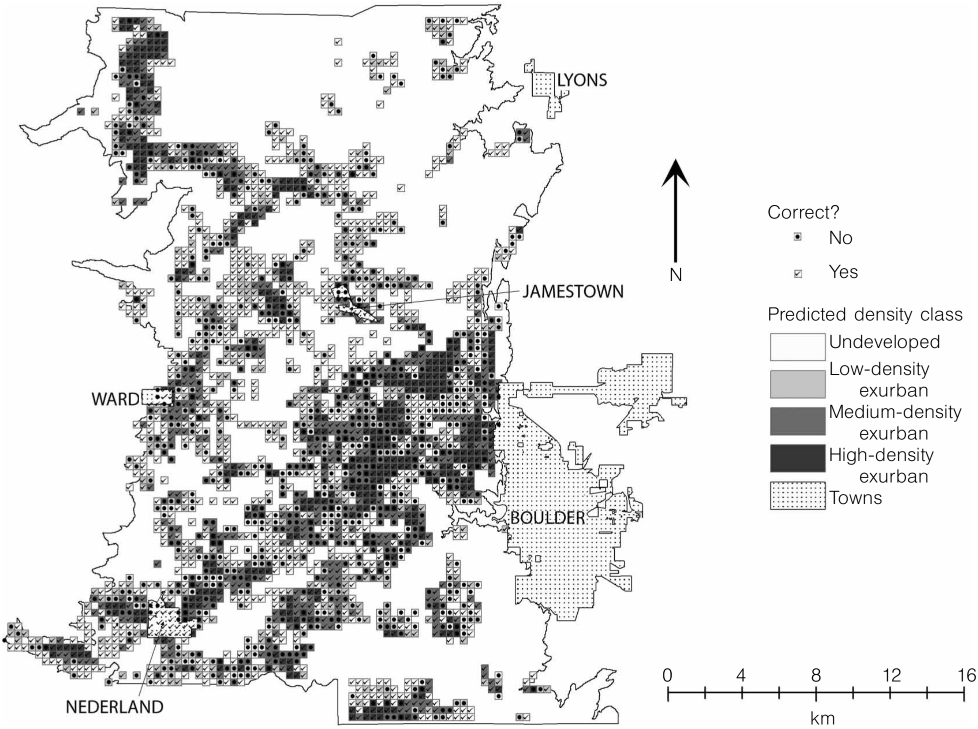

Figure 2. Confusion map of the montane zone of Boulder County, CO, showing predicted development density categories in 2000 and whether the prediction is correct or incorrect.

the relationship between an attribute at a given location and the same attribute at a neighboring location (Anselin, 1996) and has an expected value of:

$$E_I = -(n-1) \ , \tag{2}$$

where the expected value E_I is related to the number of observations, n. Anything above this value indicates a positive spatial autocorrelation, and anything below it shows negative spatial autocorrelation.

Overall, the predicted exurban development in 2000 has a similar clustering pattern to observed exurban development in 2000. At a distance of one cell, the actual Moran's I was 0.83 and the predicted Moran's I was 0.79. At a distance of two cells, both the actual and predicted Moran's I were 0.2. At a distance of three cells, the actual Moran's I was 0.24 and the predicted Moran's I was 0.2. All of these values are significant at $p < 0.05$. At greater distances Moran's I ceases to be significant at the $p < 0.05$ level. In short, the analysis of Moran's I shows that the predicted degree of clustering is similar to the observed degree.

3.4.4 *Persistence map*

The persistence map shows the percentage of times the model correctly predicts the density category of a cell. From a visual assessment of this map (figure 3), it is clear that the cells surrounding Ward and at the center of the study area are correctly predicted less often than elsewhere in the study area. These areas have developed sporadically from 1978 to 2000 so it is not surprising that the persistence map indicates high variability in correct predictions. Other areas, such as the northwestern part of the study area, the areas surrounding the town of Nederland, and the areas directly west of Boulder are correctly predicted a higher percentage of the time. These areas

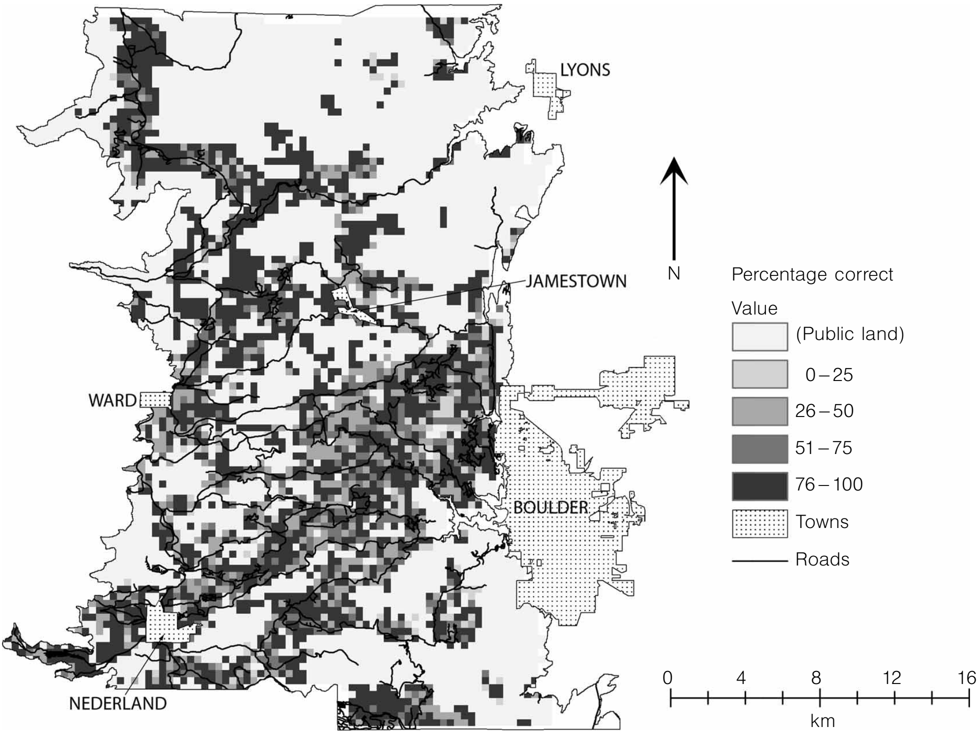

Figure 3. Persistence map of the montane zone of Boulder County, CO, showing the percentage of model runs in which the density category is correctly predicted.

have clearly and consistently 'filled in' from 1978 to 2000, so the correct predictions of development are less variable. Overall, 62% of the landscape is correctly predicted in the highest frequency class (that is, 76 – 100% of model iterations).

3.4.5 *Assessment of model performance*

The validation procedures show that the model correctly predicts density categories 72% of the time, above what would be expected by chance. They show that 62% of the landscape is correctly predicted in the highest frequency class (that is, 76 – 100% of model iterations) and that errors in the median predicted result show few discernible spatial pattern. They show that the predicted degree of clustering is close to, but slightly lower than, the observed degree. However, the model also has a number of limitations that could be addressed to improve accuracy further. For example, independent variables such as housing costs, the presence of services such as water, and within-pixel variability of topography could be added to improve the model fit. Alternatively, a full-fledged agent-based model could be used to explain better the behavior of developers and homebuyers. Overall, however, the validation procedures suggest that the model of exurban development is appropriate for the stated use: to predict exurban development and associated land prioritized for mechanical thinning.

3.5 Prioritization of mechanical thinning

3.5.1 *Criteria for prioritization of mechanical thinning*

Two different sets of criteria for prioritizing mechanical thinning were implemented in WHAMED: the definition of the CPZ and the WUI as defined by the HFRA. Both criteria prioritize mechanical thinning within a certain distance of communities. The Federal Register defines an 'intermix community' as an area with one or more structures per

16 ha (40 acres), surrounded by wildland vegetation (USDI, USDA, 2001b). In this study a community is defined as an area with one or more structures per 14 ha (35 acres), because this is the cell size of the model, as well as the minimum size at which land can be subdivided in Boulder County.

One set of criteria for prioritizing mechanical thinning is specified by the CPZ, defined as a buffer surrounding a community in which trees are thinned to help firefighters defend structures (Nowicki, 2002). Within the CPZ, canopy cover should be thinned to under 35% and crowns should be spaced a minimum of 10 ft apart, small-diameter trees and ladder fuels up to 10 ft high should be removed, and large trees should be retained. These general guidelines may vary by site conditions (Nowicki, 2002). The recommended width of the CPZ is four times the average sustained flame length, which in turn is approximately two times the average overstory tree height (Cohen and Butler, 1998). The maximum possible treatment area is 488 m (1600 ft) from a community, assuming a tree height of 60 m (200 ft) (Nowicki, 2002). In a ponderosa-pine-dominated ecosystem such as the montane zone of Boulder County, maximum overstory tree height would be closer to 25 m (82 ft), resulting in a maximum flame height of 50 m (164 ft) and a CPZ of 200 m (665 ft). This study uses the maximum possible treatment under CPZ, a conservative prescription from a structure-protection or firefighter-safety perspective. It is important to note that the CPZ guidelines are designed both with structure protection and with fire-fighting safety and effectivess in mind.

A second set of criteria for prioritizing mechanical thinning comes from the definition of the WUI under the HFRA. Under the HFRA, the WUI is prioritized in two ways: fuel reduction in the WUI qualifies for expedited review procedures and a minimum of 50% of funds for fuel reduction must be allocated to the WUI (US Government, 2003). For communities without an existing community wildfire protection plan that specifies otherwise, HFRA defines the WUI as an 805 m (0.5 mile buffer) around an at-risk community within the vicinity of federal lands. This buffer extends out to 2414 m (1.5 miles) from the community if the land surrounding the community contains an evacuation route, contains a sustained steep slope, is fire regime condition class 3 (high departure from historical conditions) (Schmidt et al, 2002), or contains a feature that creates a fire break, such as a road. With the exception of the fire regime condition class, the HFRA does not explicitly define these condition (for example, what is a 'sustained steep slope'?) or how close the conditions have to be to a community. In this study it is assumed that the entire study area qualifies for the 2414 m buffer because the study area is characterized by extensive federal land, evacuation routes, steep slopes, condition class 3 land, and fire breaks.

3.5.2 *Caveats in modeling the prioritization of mechanical thinning*

It is important to note that this study does not consider criteria other than the density of exurban development for the prioritization of mechanical thinning. Under the HFRA, for example, land *outside* the WUI may be prioritized if it is (1) fire regime condition class 3 (a high departure from historic conditions), (2) fire regime condition class 2 (a moderate departure from historic conditions) with a mean fire interval of less than 100 years and close to a municipal watershed, or (3) a habitat for a threatened or endangered species that is dependent on a natural fire regime or vulnerable to catastrophic fire. Furthermore, local communities and land managers may choose a set of criteria that differs from that of HFRA. For example, managers may prioritize land in which ecological goals, such as restoring historic forest structure, could be achieved with mechanical thinning (Schoennagel et al, 2004; Veblen, 2003). To evaluate the theoretical effects of exurban development over a large area, however, this model only implements national criteria rather than small-scale community plans.

A second important caveat is that this model operates on a coarse scale; it does not predict the exact sites of mechanical thinning on a fine scale. The distinction is vital. Within a prioritized area, local planners and managers will ultimately treat only a portion of the land. Furthermore, much of the private land that is marked 'priority' will never be treated because most funding is reserved for federal land. Indeed, no money was committed to mechanical thinning on nonfederal lands in the 2005 federal budget.

A third caveat is that neither of the two sets of criteria, if applied on the ground, would necessarily prevent structure loss. For one thing, mechanical thinning is most effective when it takes place within 60 m of structures (Cohen, 2000; 2001). Furthermore, over larger areas thinning may be ineffective during extreme weather events (Bessie and Johnson, 1995; Schoennagel et al, 2004). This model operationalizes the criteria but does not evaluate its effectiveness or efficiency in achieving the stated goals.

4 Results and discussion

WHAMED was run 100 times to predict potential locations of mechanical thinning and exurban development between the years 2000 and 2022 in one-year time steps. To illustrate the effect of exurban land-use change, the variation in prioritized areas for mechanical thinning under CPZ and HFRA criteria are presented.

4.1 Change in prioritized land under the CPZ

In this study the CPZ is defined as an area out to 488 m (1600 ft) from a community, in which mechanical thinning should take place to facilitate fire fighting and to reduce the wildfire hazard. This distance is the maximum possible treatment under CPZ (Nowicki, 2002); a conservative prescription from a structure-protection or firefighter-safety perspective. As of 2000, private land constituted 52% of all land that met the CPZ criteria (table 4). From 2000 to 2022, private land is expected (probability $> 50\%$) to constitute 22% of 'newly prioritized' areas, and USFS land is expected to increase to 56%. The land that is projected to meet the CPZ criteria by 2022 is

Table 4. Percentage of land within land-management categories for (1) the entire study area, (2) the land prioritized for mechanical thinning in 2000 according to the criteria of the community protection zone (CPZ) and Healthy Forest Restoration Act (HFRA), and (3) the land that is projected to be prioritized by 2022 (probability $> 50\%$).

	Study area within land-management categories (%)	Land that met criteria by 2000 within land-management categories (%)		Land that is expected to meet criteria between 2000 and 2022 within land-management categories (%)	
		CPZ	HFRA	CPZ	HFRA
Open space or other	28	18	30	22	37
BLM [a]	2	3	3	0	0
Private	30	52	16	22	0
USFS [b]	40	26	51	56	63

[a] Bureau of Land Management.
[b] US Forest Service.

generally located adjacent to land that met the criteria in 1978, or is located in isolated cells to the west of Lyons (figure 4, over).

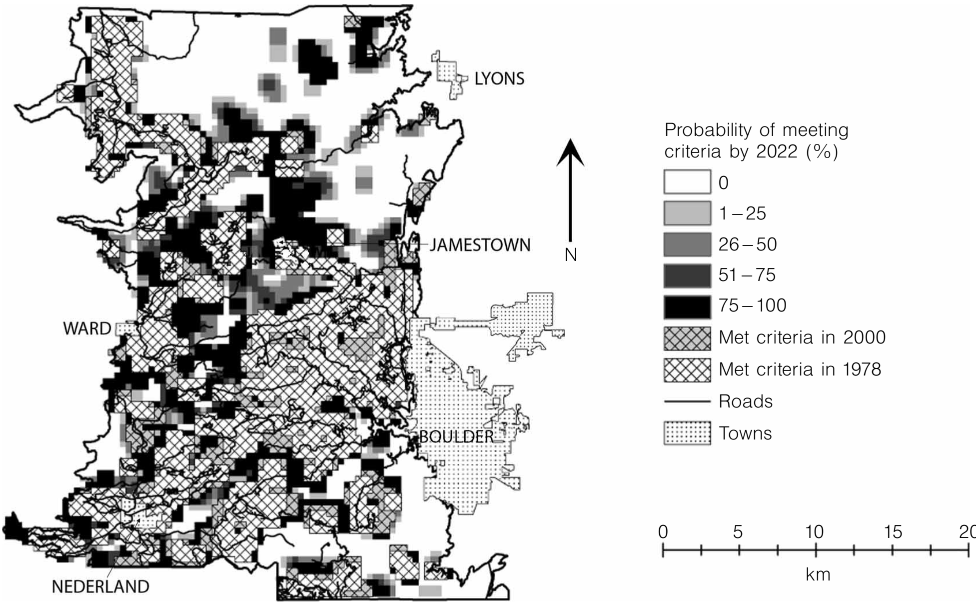

Figure 4. Land in the montane zone of Boulder County that met the Community Protection Zone criteria for prioritizing mechanical thinning in 1978 and 2000, or the probability that it will meet it by 2022.

4.2 Change in prioritized land under the HFRA

The HFRA qualifies certain types of land for expedited review procedures, including all land in the WUI close to federal land. Under HFRA criteria, the WUI is projected to expand minimally from 2000 to 2022 because the bulk of the study area already qualified as WUI in 1978 and 2000 (figure 5). The main expansion of the WUI is expected to occur in the sparsely populated lands west and southwest of Lyons. As of 2000, USFS land comprised 51% of all land that met HFRA criteria (table 4). By 2022, USFS land is expected (probability $>50\%$) to constitute 63% of 'newly prioritized' areas, and 'open space or other' is expected to constitute the remainder. None of the 'newly prioritized' land is expected to be private or BLM land because all such land was already prioritized by 2000.

5 Conclusions

WHAMED is designed to explore the effects of exurban development on the prioritization of areas for mechanical thinning at coarse scales. The model output shows the land that is prioritized for mechanical thinning from 1978 to 2022 under two sets of criteria. In the case of CPZ criteria, prioritized areas are projected to expand from 48% of the study area in 1978 to 63% of the study area by 2022. The land that is projected to be prioritized by 2022 is for the most part located adjacent to the land that is currently prioritized (figure 4). Such areas are largely located at middle-to-upper elevations, which are within the western half of the study area. In contrast, under HFRA criteria, the areas defined as WUI are projected to expand minimally by 2022 because most of the study area has long since met the definition of WUI. That most of the montane zone of Boulder County in 1978 and 2000 qualified as priority areas under the current HFRA criteria is an important finding in itself; it shows that the HFRA is not particularly useful for prioritizing land for treatment at coarse scales in this study area.

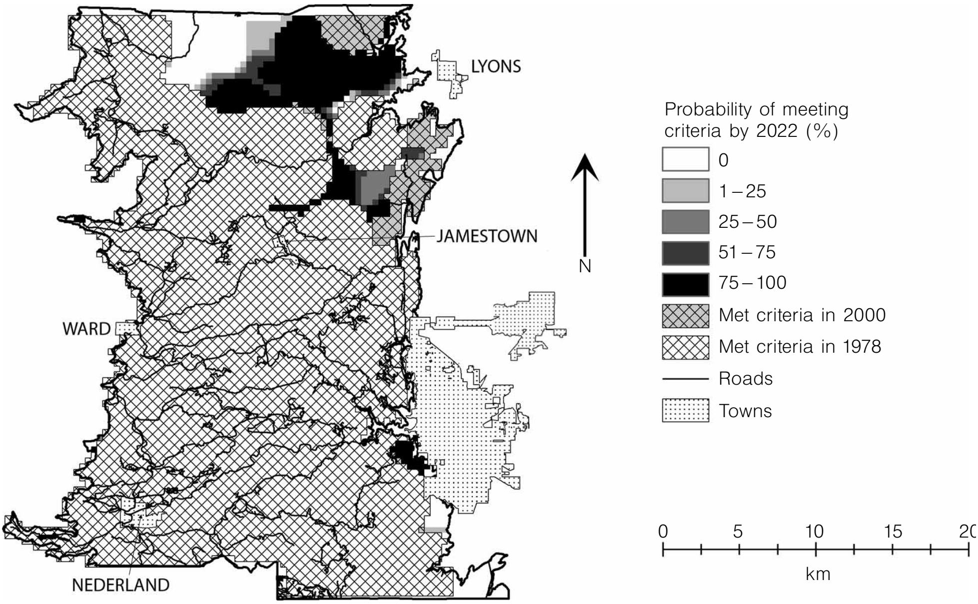

Figure 5. Land in the montane zone of Boulder County, CO, that met the Healthy Forest Restoration Act criteria for prioritizing mechanical thinning (that is, which lies within the WUI) in 1978 and 2000, or the probability that it will meet it by 2022.

The results also show that prioritized areas in 2000 under the CPZ criteria constitute relatively little USFS land (26%) relative to its proportion in the study area (42%). This is common in many WUI environments; nationwide 85% of land in the CPZ is private and only 15% constitutes federal lands (Aplet and Wilmer, 2003). In contrast, under the HFRA criteria prioritized areas in 2000 are dominated by USFS land (51%) and also have a high percentage of private land (16%) and open space or other land (30%). Under either set of criteria an increasing percentage of 'newly prioritized' land by 2022 will constitute USFS land and open space or other land, and a lower percentage will constitute private land. Today, most federal money for fuel reduction is already being spent for federal land; in the future the demand for this money will only increase as the amount of prioritized federal land increases.

More generally, this study demonstrates the utility of spatially explicit dynamic models to understand better where the WUI is, how it might change in the future, and how this might affect what land would be prioritized for mechanical thinning. The study also reinforces the importance of making variability transparent and of reporting multiple forms of model validation.

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