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Analysis

The effects of a spruce bark beetle outbreak and wildfires on property values in the wildland–urban interface of south-central Alaska, USA

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ABSTRACT

Climate warming is causing the frequency, extent, and severity of natural disturbances to increase. To develop innovative approaches for mitigating the potential negative social consequences of such increases, research is needed investigating how people perceive and respond to natural disturbance. This study uses spatial econometric techniques in a hedonic pricing framework to estimate how wildfires and a spruce bark beetle (*Dendroctonus rufipennis*) outbreak affect assessed property values on the Kenai Peninsula of south-central Alaska in 2001 and 2010. We find that large wildfires and the spruce bark beetle outbreak increase property values while small wildfires decrease property values. These findings suggest that homeowners may form complex viewpoints, weighing enhancements to environmental amenities with negative consequences that stem from the occurrence of natural disturbance.

1. Introduction

People in the western United States increasingly choose to live in the wildland–urban interface (WUI), areas of undeveloped natural vegetation, within which, at least six homes per square km are interspersed (Radeloff et al., 2005; Stewart et al., 2007). Many WUI ecosystems are dependent on natural disturbances, such as wildfire and bark beetle outbreak. These disturbances are becoming increasingly frequent, larger, and more severe, with warming trends (Balshi et al., 2008; Flannigan et al., 2009; Littell et al., 2009; Raffa et al., 2008; Westerling et al., 2006, 2011). Thus, there is a pressing need for new management approaches that can preserve the roles of natural disturbance in WUI ecosystems while still protecting life and property (Chapin et al., 2003; Donovan et al., 2007; Gill et al., 2013). Finding such approaches will likely require improving our understanding of how WUI homeowners perceive and respond to natural disturbances (Steelman et al., 2004; Sturtevant and Jakes, 2008). In this paper we estimate a hedonic pricing model to quantify the economic impacts of a massive spruce bark beetle (*Dendroctonus rufipennis*) (SBB) outbreak and wildfires on WUI property values in south-central Alaska.

Since 1970, the WUI in the United States expanded by over 50%, much of it located in areas where wildfires burn at high intensity and are difficult to suppress (Theobald and Romme, 2007). Costs of managing wildfire in the United States have increased dramatically in recent decades. Federal agencies currently spend over 2.5 billion U.S. dollars per year suppressing wildfires (Weeks, 2012). There is growing pressure on agencies to reduce these expenditures and more effectively manage disturbances in the WUI (Calkin et al., 2005). Managers are experimenting with several alternative approaches (Brummel et al., 2010). One example is to proactively engage homeowners in wildfire preparedness through the Firewise Communities program (Kyle et al., 2010). These collaborative education and outreach projects teach people how to create defensible space around their homes and the value of using fire-resistant building materials. However, convincing homeowners to invest time and money in Firewise Communities depends on how motivated they are to minimize the potential loss of environmental amenities (i.e. ecosystem services; human benefits derived from ecosystems; Daily et al., 1997), caused by fire, or to reduce perceived threat of fire to their property and personal safety (Bright and Burtz, 2006).

Homeowners do not always associate the occurrence of natural disturbances with negative impacts. Instead, homeowners often perceive natural disturbance in complex ways. These views emerge from weighing the costs of diminished environmental amenities, and perceived threat, with the benefits incurred from environmental amenities that are enhanced by disturbance (Donovan et al., 2007). For example, insect outbreaks can kill trees, an outcome that is often viewed negatively.

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However, outbreak also can shift tree-species composition, an appealing outcome in some geographic locations (Holmes et al., 2006).

How homeowners evaluate the consequences of one natural disturbance may also be influenced by other natural disturbances that co-occur (Berg and Anderson, 2006). For example, bark beetle outbreaks and wildfire can be interrelated, with bark beetle outbreak affecting the probability of subsequent wildfires, as well as their consequences (Bebi et al., 2003; Hicke et al., 2012; Simard et al., 2011). In south-central Alaska SBB outbreak has increased the probability of subsequent large wildfire (Hansen, 2013). Thus, WUI homeowners of south-central Alaska likely account for the effects of the SBB outbreak when they assess wildfire risk (Flint, 2006). Management strategies that more effectively mediate human–natural disturbance interactions in the WUI must better account the interlinked nature of disturbances (Venn and Calkin, 2011).

In this study, we evaluate how wildfires and a massive SBB outbreak in south-central Alaska jointly influence assessed WUI property values. Past studies have looked at the effects of wildfire and insect outbreaks on property values independently. Secondly, we determine whether the relationships between natural disturbances and assessed property values vary with distance from property center and change over time since the disturbances occurred. Quantifying spatial and temporal dynamics provides a more comprehensive perspective of how homeowners perceive the SBB outbreak and wildfires.

We also model spatial interactions inherent to property values. Failing to account for spatial autoregression and spatial autocorrelation can lead to biased and inefficient coefficient estimates. In our analysis we estimate the OLS, the spatial lag, the spatial error, and the spatial mixed models. Additionally, we present formal test statistics for choosing between them. We find that spatial econometric models are statistically superior to the OLS model, highlighting their importance in this context.

In section two we discuss contextual background including the ecological roles of wildfires and SBB outbreaks and their effects on property values. Section three describes the dataset used in our models. Section four explains the modeling methodology. Section five presents results and section six concludes our study.

2. Contextual Background

2.1. The Ecological Role of Wildfire and Bark Beetle Outbreaks

Natural disturbances, such as wildfire and bark beetle outbreaks, are integral to the function of many ecosystems. These disturbances foster landscape heterogeneity, shape system states and re-direct ecological trajectories (Turner, 2010; Turner et al., 1998, 2003). Thus, wildfires and bark beetle outbreaks often play key roles in determining the quality and quantity of environmental amenities provisioned to people (Turner et al., 2012). Environmental amenities affected by wildfire and bark beetle outbreaks include carbon storage, timber production, wildlife habitat, and forest aesthetics (Balshi et al., 2009; Chapin et al., 2003; Cyr et al., 2009; Gallant et al., 2003; Hammer et al., 2007; Hunt and Haider, 2004; Rupp et al., 2006).

Wildfire and bark beetles respond strongly to climate drivers, particularly temperature increases. In the North American boreal forest, studies estimate that by the end of the 21st century, annual area burned by wildfire is likely to increase by 74 to 118% (Balshi et al., 2008; Flannigan et al., 2005). Similar trends are also projected in the western U.S. (Westerling et al., 2006, 2011). Also, bark beetle outbreaks are becoming larger, occur in more northerly forests, and at higher elevations than previous outbreaks, a trend that is expected to continue (Bentz et al., 2010; Hansen et al., 2001; Raffa et al., 2008). Several current outbreaks are some of the most severe ever recorded. How climatically induced changes to natural disturbance regimes will influence the provision of environmental amenities is a pressing and unanswered question in sustainability science (Turner et al., 2012). However, it is clear these changes will have substantial consequences for people.

2.2. Wildfire Effects on Property Values and Spatial Interactions

Several studies have been conducted to evaluate the effects of wildfire on property values using a hedonic pricing framework, none of which evaluate the effects of fire on property values in the boreal forest or have accounted for confounding effects of bark beetle outbreak. In 1994, several wildfires burned over 73,000 ha of forest in Chelan County, Washington, with significant loss of personal property. Suppression costs exceeded 69 million U.S. dollars. Huggett (2003) found that properties close to wildfires decrease in value. However, the negative effects on property values only last for 6 to 12 months. Results of the model suggest that wildfires can negatively affect environmental amenities. This finding is supported by a study of residential property values following a 1996 fire in Colorado, where property value decreases by an average of 15% (Loomis, 2004). Yet, property values can also recover with time since fire burns.

The fire department in Colorado Springs, Colorado assessed wildfire risk on lands surrounding 35,000 WUI homes and shared results with homeowners in 2002. A study evaluated how environmental amenities and characteristics determining wildfire risk, such as forest density and dangerous topography, influence home sale prices before homeowners are aware of fire risk (1998–2001) and after (2002–2004) (Donovan et al., 2007). Increased awareness of wildfire risk has a negative influence on home sale prices. The selling price of a representative home decreases by $40,000 after homeowners become aware of high-fire risk. Yet, different determinants of wildfire risk influence sale prices differently. Dangerous topography around homes leads to high fire risk but does not change selling prices after homeowners become aware. This suggests that benefits of living on a ridge outweigh the costs associated with higher wildfire risk. Homes that were constructed with wood roofs or siding sell for more before people are aware of fire risk and for less after people become aware. Higher fire risk overshadows the aesthetic value of wood homes.

The importance of spatial econometrics in hedonic property-value studies has been demonstrated.[i] In the fire-risk map analysis, Donovan et al. (2007) provide formal diagnostics to choose between different model specifications and find support for the joint spatial lag/spatial error model (spatial mixed model). The authors further estimate economically significant absolute percentage of bias of the OLS marginal effects. The average bias ranges from 37% to 167% in the four models.

A small WUI area near Los Angeles, California experienced five wildfires during the 1990s. Mueller et al. (2009) quantified the effects of multiple wildfires on home sale prices in the area. Findings indicate that wildfires have a negative effect on sale prices, though successive wildfires have different effects. The first wildfire decreases sale prices by 10%, the second by 23%. Using the same dataset, Mueller and Loomis (2008) find evidence of the spatial error process. However, controlling for spatial error did not greatly change coefficient estimates.

Most studies have evaluated the influence of one or a few wildfires on property values. Often, the landscape is a patchwork of many fire scars that accumulate over time. Stetler et al. (2010) looked at the effects of 256 wildfires and a number of environmental amenities on home sale prices from 1996 to 2007 in northwestern Montana. They included home distance from past wildfire, whether there was a view of past wildfire, and time since wildfire burned. Selling prices of homes with a view of the fire decrease more and take longer to recover than those without a view of the burn.

[i] See for example Can (1990), Dubin et al. (1999), Bowen et al. (2001), Kim et al. (2003), Brasington and Hite (2005), Donovan et al. (2007), Small and Steimetz (2012), Mueller and Loomis (2008), Anselin & Lozano-Garcia (2009), Osland (2010), Brady and Irwin (2011), and Ham et al. (2012).

2.3. Insect Outbreak Effects on Property Values and Spatial Interactions

The hemlock woolly adelgid (*Adelges tsuga*) was introduced to forests of the northeastern United States accidentally in the early 1950s, and spread, attacking and killing hemlocks. Using records from 1992 to 2002 in Sparta, New Jersey, Holmes et al. (2006) quantified how adelgid outbreak severity influences home-sale prices. The authors included variables such as land use, proximity to water, home characteristics, and locational characteristics. They find that moderately declining stands of hemlock damage have a negative influence on home-sale prices. However, severely declining stands have no influence. Dead hemlock stands actually positively influence home-sale prices. The authors speculate more light reaches the forest floor, following severe hemlock mortality. This stimulates the growth of other deciduous tree species that are associated with increases in property values. Expanding deciduous tree cover likely outweighs diminished environmental amenities from losing hemlock. The authors also estimate spatial lag and spatial error models. Finding both significant, they present a final spatial mixed model. In this specification, the spatial error remains significant, while the spatial lag does not.

From 1996 and 2010, a Mountain Pine Beetle (MPB) (*Dendroctonus ponderosae*) outbreak infested 769,000 ha of Colorado forest. A study was conducted in the WUI of Grand County, to determine how the number of trees killed by MPB within 0.1, 0.5, and 1.0 km of homes affect their sale price (Price et al., 2010). Home sale prices decline by $648, $43, and $17 for each tree killed within the 0.1, 0.5, and 1 km radii, respectively. The authors also estimate a spatial lag model and find the spatial lag coefficient to be highly significant in all three models. It appears that the effects of trees killed by MPB on home sale prices also influence the selling price of neighbors' homes. However, the study does not account for spatial autocorrelation.

3. Study Area and Data Sources

Our study area is the WUI of the Kenai Peninsula in south-central Alaska (Fig. 1), focused primarily on the western portion of the peninsula. The Kenai Peninsula extends from Cook Inlet on the west, to Prince Williams Sound on the east, and is located south of Anchorage, Alaska. Mean annual precipitation varies from 369 mm in the northwestern portion of Kenai Peninsula to 650 mm at the southern extent

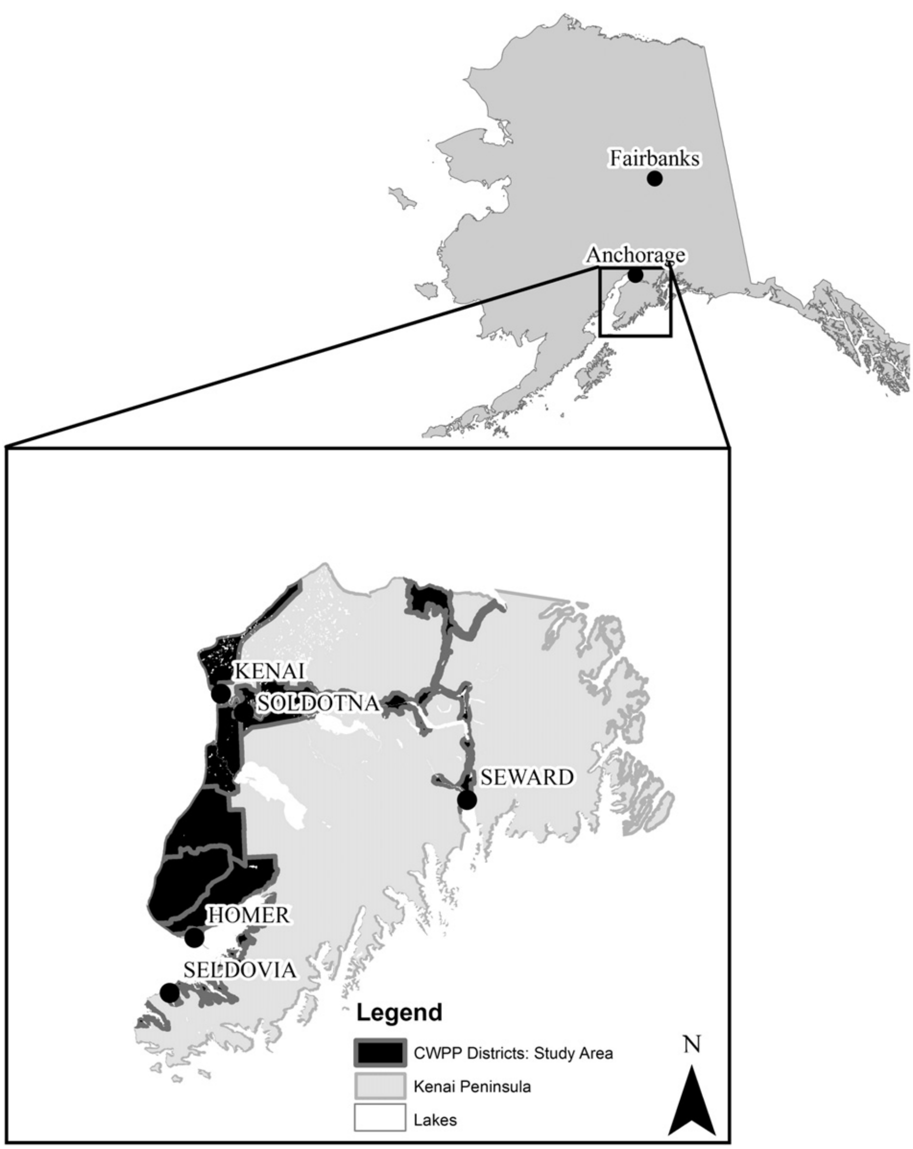

Fig. 1. Kenai Peninsula and study area.

(1970–2000) (Western Regional Climate Center, 2012). Average annual temperature is approximately 1 °C (Sherriff et al., 2011). Forests of the western Kenai are classified as boreal transition. Lutz spruce (*Picea lutzii*) and sitka spruce (*Picea sitchensis*) are located along the coast lines. Interior forest stands comprise white spruce (*Picea glauca*) and resin birch (*Betula neoalaskana*). White spruce stands of the western Kenai Peninsula have been host to an average of 66 wildfires per year that burned over 60,000 ha since 1990 (Fig. 2), including the 2007 Caribou Hills wildfire that destroyed 88 homes and cabins and 109 outbuildings (Kenai Peninsula Borough, 2011). A massive SBB outbreak began in 1989, affecting over 400,000 ha, until it petered out in the early 2000s (Fig. 3). Since then, isolated SBB outbreaks have occurred.

The Kenai Peninsula Borough is more densely populated than much of the rest of Alaska. According to the 2010 United States Census, 55,400 people reside within the borough, and population has grown by 11.5% since 2000. Per capita annual income is $29,127 (2010 U.S. real dollars). The economy in the Kenai Peninsula Borough is one of the most diverse in the state. Oil and gas exploration play an important role, as does sales and services, construction, and tourism (Kenai Peninsula Borough, 2010). There are five incorporated cities in the borough including, Homer, Kenai, Seldovia, Seward, and Soldotna, and a number of unincorporated towns. Around the road system, a pronounced WUI has developed, particularly on the western side of the peninsula. As of 2011, there were approximately 11 residential properties per square km in the WUI (Kenai Peninsula Borough, 2012).

This paper quantifies the effects of wildfires and the 1990s SBB outbreak on assessed property values in 2001 and 2010 for single household residences in the WUI of the Kenai Peninsula. We further include a suite of spatial, environmental, geographic, and property characteristics in our analysis. Assessed property values and property characteristics are publically available from the Kenai Peninsula Borough (Kenai Peninsula Borough, 2012).

As of 2010, there were over 60,000 identified properties in the Kenai Peninsula Borough. However, we limit our sample in three ways. First, we only include private, single dwelling properties (i.e. one home), located in the community wildfire protection plan zone (CWPP), or areas with a sufficient density of homes on the Kenai Peninsula for the borough to prioritize wildfire suppression. For this analysis, we consider the CWPP to delimit the WUI. The WUI does not include urban settings; hence we exclude any properties that were located

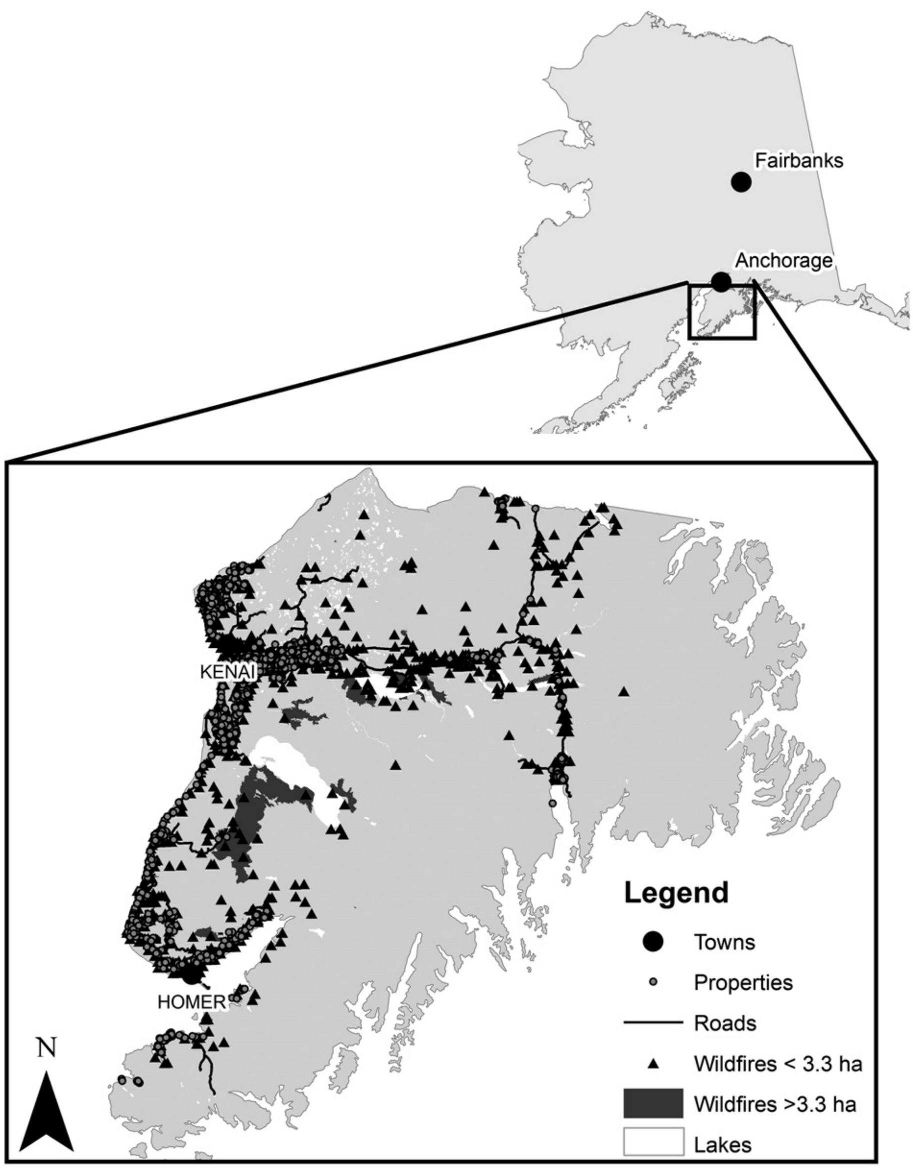

Fig. 2. Wildfires on the Kenai Peninsula (1990–2010).

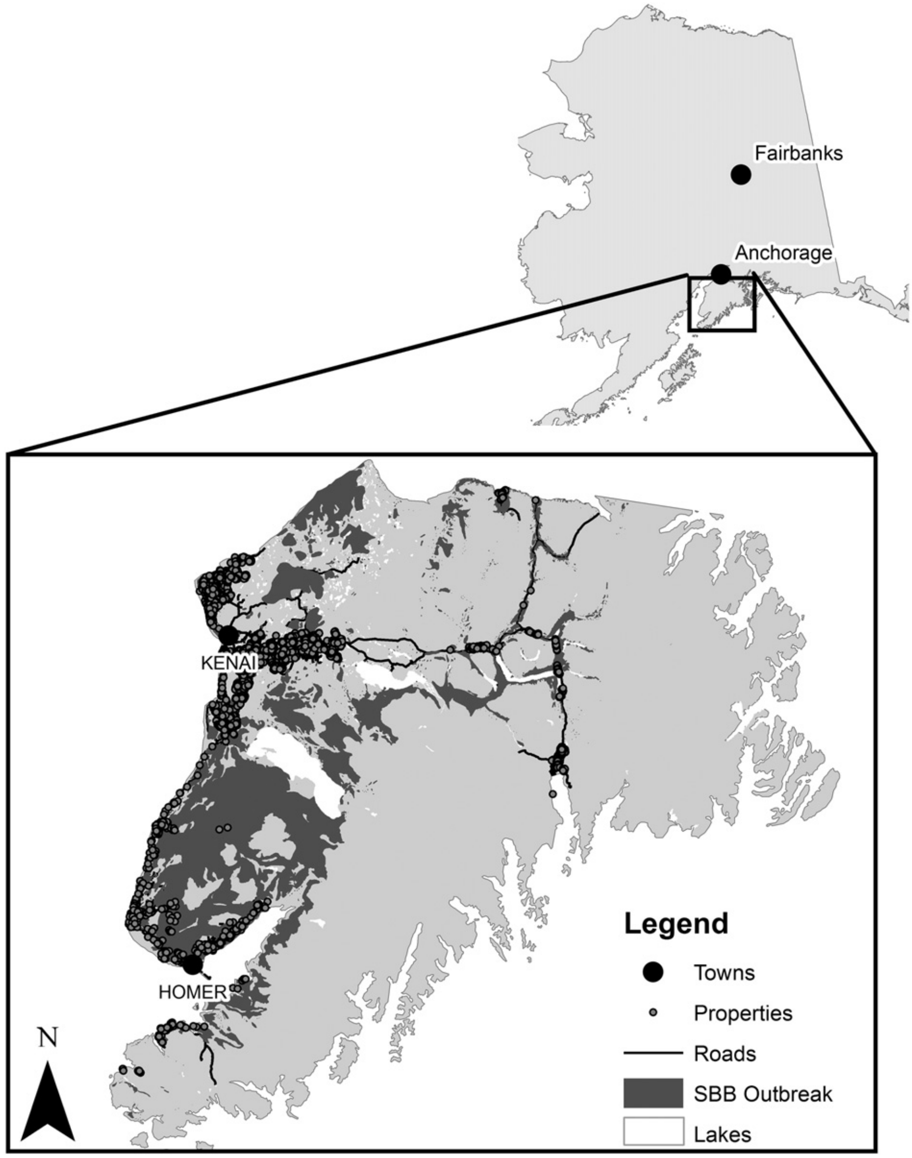

Fig. 3. Spruce bark beetle outbreak on the Kenai Peninsula (1989–2010).

within the limits of incorporated cities on the Kenai Peninsula. Further, we only include properties with at least one bathroom and one bedroom, as some homes in Alaska still have outhouses. Finally, we only include properties for which assessed land and home values were available for both 2001 and 2010. This yields 4398 residential properties for analysis. Table 1 presents descriptive statistics for the data.

Alaska is a non-disclosure state. Thus, the selling prices of properties are not publically available. Our hedonic property model estimates the logarithm of the sum of annual assessed land value and annual assessed home value.[ii] Assessments were conducted by the Kenai Peninsula Borough Assessing Department to calculate property taxes owed. Title 29, Section 45.110 of the Alaska State Constitution mandates that property in Alaska must be regularly assessed, and the assessed value must be equivalent to the property's fair market value. In other words, property must be valued at what the owner views as fair on the real estate market. The Kenai Peninsula Borough Assessing Department evaluates their own ability to meet the state's fair market valuation mandate by surveying recent homebuyers. In the Kenai Peninsula Borough, the mean assessed value to sales price ratio ranged from 92% in 2006 to 94.5% in 2010. While this undervaluation contributes to measurement error, we find no reason to believe that this measurement error is systematically related to the independent variables in our model. We believe our results provide valuable insight into the relationships between the 1990s SBB outbreak, wildfires, and property values.

Perimeters of 33 large wildfires (>3.3 ha) and the point of origin of 1160 small wildfires (<3.3 ha) that burned between 1990 and 2010 came from the Alaska Fire Service's Fire History of Alaska Database (Alaska Fire Service, 2012). Using historical records, aerial surveys, and remote sensing, the Alaska Fire Service maintains spatially explicit fire perimeter records dating back to 1940 (Kasischke et al., 2002). The U.S. Forest Service and Alaska Department of Natural Resource

[ii] There is some question as to whether assessed property values are appropriate for use in hedonic property models. Based on the empirical literature, we feel that our use of assessed property values provides conservative estimates of the values of wildfires and spruce bark beetle outbreak in Alaska. Kim and Goldsmith (2009) and Ma and Swinton (2012) review literature comparing the use of sales prices to the use of assessed property values. The studies they review overwhelmingly suggest that assessed values provide either comparable (Cole et al., 1986; Grimes and Aitken, 2008; Rush and Bruggink, 2000) or superior results (Clapp and Giaccotto, 1992; Janssen and Söderberg, 1999; Kim and Goldsmith, 2009; Schuler, 1990). In contrast Ma and Swinton (2012) offer empirical results where environmental amenity effects are diminished with the use of assessed value data. We believe their finding is prompted by small sample size and multicollinearity.

Table 1
Descriptive statistics.

	Obs	Mean	Std. Dev.	Min	Max	Data source
Large Wildfire <0.1 km	8796	0.002	0.049	0.0	1.0	AFS 2012
Large Wildfire 0.1 km–0.5 km	8796	0.003	0.058	0.0	1.0	AFS 2012
Large Wildfire 0.5 km–1.0 km	8796	0.011	0.107	0.0	1.0	AFS 2012
Small Wildfire <0.1 km	8796	0.013	0.114	0.0	1.0	AFS 2012
Small Wildfire 0.1 km–0.5 km	8796	0.308	0.462	0.0	1.0	AFS 2012
Small Wildfire 0.5 km–1.0 km	8796	0.643	0.479	0.0	1.0	AFS 2012
SBB Outbreak <0.1 km	8796	0.339	0.473	0.0	1.0	USFS 2012
SBB Outbreak 0.1 km–0.5 km	8796	0.490	0.500	0.0	1.0	USFS 2012
SBB Outbreak 0.5 km–1.0 km	8796	0.647	0.478	0.0	1.0	USFS 2012
Percent Non Forested	8796	8.341	12.841	0.0	95.0	NLCD 2001
Percent Forested	8796	51.962	18.372	0.0	98.0	NLCD 2001
Winter Temperature	8796	−6.466	1.748	−8.0	−1.0	SNAP, 2012
Winter Precipitation	8796	38.080	33.460	19.0	177.0	SNAP, 2012
Summer Temperature	8796	12.909	0.443	11.0	15.0	SNAP, 2012
Summer Precipitation	8796	41.895	12.650	31.0	96.0	SNAP, 2012
Elevation	8796	61.895	53.608	1.0	462.0	NED 2012
Ln(Incrptd. City Distance)	8796	2.321	0.733	−0.4	4.5	KPB 2012
Ln(Coast Distance)	8796	1.504	1.405	−6.9	3.7	KPB 2012
Ln(Inland Water Distance)	8796	−0.272	1.651	−6.9	3.6	KPB 2012
Ln(Primary Road Distance)	8796	0.284	1.345	−3.7	3.6	KPB 2012
Ln(Secondary Road Distance)	8796	−2.799	0.644	−6.2	2.4	KPB 2012
Ln(School Distance)	8796	1.207	0.776	−3.2	3.1	KPB 2012
Ln(Parcel Size)	8796	−0.505	0.918	−2.8	4.2	KPB 2012
Home Age	8796	26.570	11.444	11.0	107.0	KPB 2012
Bedrooms	8796	3.146	0.448	1.0	6.0	KPB 2012
Bathrooms	8796	1.816	0.691	1.0	8.0	KPB 2012
Stories	8796	1.398	0.433	1.0	4.8	KPB 2012
Ln(Home Square Feet)	8796	7.417	0.414	5.5	9.2	KPB 2012
Kenai	8796	0.251	0.433	0	1	KPB 2012
Homer	8796	0.069	0.253	0	1	KPB 2012
Seldovia	8796	0.020	0.140	0	1	KPB 2012
Soldotna	8796	0.559	0.496	0	1	KPB 2012
Seward	8796	0.101	0.302	0	1	KPB 2012

annually conduct Alaska Forest Health Aerial Surveys to detect and map insect outbreaks throughout much of the state, focusing on areas of high priority and known outbreaks (United States Forest Service and Alaska Department of Natural Resources, 2012). Perimeters of the SBB outbreak between 1990 and 2010 in the study area came from these surveys.

We include dummy variables to account for the occurrence of large wildfires, small wildfires, and the 1990s SBB outbreak within three distance bands from property center: <0.1 km, 0.1 to 0.5 km, and 0.5 to 1.0 km, matching the distance bands of Price et al. (2010). We also include dummy variables accounting for time since natural disturbances occurred at these different distance bands. The two-time intervals in this model accounted for disturbances that occurred within the previous five years of an observation and disturbances that had occurred in the previous 6–20 years. Unlike wildfire, SBB outbreaks are not events that take place during an individual season, but may continue over several summers. In this study, we define time since the SBB outbreak as the number of years since the outbreak was initially detected.

Percent upland non-forested (grassland, shrubland and cultivated pasture) and percent forested (coniferous, deciduous, and mixed forest) land cover within a 500 m radius of each property's center were calculated using data from the 2001 National Land Cover Database (Homer et al., 2004). Vegetation categories not in this analysis include wetlands, developed areas, and barren soil. Developed by the United States Geological Survey's Multi-Resolution Land Characteristics Consortium, the NLCD vegetation classification is comprised of information from circa 2001 Landsat ETM+ satellite imagery. Data on property elevation came from the United States Geological Survey's National Elevation Dataset (Gesch, 2007; Gesch et al., 2002).

We included variables such as mean winter (December through February) and summer (June through August) temperature and precipitation between 2000 and 2009 to control for climatic differences across the study site. Gridded CRU TS 3.1 temperature and 3.1.01 precipitation data were downscaled to a 1 km resolution by Scenarios Network for Alaska and Arctic Planning (Jones and Harris, 2008; Mitchell and Jones, 2005; SNAP, 2012).

Several geographic characteristics are included in this analysis: distance to the nearest incorporated city, a dummy representing which incorporated city is nearest, distance from the coast, distance from the nearest inland water body (i.e. lakes and rivers), distance to the nearest primary road, distance to the nearest secondary road, and distance to the nearest school. These were calculated using geo-spatial data provided by the Kenai Peninsula Borough Geographic Information Department.[iii] While assessing property values, the Kenai Peninsula Borough Assessing Department records details on structure and property characteristics. Our analysis incorporates property size, home finished square footage, the number of stories, the number of bedrooms, the number of bathrooms, and home age. Data on home quality would have been of utility in our models. However, these data were not readily available.

4. Empirical Model

Proposed by Rosen (1974), the hedonic pricing framework relates the value of a home to the home's individual characteristics:

$$Home\ Value = f(E, G, D), \tag{1}$$

where E represents environmental, G geographic and D dwelling and other property characteristics. Following past research that demonstrates the importance of spatial processes in hedonic pricing analyses (Donovan et al., 2007; Ham et al., 2012; Mueller and Loomis, 2008), central to this analysis is the maximum likelihood estimation of the spatial mixed model with the spatial lag and spatial error terms. Our spatial maximum likelihood model estimates the log-transformed assessed value of property i in year t, P_{it}:

$$P_{it} = \rho \sum_{i \neq t} \omega_{it} P_{it} + \beta_0 + \beta_1 Z_{it} + \beta_2 E_i + \beta_3 G_i + \beta_4 D_i + \gamma Yr2010_t + u_{it} \tag{2}$$

where

$$u_{it} = \lambda \sum_{i \neq t} \omega_{it} u_{it} + E_{it} \tag{3}$$

The spatial lag, $\sum_{i \neq t} \omega_{it} P_{it}$, is the weighted average of the other properties' assessed values. Weights are based on the inverse distance between properties in the sample.[iv] The spatial lag coefficient, ρ, provides insight into strategic interactions between properties. In other words, ρ describes how the assessed value of one property is influenced by the assessed values of other neighboring properties. For

[iii] All distances included in analysis were calculated as the distances from points representing the centroids of each property in our sample to the closest above features. These were calculated using Arc GIS Desktop 10.0 (ESRI, 2011).

[iv] To create the matrices necessary for modeling spatial spillovers, we calculated the x,y coordinates for the centroid of each property using Arc GIS Desktop 10.0 (ESRI, 2011). Coordinates were converted into a text file and imported into R statistical software (R Development Core Team, 2012). Using the spatial package "Fields" to calculate the Euclidian distances between all of the centroids in km, we generated a distance matrix for 2001 and 2010 (Furrer et al., 2009). We then used Stata (2011) software to aggregate the matrices into one with the two distance matrices on the diagonal and the rest filled with null values. We then calculate the inverse distance and row-standardize the matrix.

example, if neighboring properties have a high value, a particularly strong tax base may lead to infrastructure improvements close to homes and higher quality schools, increasing both demand for properties in that area and their values.

The spatial error, $\sum_{i \neq t}\omega_{it}u_{it}$, is the weighted average of other observations' error terms, using the same weights as the spatial lag. The spatial error coefficient, λ, is not interpretable in terms of strategic interactions, but does provide evidence of either spatial similarity (λ > 0) or dissimilarity (λ < 0) between the properties located near one another.[v]

The natural disturbance variables in Z_{it} vary across properties and over time. These include large wildfire, small wildfire, and SBB outbreak dummy variables for three different distance bands. For the statistically significant disturbance distance bands we then separately estimate short-term (1–5 years) and long-term (6–20 years) effects. Including all eighteen natural disturbance distance and time dummies at once causes multicollinearity problems.

Environmental characteristics, E_i, vary across properties but remain constant over time. These include summer and winter temperature and precipitation, percent area forested, percent area non-forested, and elevation. Time invariant geographic variables, G_i, include incorporated city fixed effects and distances to the nearest incorporated city, school, primary road, secondary road, section of coast and inland water body. Dwelling and property characteristics, D_i, also constant over time, include property size, finished home square footage, home age, number of bedrooms and bathrooms, and number of stories. The models also include a dummy variable for year 2010, $yr2010_t$, and an i.i.d. random error term, ε_{it}.

To provide a baseline, we first assume that both the spatial lag and spatial error coefficients equal zero and estimate the OLS model. Next, we estimate the spatial lag and spatial error models separately, allowing each to sequentially take on non-zero values. Finally we estimate the full spatial mixed model. The spatial hedonic property value literature often relies on the Lagrange Multiplier test, employing OLS residuals to test for the spatial error and spatial lag processes. In contrast, we use the likelihood ratio (LR) test with Hendry's general-to-specific (Gets) approach outlined by Florax et al. (2003). The Gets approach is robust to anomalies in the data generating process (Angulo and Mur, 2011; Mur and Angulo, 2009).

We also estimate direct and indirect effects on homeowner welfare. For the analysis of homeowner welfare, the indirect spillover effects may or may not be relevant, as discussed by Small and Steimetz (2012). Pecuniary, or purely monetary, spillovers should not be included in welfare analysis because these do not affect neighboring properties' amenities. Conversely, with technical spillovers, where nearby homes' amenities change in response to natural disturbance, both direct and indirect effects of the natural disturbance should be considered. As Small and Steimetz (2012) discuss, it is difficult to determine which type of spillover dominates. It may be that some neighbors near a fire benefit from more open views implying technical spillover while other neighbors do not. The latter properties only experience pecuniary spillovers.

5. Results

In our analysis, the LR chi-squared statistics, reported in Tables 2 and 4 (>250), demonstrate that the general spatial mixed models are statistically superior to models that restrict spatial lag and/or spatial error coefficients to equal zero. Thus, we focus subsequent discussion on results of the spatial mixed models. Table 2 presents the models for assessed property values with the natural disturbance dummy variables at different distance bands. Qualitatively similar first-differenced results are also available in Appendix 2. These models provide insight into how the occurrence of the SBB outbreak, large wildfires, and small wildfires affect property values. We find that the occurrence of natural disturbances do influence assessed property values. However, the direction and magnitude of effects varies by disturbance type and distance from property.

The spatial lag coefficient, ρ, was positive and significant, providing evidence of spatial spillovers between the assessed values of neighboring properties. An increase in neighboring properties' assessed values of 1% increases the assessed property value by 0.94%. This suggests that the factors influencing the assessed value of one property such as natural disturbances, infrastructure development, and school quality will spillover to affect the value of neighboring properties.

In Table 3 we report both direct and indirect benefits of statistically significant natural disturbance effects from Table 2. Large wildfires that occur within 0.1 km of a property increase assessed property values by 18.6%.[vi] This direct effect on a property experiencing a large wildfire amounts to $30,977 at mean property value of $166,254. Small wildfires decrease assessed property values by 5.5% ($9160) when located within 0.1 km of property center and increase property values by 2.4% ($3,997) when located between 0.1 km and 0.5 km of property center. The occurrence of SBB outbreak within 0.1 km to 0.5 km and 0.5 km to 1.0 km of property center increases assessed property value by 3.7% ($6162) and 2.1% ($3497), respectively. With the exception of small wildfires at close distances, the natural disturbances included in these models have a positive effect on property values. This suggests that the benefits of enhanced environmental amenities associated with wildfires and the SBB outbreak at certain distances outweigh the costs.

In addition to natural disturbance, a number of other environmental amenities influence property values in our analysis. For example, a one percentage-point increase in the percent area that is non-forested upland grassland or shrubland around a home increases property values by 0.1%. Conversely, increasing the percent forest cover by one percentage-point decreases assessed property values by 0.2%. This finding is supported by other studies that find a negative correlation between forest density and property values (Holmes et al., 2006; Kim and Wells, 2005). A 1 °C increase in average winter temperature decreases assessed property values by 2.3% and a 1 mm increase in average summer precipitation decreases property values by 1.4%. This finding is supported in the literature as well (Englin, 1996).

As expected, a 1% increase in the distance to the nearest incorporated city decreases assessed property values by 0.08%. Increasing distances from both the coast and inland water bodies by 1% decreases assessed property values by 0.03% and 0.08%, respectively. A 1% increase in distance from the nearest secondary road increases property values by 0.02%. Distance from the nearest primary road had a statistically insignificant effect. The effects of property and home characteristics were all intuitive. Homes on larger parcels have higher assessed values. Older homes have lower assessed property values. Homes with more bedrooms and more bathrooms, and larger homes all have higher values.

To distinguish between the short-term and long-term effects of natural disturbances on housing prices we estimate the natural disturbance effects during the first five years and the subsequent sixteen years for the statistically significant distance bands in

[v] We use Jeanty's (2010) Stata code *spmlreg* to run our models on the Social Science Gateway hosted by Cornell University and funded by the NSF grant SES-0922005.

[vi] We use the standard transformation of $100 * [\exp(\beta) - 1]$ for interpreting estimated coefficients for dummy variables (Wooldridge, 2009).

Table 2
Ln(assessed property values), natural disturbance distance variables.

Variables	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
Rho		0.989***		0.940***
		(0.008)		(0.034)
Lambda			0.994***	0.984***
			(0.004)	(0.011)
Large Wildfire <0.1 km	0.227***	0.163**	0.212***	0.171**
	(0.059)	(0.069)	(0.078)	(0.077)
Large Wildfire 0.1 km–0.5 km	0.184**	0.057	0.143**	0.097
	(0.090)	(0.078)	(0.066)	(0.065)
Large Wildfire 0.5 km–1.0 km	0.058	−0.080**	0.005	−0.047
	(0.041)	(0.034)	(0.047)	(0.046)
Small Wildfire <0.1 km	−0.069**	−0.067**	−0.063**	−0.057*
	(0.033)	(0.030)	(0.031)	(0.030)
Small Wildfire 0.1 km–0.5 km	0.021***	0.021***	0.027***	0.024***
	(0.008)	(0.007)	(0.008)	(0.008)
Small Wildfire 0.5 km–1.0 km	0.001	0.001	0.010	0.008
	(0.009)	(0.008)	(0.009)	(0.009)
SBB Outbreak <0.1 km	0.007	0.008	0.007	0.005
	(0.009)	(0.009)	(0.010)	(0.010)
SBB Outbreak 0.1 km–0.5 km	0.050***	0.037***	0.042***	0.036***
	(0.008)	(0.008)	(0.009)	(0.009)
SBB Outbreak 0.5 km–1.0 km	0.053***	0.031***	0.029***	0.021**
	(0.009)	(0.008)	(0.009)	(0.009)
Percent Non Forested	0.001**	0.002***	0.002***	0.001**
	(0.001)	(0.001)	(0.001)	(0.001)
Percent Forested	−0.003***	−0.002***	−0.002***	−0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Winter Temperature	−0.071***	−0.033***	−0.046***	−0.023**
	(0.008)	(0.008)	(0.011)	(0.010)
Winter Precipitation	0.009***	0.006***	0.007***	0.006***
	(0.001)	(0.001)	(0.001)	(0.001)
Summer Temperature	0.023	0.027	0.004	0.004
	(0.019)	(0.018)	(0.020)	(0.019)
Summer Precipitation	−0.019***	−0.014***	−0.019***	−0.014***
	(0.002)	(0.002)	(0.002)	(0.002)
Elevation	−0.001***	−0.001***	−0.001***	−0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Ln(Incrptd. City Distance)	−0.111***	−0.049***	−0.124***	−0.077***
	(0.007)	(0.007)	(0.010)	(0.010)
Ln(Coast Distance)	−0.021***	−0.014***	−0.036***	−0.028***
	(0.005)	(0.005)	(0.006)	(0.006)
Ln(Inland Water Distance)	−0.073***	−0.064***	−0.085***	−0.075***
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Primary Road Distance)	0.021***	0.010***	0.009**	0.002
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Second. Road Distance)	0.017**	0.019***	0.024***	0.023***
	(0.007)	(0.007)	(0.007)	(0.007)
Ln(School Distance)	0.046***	0.009*	0.029***	0.006
	(0.005)	(0.005)	(0.007)	(0.007)
Ln(Parcel Size)	0.087***	0.079***	0.095***	0.092***
	(0.006)	(0.006)	(0.005)	(0.005)
Home Age	−0.006***	−0.005***	−0.005***	−0.005***
	(0.000)	(0.000)	(0.000)	(0.000)
Bedrooms	0.039***	0.041***	0.042***	0.043***
	(0.009)	(0.008)	(0.008)	(0.008)
Bathrooms	0.106***	0.100***	0.099***	0.097***
	(0.008)	(0.007)	(0.007)	(0.006)
Stories	−0.057***	−0.056***	−0.050***	−0.051***
	(0.009)	(0.009)	(0.009)	(0.008)
Ln(Home Square Feet)	0.511***	0.500***	0.506***	0.501***
	(0.013)	(0.012)	(0.012)	(0.012)
Year2010	0.402***	−0.001	0.952	0.196
	(0.001)	(0.007)	(1.16)	(0.421)
Kenai	−0.02	−0.013	−0.023	−0.015
	(0.013)	(0.013)	(0.020)	(0.020)
Homer	0.221***	0.150***	0.166***	0.125***
	(0.039)	(0.038)	(0.046)	(0.045)
Seldovia	−0.244***	0.002	−0.257***	−0.113
	(0.068)	(0.067)	(0.090)	(0.088)
Seward	0.386***	0.216***	0.360***	0.256***

Table 2 (*continued*)

Variables	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
	(0.045)	(0.043)	(0.059)	(0.058)
Constant	7.915***	−3.604***	7.235***	−2.889***
	(0.294)	(0.294)	(1.23)	(0.617)
Sigma		0.312***	0.310***	0.305***
		(0.004)	(0.002)	(0.002)
Observations	8796	8796	8796	8796
R-squared	0.602			
Log-likelihood	−2658.658	−2274.141	−2223.735	−2093.629
LR chi^2 (vs. OLS)		769.034	869.845	1130.057
P-value		(<0.01)	(<0.01)	(<0.01)
LR chi^2 (vs. Spatial Lag)				361.024
P-value				(<0.01)
LR chi2 (vs. Spatial Error)				260.212
P-value				(<0.01)

Robust standard errors in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 2. Regressions incorporating these short-term and the long-term effects are found in Table 4. Direct and indirect benefits estimated from Table 4 are found in Table 5. This form of the regression captures how the effects of large wildfires, small wildfires, and SBB outbreak on assessed property values change with time since the disturbances occurred, reflecting ecosystem recovery from disturbance events.

We find that the effects of large wildfires and SBB outbreak on property values are magnified with time since the disturbance occurred. For example, large wildfires that burned within 0.1 km of property center in the previous five years have a statistically insignificant effect on assessed property values. However, large fires that burned within the same distance, but between 6–20 years previously, increase assessed property values by 21.3% ($35,473). The effects of SBB outbreak between 0.1 km and 1.0 km from property center are also magnified through time, increasing property values by 2.2% ($3664) and 3% ($4996) when they occur in the previous five years and in the previous 6–20 years, respectively.

The negative effects of small wildfires diminish with time. Small wildfires that occurred within 0.1 km of property center decrease property values by 7.3% ($12,158) in the first five years since their occurrence, and diminish but are statistically insignificant after the first five years. Similarly, the positive effects of small wildfires that burned between 0.1 km and 0.5 km from property center diminish with time. The coefficients of other variables remain largely unchanged with the addition of time effects.

6. Conclusion

Past research investigating the effects of wildfire and insect outbreaks on property values have overlooked the potentially confounding influence of co-occurring natural disturbances. Our spatial econometric analysis suggests that wildfires and SBB outbreaks affect assessed property values on the Kenai Peninsula. However, the nature of their influence differs as a function of disturbance type, with distance from property centers, and with time since disturbance occurred. Our most surprising result is that large wildfires and the SBB outbreak were associated with increases in assessed property values. As expected though, small wildfires that burn very close to properties (<0.1 km) have a negative effect on assessed property values. We offer some potential explanations.

One possible explanation for the positive effects of natural disturbances on WUI property values is that the benefits of enhanced environmental amenities, as a result of the SBB outbreak and large wildfires, outweigh the costs of diminished environmental amenities. Before the occurrence of a large natural disturbance, properties located in the WUI of the western Kenai Peninsula were surrounded by relatively dense forest. Following a disturbance, the trees are killed and fall, opening up aesthetically pleasing views of Cook Inlet and the Aleutian Mountain Range beyond. The improved views of the ocean and mountains may outweigh the negative impacts associated with natural disturbances. This hypothesis is further supported by the estimated positive effect of percent non-forested land cover on property values, in ours, as well as other studies (Holmes et al., 2006; Kim and Wells, 2005). Further, Englin et al. (2001) and Hilger and Englin (2009) show that hikers in the Rocky Mountain west and Washington state enjoy trails that run through recent burns. They speculate this is due to the ecological novelty. The magnification over time of these positive effects on property values likely reflects ecological recovery that reduces the less pleasing consequences of disturbance, such as charred biomass, while views remain. This is consistent with forest succession patterns on the Kenai Peninsula.

Secondly, following SBB outbreak or the occurrence of a large wildfire, homeowners may perceive a decreased risk of future wildfire. For large wildfires this hypothesis is intuitive, as once a large wildfire has burned an area, it is unlikely another will occur for potentially hundreds of years (Berg and Anderson, 2006). However, recent research suggests that the SBB outbreak actually increases risk for subsequent wildfire (Hansen, 2013). Yet, following the SBB outbreak, extensive salvage logging was conducted. It may be that salvage logging fosters a perception of decreased wildfire risk, whether the risk is actually reduced or not. The positive effects are also likely magnified over time as people continue to perceive a reduced risk of fire while early successional plants establish and diminish the unpleasant impacts of wildfire or salvage logging on the landscape.

Small wildfires that burned very close to properties are the only natural disturbance to have a negative effect on assessed property values in this study. We hypothesize these wildfires burn close enough that homeowners are reminded of wildfire risk. However, the wildfires are small enough that they do not kill the majority of vegetation or open up aesthetically pleasing views. Thus, homeowners do not perceive a decreased risk of future wildfire as they would with large wildfires that destroy most vegetation, nor do they benefit from views of the ocean and mountains. The effects diminish with time as these past wildfires slip into the backs of peoples' minds.

In south-central Alaska, our findings could help inform solutions that balance the integral roles wildfires and SBB outbreaks play in the boreal ecosystem with the protection of life and property in an expanding WUI.

Table 3
Direct and indirect natural disturbance effects.

Variables	(1) Direct Effect[a]	(2) Direct Effect at Mean Value[b]	(3) Spatial Multiplier[c]	(4) Indirect Effect at Mean Value
Large Wildfire <0.1 km	18.6%	\$30,977	16.67	\$516,383
Small Wildfire <0.1 km	−5.5%	−\$9160	16.67	−\$152,697
Small Wildfire 0.1 km–0.5 km	2.4%	\$3997	16.67	\$66,630
SBB Outbreak 0.1 km–0.5 km	3.7%	\$6162	16.67	\$102,721
SBB Outbreak 0.5 km–1.0 km	2.1%	\$3497	16.67	\$58,295

Note:
[a] Direct effects calculated based on the statistically significant effects from Table 2 using the transformation $100 * [\exp(\beta) - 1]$ for interpreting estimated coefficients for dummy variables (Wooldridge, 2009).
[b] Mean value of the property is \$166,542.
[c] Spatial multiplier is $1/(1 - \text{Rho}) = 1/(1 - 0.94)$.

For example, research in the western United States suggests that targeting fuels reduction treatments to create defensible space around homes in the WUI is a substantially more cost-effective approach than treating all forests affected by bark beetle outbreak (Aronson and Kulakoski, 2013). Managers could potentially garner more public support, active involvement, and financial backing to conduct targeted wildfire fuel reduction treatments in the WUI if they design treatments to maximize the improvement of aesthetically pleasing views around homes. Homeowners may be more receptive to explanations of how fuel reduction treatments allow wildfire to burn naturally, while still keeping their homes safe, if they see that such treatments will also increase their property values.

Accounting for spatial interactions provides valuable insight with direct policy application, in addition to ensuring unbiased coefficient estimation. The positive spatial spillovers found in this study could help demonstrate to homeowners that reducing fuel loads around homes not only increases their own property values but also positively affects the property values of their neighbors' homes. Conveying how the benefits of proactively managing human-natural disturbance interactions spill over among properties might help bring neighborhoods together around the issue, motivate broader public participation, and increase pressure on those resistant to action.

Past research using stated preference techniques to document the perceptions of Kenai Peninsula residents identified a mixed relationship between the 1990s SBB outbreak and property values (Flint, 2006). Interviews with residents provided evidence for our emerging views hypothesis. Improved views were considered to be a positive outcome of the SBB outbreak. However, in surveys conducted for the same study, 67% of respondents presumed that their property values had decreased as a result of the outbreak. Flint (2006) does not speculate why respondents associated the outbreak with reductions in property values. Participants also expressed concern for personal safety as a result of falling dead trees, an emotional sadness associated with changing natural aesthetics, and a mixed outlook on future wildfire risk, depending on the community sampled. Differences in the results of our study and past work on the Kenai Peninsula highlight the complex and dynamic viewpoints people develop regarding the perceived consequences of natural disturbances.

In general, to create and implement innovative management strategies, we must better understand the mechanisms through which people evaluate the consequences of natural disturbance and the magnitude of their influence (Kovacks et al., 2011; Venn and Calkin, 2011). This presents a substantial challenge because perceptions of natural disturbances are likely to vary significantly between geographic locations, over time and, as Flint (2006) demonstrates, between people within a single location. In addition, it has long been shown that revealed preference versus stated preference techniques can yield different views of how the same group of people perceives environmental amenities (Adamowicz et al., 1994, 1997). Yet, both techniques may provide complementary manager-relevant insights into two different dimensions of complex human-perception dynamics (Chasco and Gallo, 2013). Continued research is needed to better integrate the results of revealed preference and stated preference studies, determining in what contexts the approaches yield similar results and to what extent the results of each are useful for managing natural disturbance–human interactions in the WUI.

Further, we must better integrate ecological and economic research. A disconnect exists between recent advances in our ecological understanding of natural disturbances, context-specific ecological nuances, and the economic valuation of environmental amenities. “The reliability of natural science data is generally unquestioned in economic analysis of environmental change. Rarely is an economic study conducted in association with a new piece of scientific research or are site specific current damage estimates obtained” (Spash and Vatn, 2006, p. 381). Recent ecological research suggests that the occurrence of one form of natural disturbance can alter the

Table 4
Ln(assessed property values), short- & long-term disturbance effects.

	(1)	(2)	(3)	(4)
Variables	OLS	Spatial Lag	Spatial Error	Spatial Mixed
Rho		0.988***		0.941***
		(0.008)		(0.034)
Lambda			0.994***	0.984***
			(0.004)	(0.011)
Large Wildfire <0.1 km 1–5 yr	0.171**	0.134	0.166	0.141
	(0.080)	(0.096)	(0.101)	(0.099)
Large Wildfire <0.1 km 6–20 yr	0.247***	0.203**	0.226*	0.193*
	(0.077)	(0.083)	(0.116)	(0.114)
Small Wildfire <0.1 km 1–5 yr	−0.120**	−0.095**	−0.092**	−0.076*
	(0.048)	(0.043)	(0.046)	(0.045)
Small Wildfire <0.1 km 6–20 yr	−0.038	−0.046	−0.045	−0.045
	(0.045)	(0.041)	(0.041)	(0.040)
Small Wildfire 0.1 km–0.5 km 1–5 yr	0.017	0.017*	0.029**	0.026**
	(0.010)	(0.010)	(0.011)	(0.011)
Small Wildfire 0.1 km–0.5 km 6–20 yr	0.023**	0.024***	0.022**	0.021**
	(0.009)	(0.009)	(0.010)	(0.010)
SBB Outbreak 0.1–1.0 km 1–5 yr	0.052***	0.035***	0.028***	0.022**
	(0.009)	(0.008)	(0.010)	(0.010)
SBB Outbreak 0.1–1.0 km 6–20 yr	0.064***	0.037***	0.042***	0.030***
	(0.008)	(0.008)	(0.009)	(0.009)
Percent Non Forested	0.001**	0.002***	0.002***	0.001***
	(0.001)	(0.001)	(0.001)	(0.001)
Percent Forested	−0.003***	−0.002***	−0.002***	−0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Winter Temperature	−0.063***	−0.027***	−0.043***	−0.020*
	(0.008)	(0.007)	(0.010)	(0.010)
Winter Precipitation	0.008***	0.006***	0.007***	0.005***
	(0.001)	(0.001)	(0.001)	(0.001)
Summer Temperature	0.016	0.017	−0.002	−0.001
	(0.018)	(0.017)	(0.020)	(0.019)
Summer Precipitation	−0.020***	−0.014***	−0.020***	−0.015***
	(0.002)	(0.002)	(0.002)	(0.002)
Elevation	−0.001***	−0.001***	−0.001***	−0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Ln(Incrptd. City Distance)	−0.110***	−0.049***	−0.125***	−0.078***
	(0.007)	(0.007)	(0.010)	(0.010)
Ln(Coast Distance)	−0.021***	−0.013***	−0.036***	−0.028***
	(0.005)	(0.005)	(0.006)	(0.006)
Ln(Inland Water Distance)	−0.073***	−0.062***	−0.085***	−0.074***
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Primary Road Distance)	0.022***	0.011***	0.010**	0.003
	(0.003)	(0.003)	(0.004)	(0.004)
Ln(Secondary Road Distance)	0.015**	0.021***	0.025***	0.023***
	(0.007)	(0.007)	(0.007)	(0.007)
Ln(School Distance)	0.046***	0.010**	0.027***	0.005
	(0.005)	(0.005)	(0.007)	(0.007)
Ln(Parcel Size)	0.086***	0.076***	0.094***	0.091***
	(0.006)	(0.006)	(0.005)	(0.005)
Home Age	−0.006***	−0.005***	−0.005***	−0.005***
	(0.000)	(0.000)	(0.000)	(0.000)
Bedrooms	0.040***	0.042***	0.043***	0.044***
	(0.009)	(0.008)	(0.008)	(0.008)
Bathrooms	0.106***	0.100***	0.099***	0.097***
	(0.008)	(0.007)	(0.007)	(0.006)
Stories	−0.057***	−0.055***	−0.050***	−0.050***
	(0.009)	(0.009)	(0.009)	(0.008)
Ln(Home Square Feet)	0.511***	0.500***	0.506***	0.501***
	(0.013)	(0.012)	(0.012)	(0.012)
Year2010	0.404***	0.002	0.921	0.191
	(0.007)	(0.008)	(1.160)	(0.425)
Kenai	−0.026*	−0.020	−0.027	−0.019
	(0.013)	(0.013)	(0.020)	(0.020)
Homer	0.221***	0.142***	0.168***	0.125***
	(0.039)	(0.038)	(0.046)	(0.045)
Seldovia	−0.245***	0.015	−0.259***	−0.110
	(0.067)	(0.066)	(0.090)	(0.088)
Seward	0.434***	0.235***	0.392***	0.278***
	(0.044)	(0.042)	(0.059)	(0.058)
Constant	8.107***	−3.429***	7.403***	−2.773***
	(0.286)	(0.287)	(1.225)	(0.615)
Sigma		0.312***	0.311***	0.305***
		(0.004)	(0.002)	(0.002)
Observations	8796	8796	8796	8796
R-squared	0.600			

Table 4 (*continued*)

Variables	(1) OLS	(2) Spatial Lag	(3) Spatial Error	(4) Spatial Mixed
Log-likelihood	−2672.363	−2284.612	−2233.374	−2102.036
LR chi^2 (vs. OLS)		769.034	880.177	1142.653
P-value		(<0.01)	(<0.01)	(<0.01)
LR chi^2 (vs. Spatial Lag)				365.152
P-value				(<0.01)
LR chi2 (vs. Spatial Error)				262.676
P-value				(<0.01)

Robust standard errors in parentheses.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

characteristics of another natural disturbance, and thus its consequences for people, a concept known as linked disturbance interactions (Donato et al., 2013; Hansen, 2013; Simard et al., 2011; Turner, 2010). Thus, models of how wildfires affect property values in the WUI may be incomplete without considering the confounding influence of co-occurring natural disturbances, such as SBB outbreak.

We also need to develop ecological research to better understand the consequences of natural disturbances that are particularly relevant to human wellbeing (Venn and Calkin, 2011). What suites of environmental amenities, important to people, are affected by different types of natural disturbances? How do varying characteristics (e.g. frequency and severity) of those disturbances change the extent to which they affect environmental amenities? Does variation in the extent to which environmental amenities are affected by disturbance influence how people perceive the consequences of that disturbance? Meaningful collaborations between ecologists and economists could help to better assimilate social and ecological complexities into single, more comprehensive forms of analysis that accommodate multifaceted, non-linear interactions and feedbacks between multiple drivers.

One promising approach for assimilating the influence of complex social and ecological characteristics is the use of systems dynamics analysis (Meadows, 2009). The technique allows researchers to visually map out potential actors, drivers, and feedbacks of a system and quantitatively define the nature and magnitude of their interactions (Ford, 1999). This could provide researchers with a framework to conceptualize what is known about how natural disturbances affect ecosystem structure and function, environmental amenities, peoples' perceptions of the consequences of disturbance, and identify where further research is needed. Once a system has been mapped, interactions parameterized, and the model is validated, sensitivity analysis could simulate how changes in key variables will play out through the system. This will help managers identify promising leverage points where intervention may foster improved social and ecological outcomes.

Future research is needed to continue characterizing WUI human–natural disturbance interactions on the Kenai Peninsula, across the North American boreal forest, and more broadly. Encouraging support for proactively managing human–natural disturbance interactions will likely require tailoring the scope and benefits of specific management actions to fit the needs of diverse citizen groups on the Kenai Peninsula. However, this study does highlight promising opportunities for fuels reduction treatments that could let naturally caused wildfire burn more safely. We also offer ways to incentivize participation and support for those treatments. Some of the hypotheses and management prescriptions presented in this paper are built on characteristics specific to the Kenai Peninsula, Alaska, such as emerging views of mountains and ocean. However, the unique findings of this study also call attention to the complex ways in which homeowners perceive the consequences of disturbances. This paper identifies and prioritizes future research needs, exploring homeowner perceptions, which could improve our understanding of complex human–natural disturbance interactions and help us to more effectively manage such interactions in the WUI across the United States.

Table 5
Direct and indirect natural disturbance effects over time.

Variables	(1) Direct Effect[a]	(2) Direct Effect at Mean Value[b]	(3) Spatial Multiplier[c]	(4) Indirect Effect at Mean Value
Large Wildfire <0.1 km 6–20 yr	21.3%	$35,473	16.67	$591,335
Small Wildfire <0.1 km 1–5 yr	−7.3%	−$12,158	16.67	−$202,674
Small Wildfire 0.1 km–0.5 km 1–5 yr	2.6%	$4330	16.67	$72,181
Small Wildfire 0.1 km–0.5 km 6–20 yr	2.1%	$3497	16.67	$58,295
SBB Outbreak 0.1 km–0.5 km 1–5 yr	2.2%	$3664	16.67	$61,079
SBB Outbreak 0.1 km–1.0 km 6–20 yr	3.0%	$4996	16.67	$83,283

Note:
[a] Direct effects calculated based on the statistically significant effects from Table 3 using the transformation $100 * [\exp(\beta) - 1]$ for interpreting estimated coefficients for dummy variables (Wooldridge, 2009).
[b] Mean Value of the property is $166,542.
[c] Spatial multiplier is $1/(1 - \text{Rho}) = 1/(1 - 0.94)$.

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Appendix 1. OLS estimates Ln(assessed property values), natural disturbance distance variables

Variables	(1) No disturbance	(2) Large wildfire	(3) Small wildfire	(4) SBB	(5) All disturbance
Large Wildfire <0.1 km		0.211***			0.227***
		(0.059)			(0.059)
Large Wildfire 0.1 km–0.5 km		0.190**			0.184**
		(0.092)			(0.090)
Large Wildfire 0.5 km–1.0 km		0.070*			0.058
		(0.042)			(0.041)
Small Wildfire <0.1 km			−0.067**		−0.069**
			(0.033)		(0.033)
Small Wildfire 0.1 km–0.5 km			0.020***		0.021***
			(0.008)		(0.008)
Small Wildfire 0.5 km–1.0 km			0.002		0.001
			(0.009)		(0.009)
SBB Outbreak <0.1 km				0.010	0.007
				(0.009)	(0.009)
SBB Outbreak 0.1 km–0.5 km				0.050***	0.050***
				(0.008)	(0.008)
SBB outbreak 0.5 km–1.0 km				0.051***	0.053***
				(0.009)	(0.009)
Percent non forested	0.001*	0.001**	0.001*	0.001**	0.001**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Percent forested	−0.003***	−0.003***	−0.003***	−0.003***	−0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Winter temperature	−0.050***	−0.049***	−0.050***	−0.073***	−0.071***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Winter precipitation	0.007***	0.006***	0.007***	0.009***	0.009***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Summer temperature	−0.010	−0.012	−0.009	0.026	0.023
	(0.018)	(0.018)	(0.018)	(0.019)	(0.019)
Summer precipitation	−0.020***	−0.019***	−0.020***	−0.020***	−0.019***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Elevation	−0.001***	−0.001***	−0.001***	−0.001***	−0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Ln(Incrpt. City Distance)	−0.115***	−0.116***	−0.112***	−0.112***	−0.111***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Ln(Coast Distance)	−0.027***	−0.025***	−0.027***	−0.023***	−0.021***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Ln(Inland Water Distance)	−0.074***	−0.072***	−0.074***	−0.074***	−0.073***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Ln(Primary Road Distance)	0.025***	0.024***	0.025***	0.022***	0.021***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Ln(Secondary Road Distance)	0.014*	0.016**	0.014**	0.015**	0.017**
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Ln(School Distance)	0.045***	0.046***	0.045***	0.044***	0.046***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Ln(Parcel Size)	0.083***	0.082***	0.083***	0.088***	0.087***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
Home Age	−0.006***	−0.005***	−0.006***	−0.006***	−0.006***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Bedrooms	0.039***	0.040***	0.038***	0.038***	0.039***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Bathrooms	0.107***	0.107***	0.106***	0.106***	0.106***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Stories	−0.059***	−0.058***	−0.058***	−0.058***	−0.057***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Ln(Home Square Feet)	0.514***	0.513***	0.514***	0.512***	0.511***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Year2010	0.415***	0.414***	0.414***	0.403***	0.402***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Kenai	−0.043***	−0.046***	−0.039***	−0.023*	−0.022
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Homer	0.200***	0.197***	0.201***	0.224***	0.221***
	(0.039)	(0.039)	(0.039)	(0.039)	(0.039)
Seldovia	−0.258***	−0.237***	−0.249***	−0.270***	−0.244***
	(0.067)	(0.067)	(0.068)	(0.067)	(0.068)
Seward	0.528***	0.513***	0.526***	0.402***	0.386***
	(0.043)	(0.043)	(0.043)	(0.045)	(0.045)
Constant	8.623***	8.644***	8.608***	7.900***	7.915***
	(0.282)	(0.283)	(0.282)	(0.292)	(0.294)
n	8796	8796	8796	8796	8796
R-squared	0.596	0.597	0.596	0.600	0.602
F	509.84***	455.00***	455.21***	461.22***	380.27***

Robust standard errors in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Appendix 2. First-differenced estimates LN (assessed property values), natural disturbance variables

	(1)	(2)	(3)	(4)
Variables	OLS	Spatial Lag	Spatial Error	Spatial Mixed
Rho		0.988***		0.884***
		(0.012)		(0.089)
Lambda			0.989***	0.865***
			(0.011)	(0.097)
Large Wildfire <0.1 km	0.357**	0.333**	0.379***	0.363***
	(0.163)	(0.158)	(0.128)	(0.126)
Large Wildfire 0.1 km–0.5 km	−0.025	−0.030	−0.011	−0.013
	(0.071)	(0.070)	(0.104)	(0.103)
Large Wildfire 0.5 km–1.0 km	0.174	0.164	0.191	0.188
	(0.147)	(0.142)	(0.127)	(0.125)
Small Wildfire <0.1 km	−0.031	−0.028	−0.019	−0.015
	(0.062)	(0.060)	(0.061)	(0.060)
Small Wildfire 0.1 km–0.5 km	0.030	0.008	0.004	0.001
	(0.021)	(0.020)	(0.024)	(0.023)
Small Wildfire 0.5 km–1.0 km	0.025	0.013	0.013	0.011
	(0.017)	(0.016)	(0.019)	(0.019)
SBB Outbreak <0.1 km	0.066***	0.047**	0.048**	0.043**
	(0.020)	(0.020)	(0.019)	(0.019)
SBB Outbreak 0.1 km–0.5 km	0.056***	0.035**	0.036**	0.030*
	(0.017)	(0.017)	(0.018)	(0.018)
SBB Outbreak 0.5 km–1.0 km	0.079***	0.042***	0.039**	0.031*
	(0.015)	(0.015)	(0.017)	(0.017)
Constant	0.390***	−0.006	0.697	0.058
	(0.006)	(0.007)	(0.506)	(0.058)
Sigma		0.311***	0.311***	0.309***
		(0.006)	(0.003)	(0.003)
Observations	4,398	4,398	4,398	4,398
R-squared	0.017			
Log-likelihood	−1287.91	−1122.03	−1125.211	−1097.058
LR chi2 (vs. OLS)		331.76	325.40	381.70
P-value		(<0.001)	(<0.001)	(<0.001)
LR chi2 (vs. Spatial Lag)				49.94
P-value				(<0.001)
LR chi2(vs. Spatial Error)				56.306
P-value				(<0.001)

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