Forest Policy and Economics 12 (2010) 415–422

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Insect infestation and residential property values: A hedonic analysis of the mountain pine beetle epidemic

James I. Price [a,*], Daniel W. McCollum [b], Robert P. Berrens [c]

[a] Department of Economics, MSC 05 3060, 1 University of New Mexico, Albuquerque, NM 87131-0001, United States
[b] Rocky Mountain Research Station, Natural Resources Research Center, 2150-A Centre Avenue, Fort Collins, CO 80526-1891, United States
[c] Department of Economics, MSC 05 3060 1 University of New Mexico, Albuquerque, NM 87131-0001, United States

ARTICLE INFO

Article history:
Received 25 September 2009
Received in revised form 23 March 2010
Accepted 3 May 2010

Keywords:
Mountain pine beetle
Wildland-urban interface
Hedonic pricing analysis
Spatial lag

ABSTRACT

In recent years mountain pine beetles (MPB), *Dendroctonus ponderosae,* along with several other bark beetle species, have severely damaged coniferous forests in the western United States (U.S.) and Canada (Morris and Walls, 2009). Colorado provides one example of a region that has been heavily affected. The Colorado State Forest Service estimates that 769,000 ha of Colorado's forests, of all jurisdictions, have been infested with MPB since the outbreak began in 1996 (Leatherman, 2009). An important consequence of this damage is declining utility (i.e. a reduction in the level of satisfaction derived from goods and services, both market and nonmarket) for residents of the wildland-urban interface (WUI). Specifically, beetle infestations lower utility by reducing the value of forest amenities and increasing the risk of wildfire. We use a hedonic pricing model to estimate willingness-to-pay (WTP) to prevent MPB damage in Grand County, Colorado. The hedonic model establishes a statistical relationship between property prices and various characteristics. In this case, the characteristic of interest is the number of trees killed by MPB infestations. A Geographic Information System (GIS) is used to determine the number of these trees within 0.1, 0.5, and 1.0 kilometer buffers of each property. Marginal implicit prices for MPB damage are calculated, after controlling for structural and spatial characteristics. Results indicate that property values decline by \$648, \$43, and \$17 for every tree killed by MPB infestations within a 0.1, 0.5, and 1.0 km buffer, respectively.

1. Introduction

In recent years mountain pine beetles (MPB), *Dendroctonus ponderosae*, along with several other species of bark beetles, have severely damaged coniferous forests in the western United States (U.S.) and Canada (Morris and Walls, 2009). These infestations have been most pronounced in Colorado and British Columbia. Estimates from the Colorado State Forest Service and the British Columbia Ministry of Forests and Range indicate that 14 million hectares were infested with MPB between 1996 and 2007 (Leatherman, 2009; BCMOFR, 2008). An important consequence of this damage is declining utility (i.e. a reduction in the level of satisfaction derived from goods and services) for residents of the wildland-urban interface (WUI). Specifically, beetle infestations lower utility by reducing the value of forest amenities and increasing the risk of wildfire. To avoid these losses many residents attempt to control the spread of MPB using chemical (e.g. pesticides) and physical (e.g. burning and stripping bark) means. These methods have proven effective when beetle populations are small and isolated. However, when populations reach epidemic levels, as they have in the U.S. and Canada, these techniques are entirely ineffectual (Carroll, 2007). Instead, the best means of mitigating ecosystem damage and utility loss is to prevent MPB populations from reaching these levels (Romme et al., 2006).

Recent research indicates that the severity of the current MPB outbreak is due largely to fire suppression practices and drought conditions (van Mantgem et al., 2009; Taylor and Carroll, 2003).[1] Fire suppression practices in particular have substantially altered forest ecosystems, which are now characterized by greater average age, greater density, and increased stress levels (Donovan and Brown, 2007; Taylor and Carroll, 2003). The end result is that forests are increasingly susceptible to MPB attack.

All this implies that restoring natural forest ecosystems can lessen, and possibly prevent, MPB epidemics and other insect infestations. Such benefits may justify efforts to improve forest health through established silviculture techniques such as thinning and controlled

* Corresponding author. Department of Economics MSC 05 3060, 1 University of New Mexico, Albuquerque, NM 87131-0001, United States. Tel.: +1 505 277 5304; fax: +1 505 277 9445.
E-mail address: jprice14@unm.edu (J.I. Price).

[1] There is some evidence to suggest that climate change might also be contributing to the MPB outbreak. van Mantgem et al. (2009) find a statistical relationship between regional warming in the western U.S. and increased tree mortality rates. They argue that regional warming increases water deficits and enhances the reproduction of tree attacking insects.

1389-9341/\$ – see front matter
doi:10.1016/j.forpol.2010.05.004

burns. When properly implemented these techniques have been shown to reduce the impact of beetle infestation (Schmid and Mata, 2005). But, applying proper silviculture practices throughout North American forests is expensive. With estimates ranging from \$100 to \$1000 per acre the costs are substantially greater than current levels of public funding (Donovan and Brown, 2005).[2]

Residents of the WUI receive considerable benefit from forested areas in the form of recreation opportunities, scenic views, and higher property values. It follows that these residents have vested interests in maintaining healthy forest environments and should be willing to help partially fund or support forest restoration programs (e.g. through private mitigation actions, local property taxes, participation in a range of federal, state and local cost-share programs, and participation in watershed and community forest restoration programs). In doing so they protect the value of their home and the utility received from forest amenities.

As evidence of the magnitude of off-site benefits from forest restoration, this paper uses a hedonic pricing model to estimate WUI residents' willingness-to-pay (WTP) to prevent MPB damage in Grand County, Colorado. The hedonic model establishes a statistical relationship between property values and environmental characteristics, while controlling for other effects. In this case, the environmental characteristic of interest is the number of trees killed by MPB infestations. A Geographic Information System (GIS) is used to determine the number of trees destroyed within 0.1, 0.5, and 1.0 km radius of each property. After controlling for other factors, we calculate the marginal implicit price for MPB damage. Results indicate a WTP of \$648, \$43, and \$17 for every tree killed within a 0.1, 0.5, and 1.0 km radius, respectively.

2. Literature review

There are a variety of recent studies indicating the general importance of protecting, restoring and maintaining forest amenities in the Southwestern U.S. and the Rocky Mountain region (e.g. Hand et al., 2008a,b; Izon et al., 2010; Kim and Wells, 2005; Loomis, 2004). A review of recent hedonic literature identified three studies particularly relevant to analyzing MPB damage. In a New Jersey study, Holmes et al. (2006) dealt directly with the impact of insect infestation on property values. The other two studies, Kim and Wells (2005) and Loomis (2004), analyzed forest density levels and wildfire risk perception, respectively. Although the latter two are not concerned with insect infestations, these studies offer important insights into the relationship between property values and forest disamenities.

Holmes et al. (2006) used a hedonic model to evaluate the effect of hemlock woolly adelgid in New Jersey. The hemlock woolly adelgid, an invasive species, was introduced to North America in the early 1950s. Since its introduction it has severely damaged hemlock trees along the eastern coast of the U.S. and Canada. Holmes et al. (2006) used GIS to estimate the percentage of healthy, moderately unhealthy, severely unhealthy, and dead hemlock trees within a given distance of each home. The analysis yielded three important findings. First, healthy hemlock trees are positively correlated with housing prices. This supports the findings of Paterson and Boyle (2002) and Kim and Wells (2005), which indicated that healthy forest landscapes will increase housing values. Second, unhealthy hemlock trees were negatively correlated with housing prices, indicating that infestation damage lowers property values. Third, the impact of unhealthy hemlock trees extends beyond property boundaries. In particular, housing prices were significantly correlated with unhealthy trees up to 1 km from the home.

Kim and Wells (2005) analyzed the impact of forest density in Flagstaff, AZ. Using aerial photographs they classified woodlands by the percentage of canopy closure. Woodlands with 70–100% and 40–69% canopy closure are classified as high- and medium-density, respectively. Using GIS they determined the proportion of each density classification within a 0.5 km buffer of residential properties. Findings show that sales prices increased by \$0.14 per square meter of medium-density forest. In contrast, sales prices decreased by \$0.05 per square meter of high-density forest. The authors concluded that property values reflect the increased risk of wildfire associated with high-density forests. Furthermore, the authors argued that residents of the WUI should take partial responsibility for thinning woodlands within the vicinity of their home. In doing so, they protect the value of their property.

Loomis (2004) evaluated the effect of a nearby wildfire on residential property values in Colorado's WUI. In 1996 a wildfire burned 12,000 acres and several homes in the town of Buffalo Creek. The fire was followed by severe flooding that destroyed the town's water treatment system. Loomis estimated the effect of these events on housing values in the nearby town of Pine, which was physically unaffected by the fire. A dummy variable was used to distinguish between property sales before and after the fire. Results showed a 15% decline in housing prices after the fire. Since the fire did not directly damage the town of Pine, nor its surrounding area, these results indicated that the homebuyer's perception of fire risk is an important determinant of property value.

3. Background: mountain pine beetle

As a species native to North America, the MPB is integral to the natural forest ecosystem. Its life cycle, which typically lasts one year, begins in late July when eggs are laid in newly-infested trees (Leatherman et al., 2007). Once hatched, MPB larvae begin to feed, creating a series of tunnels throughout the trees' phloem. This stage of the life cycle continues until May the following year. In order to survive winter temperatures the larvae metabolize glycerol, an alcohol-based chemical, which counteracts freezing (Leatherman et al., 2007). Once the glycerol is produced, only extended periods of subzero temperature are capable of killing the larvae. The U.S. Department of Agriculture (USDA) estimates that temperatures must be below −30 °F for at least five days in order to substantially reduce the larvae population (Leatherman et al., 2007). MPB are more vulnerable to freezing temperatures during the early fall or late spring, when the larvae do not produce glycerol. In Colorado, MPB populations are typically reduced during these times (Leatherman et al., 2007). When the larvae reach adulthood they continue to feed for several weeks before emerging from the tree to lay eggs. An important part of the MPB lifecycle is the ability to infect trees with blue-staining fungi. As MPB attack a new tree they carry fungi spores on their bodies and in a special compartment on their heads (Amman et al., 1990). As the fungi spreads it disrupts the flow of water and sap throughout the tree, thus reducing the tree's ability to repel the beetles (Amman et al., 1990).

MPB develop in a variety of pine species, including ponderosa, western white, sugar, limber, and Scotch, but lodgepole pines are the most common hosts (Amman et al., 1990; Leatherman et al., 2007). Lodgepole pines inhabit elevations between 6000 and 11,000 ft. They are between 20 and 80 ft in height and typically grow in dense, evenly-aged stands (Colorado State Forest Service, 2009). During non-epidemic periods, MPB attack old and diseased trees — reducing overcrowding and creating space for younger trees to grow (Schowalter and Withgott, 2001). This service is vital to the process of forest regeneration. However, during epidemic periods, beetles attack indiscriminately, often altering entire forestscapes and substantially reducing environmental service flows. The current outbreak, the largest on record, has severely damaged pine forests

[2] There are approximately 75 million acres of national forest land currently in need of treatment (Donovan and Brown, 2005). The combined 2007 budget of the U.S. Forest Service and the U.S. Department of the Interior (USDI) for hazardous fuel reduction (i.e. thinning and controlled burns) on this land was only \$491,579,000. By comparison, the combined budgets for fire suppression (i.e. direct firefighting costs) and pre-suppression (i.e. costs related to preparation such as the purchase of equipment) was \$1,933,905,000 (U.S. Department of Agriculture, U.S. Department of the Interior, 2006).

throughout western North America. British Columbia provides an example of a region that has been heavily affected. Recent estimates by the British Columbia Ministry of Forests and Range show that 46% of province's mature pine trees were killed from 1998 to 2008, with a projected mortality of 71% by 2019 (Walton, 2009). This damage is so acute that it is described as an "ecosystem-altering" event (Natural Resources Canada, 2007). In the U.S., damage is less critical, although several areas are experiencing dramatic changes to their natural environment. The most severe damage has occurred in Colorado, Wyoming, South Dakota, Montana, and Idaho. In Colorado, damage from MPB has expanded rapidly since the outbreak began in 1996. The most recent assessment shows that 769,000 ha of Colorado's forest have been infested with MPB (Leatherman, 2009).

The severity of the current MPB epidemic can be attributed to a convergence of overcrowded forests, the consequence of fire suppression, and prolonged drought conditions across western North America (Taylor and Carroll, 2003; van Mantgem et al., 2009). The result is a greater number of trees competing for less water. This leaves trees in a weakened or stressed condition and more susceptible to insects and disease.[3]

Taylor and Carroll (2003) evaluated the relationship between fire regimes and MPB populations in British Columbia. Their analysis indicates that fire suppression practices have substantially increased the number of trees stands over 80 years old, the approximate age when trees become vulnerable to MPB. In particular, the analysis indicates that under natural fire regimes between 17% and 25% of tree stands are susceptible to beetle attack. In contrast, since fire suppression practices began in the early 1900s the number of tree stands susceptible to beetle attack has grown to 55%. In the U.S. fire suppression, which has been the dominant policy for many decades, has had a similar impact on forest ecosystems (Donovan and Brown, 2007).

Several methods exist for controlling MPB during non-epidemic periods. These methods include introducing natural predators (such as woodpeckers or clerid beetles), applying chemical treatments, burning infested trees, and overheating beetles by concentrating solar energy (Leatherman et al., 2007). The most effective approach, and also the most labor-intensive, is to physically remove the bark of infested trees. This exposes the larvae to unfavorable conditions, causing them to dehydrate or starve (Leatherman et al., 2007). In general, the smaller the infestation the more likely any of these methods are to succeed.

In contrast to non-epidemic periods, very little can be done to prevent the spread of infestation once an outbreak begins. Accordingly, the most effective method of controlling an epidemic is to eliminate the underlying causes (Leatherman et al., 2007). In general, this implies a need to relax fire suppression practices, allowing forests to return to more natural conditions. In certain areas, however, such as the WUI, it may be possible to create more natural conditions using established silviculture techniques such as thinning and controlled burns. When properly implemented these techniques improve tree health, diversify tree growth, and reduce density. Forests exhibiting these characteristics are considerably less vulnerable to MPB attacks and the risk of wildfire (Schmid et al., 2007).

4. Area description

The WUI refers to areas where human-made developments, such as residential neighborhoods, are in proximity to or intermingle with undeveloped wilderness (Dennis et al., 2009). The USDA distinguishes between two types of WUI: intermix communities and interface communities. Intermix communities occur where housing structures intermingle with wildland vegetation. These communities are dominated by wildland vegetation and characterized by a minimum density of 6.17 housing units per square kilometer (U.S. Department of Agriculture, U.S. Department of the Interior, Jan. 4, 2001). Interface communities occur where residential neighborhoods are adjacent to wildland vegetation. They are typically characterized by greater housing density than intermix communities (U.S. Department of Agriculture, U.S. Department of the Interior, Jan. 4, 2001). During the past few decades, the U.S. experienced rapid development in areas with recreational opportunities and natural amenities (e.g. metropolitan fringes and rural communities); dramatically increasing the number of housing units located in the WUI (Dennis et al., 2009). According to recent estimates, the WUI contains 39% of all housing units in the contiguous U.S. (Radeloff et al., 2005). Moreover, the WUI comprises 9% of the total land area of the contiguous U.S.

We estimate the impact of MPB damage on residential property values in Grand County, Colorado. There are two main reasons for selecting Grand County as the study area. First, the vast majority of the county's residential properties reside in the WUI. Second, the county has among the highest concentrations of lodgepole pine forests in Colorado; consequently it has been heavily affected by the beetle outbreak. Grand County is 4842 km^2 in size and is located in the North Central part of the state (U.S. Census Bureau, 2000). The 2000 U.S.

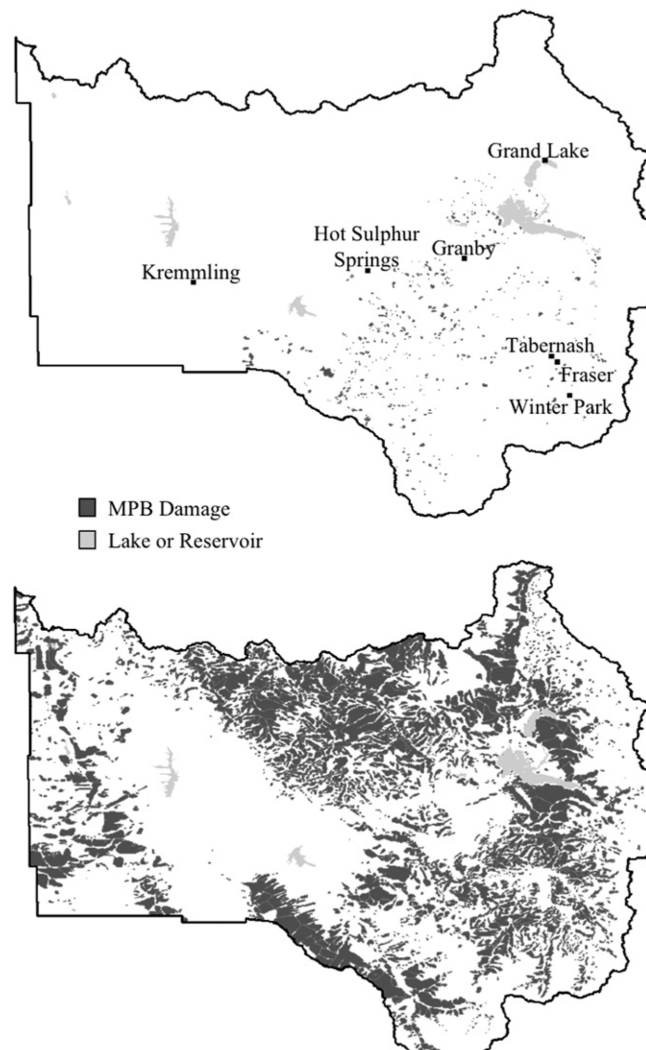

Fig. 1. Extent of MPB damage in grand Country for 1996 (top) and 2006 (bottom). The figure is constructed using GIS and aerial survey maps from the U.S. Forest Service.

[3] In addition to drought and overcrowded forests a series of mild winters may have contributed to the MPB epidemic by allowing a larger proportion of beetle larvae to survive and consequently allowing for rapid expansion of the MPB population (Taylor and Carroll, 2003).

Census indicates the total population for Grand County is 12,442 and the total number of housing units is 10,894. As reflected in these figures, the county is characterized by a large number of non-resident homeowners; nearly 44% of homes are used for seasonal or recreational purposes (U.S. Census Bureau, 2000). The median household income for full-time residents is $47,759.

Grand County's economy is highly dependent upon nature-based tourism and recreation. Situated within the county are three major reservoirs, multiple wilderness areas, part of Rocky Mountain National Park, and two prominent ski resorts. Nearly 75% of Grand County's total land area is publicly owned. Since 1996 a large proportion of the county's forests have been affected by the MPB. A recent analysis indicates that 179,276 ha of Grand County's lodgepole pine forests contain trees damaged by MPB (Witcosky, 2007). Moreover, approximately 68% of privately owned hectares of lodgepole pine and 70% of national forest hectares contain trees damaged by MPB (Witcosky, 2007). Fig. 1 depicts the extent of MPB damage in Grand Country for 1996 and 2006.

Once underway, controlling the spread of a beetle epidemic is extremely difficult. Efforts by Grand County's homeowners are limited to chemical treatments, which are typically applied in early summer and prevent MPB infestation for several months (Leatherman et al., 2007). Due to the cost of application, however, these treatments are reserved for high-value trees (Dennis et al., 2009). Efforts by county agencies have primary focused on removing MPB-killed trees in critical areas (Grand County Division of Natural Resources, 2008). Removal of these trees reduces the potential for wildfire and damage caused from falling trees. A more detailed account of MPB mitigation strategies is presented in Dennis et al. (2009).

5. Theoretical considerations

This paper uses a hedonic property-pricing model to determine the relationship between housing prices and MPB damage. At the core of the hedonic model is the concept of heterogeneous goods (Taylor, 2003). In this case, heterogeneity refers to variation in housing characteristics. For example, houses vary in total square footage, number of bathrooms, and distance to the nearest park. Importantly, variation in these characteristics gives rise to variation in sales prices. The hedonic model uses this variability to establish a statistical relationship between prices and characteristics. From this relationship it is possible to infer the marginal implicit price of any single characteristic, while controlling for the effects of other significant characteristics. This is typically referred to as a first-stage hedonic analysis (Taylor, 2003). In a second-stage analysis, implicit prices from the first-stage can be used to derive demand functions for housing characteristics (Taylor, 2003). As with most hedonic analyses, this paper is primarily concerned with determining marginal implicit price, from a first-stage analysis.

The basic theory behind the hedonic property model can be explained using the utility function presented in Eq. (1) (Freeman, 1998).

$$U = U(X, S_i, N_j, Q_k) \tag{1}$$

Here individual utility is defined over vectors of structural (S), neighborhood (N), and environmental (Q) characteristics of the residential property. Utility is also a function of X, which is composite of all other goods. For convenience the price of the composite good is normalized to one.

The consumer will maximize utility subject to a budget constraint. Assuming the consumer purchases only one residential property, the constraint can be represented as follows.

$$M - P_t - X = 0. \tag{2}$$

Here, M represents the consumer's income and P the equilibrium price of residential property t. It follows that the consumer will choose levels of X and a specific environmental characteristic q_k such that the marginal rate of substitution between q_k and X is equal to the rate at which q_k can be exchanged for X in the market.

$$\frac{\partial P_t}{\partial q_k} = \frac{\partial U / \partial q_k}{\partial U / \partial X}. \tag{3}$$

This relationship, represented in Eq. (3), reveals the marginal implicit price of characteristic q_k. Importantly, the marginally implicit price can be interpreted as the WTP. In other words, this is the WTP value for a one-unit increase in the environmental characteristic or attribute (i.e. MPB damage within proximity of the house).

6. Data

Data for this analysis is taken from three sources: the Grand County Assessor's Office, the U.S. Forest Service, and the U.S. Geological Survey (USGS). The Grand County Assessor's Office maintains an online database with information on sales prices and housing characteristics. This database indicates that 4148 residential housing transactions occurred within the study area between 1995 and 2006. Of these transactions, 3681 contained a complete record of housing characteristics. A common problem found in many hedonic datasets is below-market transactions (Cho et al., 2006; Poor et al., 2007). These transactions occur when property is sold, often between family members, for below-market prices. A review of the sales prices for the remaining observations revealed numerous below-market transactions. To correct for this problem the Grand County Assessor's Office recommended removing observations with sales prices less than

Table 1
Variable list and descriptive statistics.

Variable	Description	Mean	Std. Dev
ln(P)	Sales price of house adjusted to 2007 dollars	12.971	0.562
TREND	Year of sale (standardized such that 1995 = 1, 1996 = 2, etc.)	8.379	3.086
AGE	Age of house in years	22.844	19.642
AREA	Area of house in 100 ft^2	28.883	14.674
LAND	Area of property in acres	1.419	4.291
BEDROOMS	Number of bedrooms	2.906	0.906
BASEMENT	Whether house has a finished basement	0.378	0.485
DECK	Whether house has a deck, patio, or porch	0.964	0.187
FRAME	Whether house has a frame structure	0.174	0.379
LOG	Whether house has a log structure	0.134	0.341
PREFAB	Whether house has a prefabricated structure	0.091	0.287
CUSTOM	Whether house is custom built	0.267	0.443
QUALITY	Whether house exhibits above average construction quality	0.208	0.406
BLOCK1	Whether house is located in census track 200 block group 1	0.327	0.469
BLOCK3	Whether house is located in census track 200 block group 3	0.062	0.241
BLOCK4	Whether house is located in census track 200 block group 4	0.172	0.378
BLOCK5	Whether house is located in census track 100 block group 1	0.058	0.235
BLOCK6	Whether house is located in census track 100 block group 2	0.023	0.151
HIGHWAY	Distance to the nearest highway in kilometers	11.154	15.492
TOWN	Distance to the nearest town in kilometers	43.543	40.483
WATER	Percentage of surface area within 1 km of the house that is classified as lake or reservoir	0.046	0.101
FOREST	Percentage of surface area within 1 km of the house that is classified as forest	0.366	0.249
INDUSTRY	Percentage of surface area within 1 km of the house that is classified as industrial	0.010	0.026
MPB-0.1	Number of trees killed by MPB within 0.1 km of the house	4.072	13.570
MPB-0.5	Number of trees killed by MPB within 0.5 km of the house	93.402	222.533
MPB-1	Number of trees killed by MPB within 1 km of the house	366.620	745.891

\$100 per square foot (K. McClain, personal communication, June 5, 2008). The final number of observations is 1933. These housing units are concentrated around the towns of Winter Park, Fraser, Tabernash, Granby, Grand Lake, and to a lesser extent the towns of Hot Sulphur Springs and Kremmling. Housing units are also concentrated in the region directly west of Granby Reservoir and Shadow Mountain Lake — the two bodies of water located between the towns of Granby and Grand Lake (see Fig. 1). Summary statistics for housing characteristics are reported in Table 1. The mean sale price for the sample, standardized to 2007 dollars using the Colorado rural housing price index developed by the Office of Federal Housing Enterprise Oversight, is \$429,768. By comparison the median value of owner-occupied houses in Colorado in 2000, adjusted to 2007 dollars, is \$276,830. The average home from the sample was built in 1985. It has 2.9 bedrooms, 2888 ft^2 of total area, and sits on a 1.4 acre lot.

Data on MPB infestation is provided by the U.S. Forest Service. Since 1995, the Forest Service has used aerial detection surveys to monitor forest conditions in the Rocky Mountains. These surveys are intended to monitor the occurrence of disease, insects and other damaging agents throughout the region. One specific use has been to map the spread of MPB damage. The first step in the mapping process is to assign each dead tree in a given aerial photograph a cause of death. Trees killed by MPB are distinguished by their discoloration. Once this is complete the photographs are converted to digital map files. When viewed in GIS, these maps resemble a series of adjacent polygons. Each polygon represents the intensity of MPB damage within its boundaries. For example, a polygon may indicate five trees per acre are affected by MPB. To determine the reliability of these maps the U.S. Forest Service conducted an accuracy assessment study in 2005. The study performed onsite evaluations of insect damage for several locations in Colorado and Wyoming. Evaluation results were then compared with the aerial surveys. Findings show that accuracy ranges from 61 to 79% (Johnson and Ross, 2006).

Using GIS software these maps are combined with housing locations from the Grand County Assessor's Office. The Grand County GIS Department provides a GIS map of property boundaries. We calculate the center of each property and assume houses are located at this point. Each house is matched to the aerial survey from the appropriate year. For example, houses that were sold in 2004 are combined with the aerial survey conducted in 2004. Once combined, a buffer area of 0.1 km is created around each house. Next, we calculate the intersection between the buffer area and the MPB polygons. From this intersection, the expected number of trees killed by MPB within a 0.1 km radius of the house is determined. This process is repeated for buffer areas of 0.5 and 1.0 km, with each larger area including, or nesting, the smaller area(s).[4] The average number of MPB killed trees within the 0.1, 0.5 and 1.0 km buffer areas are 4, 93, and 367, respectively.

The third data source is the USGS, which maintains a website with multiple land use maps (U.S. Geological Survey, 2008). These maps are created using satellite imagery and differentiate between nineteen types of land cover. The 2001 land cover map is used to determine the percentage of land classified as forest, water, and industry within a 1.0 km buffer of each home.

7. Empirical model

This study employs a spatial-lag regression model in which housing prices are partially determined by the value of neighboring homes. The model is presented in Eq. (4).

$$\ln(P) = \rho W \ln(P) + \beta_i S_i + \beta_j N_j + \beta_k Q_k + \varepsilon. \quad (4)$$

[4] The 0.1, 0.5, and 1.0 km distances are based on the study conducted by Holmes et al. (2006), which uses similar techniques to evaluate damage caused by hemlock woolly adelgid.

Table 2
Spatial two-stage least squares (S-2SLS) estimation results.

Variable	Buffer Area (MBP-θ)					
	θ = 0.1 km		θ = 0.5 km		θ = 1 km	
ρ	0.213	***	0.210	***	0.210	***
CONSTANT	9.293	***	9.333	***	9.334	***
TREND	0.009	***	0.010	***	0.011	***
AGE	−0.003	***	−0.003	***	−0.003	***
AREA	0.019	***	0.019	***	0.019	***
LAND	0.007	**	0.007	**	0.007	**
BEDROOMS	0.050	***	0.050	***	0.050	***
BASEMENT	0.028	*	0.029	*	0.029	**
DECK	0.111	***	0.109	***	0.110	***
FRAME	0.100	***	0.102	***	0.102	***
LOG	0.074	***	0.073	***	0.074	***
PREFAB	−0.035		−0.037		−0.039	*
CUSTOM	0.063	***	0.063	***	0.064	***
QUALITY	0.118	***	0.118	***	0.119	***
BLOCK1	0.042	*	0.044	*	0.047	**
BLOCK3	−0.078	***	−0.079	***	−0.082	***
BLOCK4	0.068	***	0.066	***	0.067	***
BLOCK5	0.008		0.003		−0.003	
BLOCK6	−0.056		−0.057		−0.055	
HIGHWAY	0.000		0.000		0.000	
TOWN	−0.001	***	−0.001	***	−0.001	***
WATER	0.531	***	0.513	***	0.508	***
FOREST	0.068	*	0.070	*	0.071	*
INDUSTRY	−1.065	***	−1.065	***	−1.074	***
MPB-θ	−1.186E−03	***	−7.919E−05	**	−3.091E−05	***

*$P<0.05$, **$P<0.01$ and ***$P<0.001$.

This functional relationship indicates that housing prices (P) are determined by a set of structural (S), neighborhood (N), and environmental (Q) characteristics as well as an error term (ε). Spatial dependency between housing prices is incorporated into the model with the term ρW, where ρ is a spatial autocorrelation parameter and W is a spatial weight matrix. Congruent with standard practice, this model uses the natural log of housing prices (lnP) as the dependent variable (Cho et al., 2006; Poor et al., 2007).

Specifically, the structural variables used in this analysis include: age of the house (AGE), number of bedrooms (BEDROOMS), total area measured in square feet (AREA), and lot size measured in acres (LAND). Several dummy variables are also included. These variables indicate whether the house has a frame structure (FRAME), log structure (LOG), prefabricated structure (PREFAB), is custom built (CUSTOM), has above-average construction quality (QUALITY), includes a finished basement (BASEMENT), and includes a deck or patio (DECK).[5] Likewise, the neighborhood variables used in this analysis include: distance to the nearest highway (HIGHWAY) measured in kilometers, distance to the nearest town (TOWN) measured in kilometers, and a series of dummy variables indicating the census block group (BLOCK) where the house is located. Environmental variables include: the percentage of surface area within a 1 km radius of the house classified as lake or reservoir (WATER), forest (FOREST), and industry (INDUSTRY). Finally, we include variables indicating the number of trees killed by MPB within a 0.1, 0.5, and 1.0 km radius (denoted as MPB-0.1, MPB-0.5, and MPB-1, respectively) of the home.

We use a k-nearest neighbors weight matrix to capture the extent to which the price of one house is affected by the price of neighboring houses. The weight matrix is n × n, where n is the number of observations. The diagonal elements are set to zero and the row elements, which reflect the distance between observations, are standardized such that their sum is one (Kim et al., 2003). Under this construction the impact of a neighboring home on the price of the current home diminishes as the distance

[5] The Grand County Assessor's Office classifies the construction quality of each property as either poor, low, fair, average, good, very good, or excellent. We reclassified this information into a single dummy variable indicating whether the construction quality is above average.

between the two increases. Several different weight matrixes, ranging from the nearest 2 to the nearest 100 neighbors, were tested. The matrix using the 4 nearest neighbors was determined to be optimal.

Notably, endogeneity is introduced into the model with the inclusion of the Wln(P) term. As a result, OLS estimations are biased and inconsistent (Kim et al., 2003). In response, we employ a spatial two-stage least squares estimation (S-2SLS). Under this model the spatially lagged independent variables are used as instruments for the spatially lagged dependent variable (Anselin, 1988). In addition, we adjust for heteroskedasticity using the robust form of the S-2SLS estimation.

8. Results

Estimation results for separate S-2SLS hedonic pricing models, incorporating a variable for the increasingly larger (or nested) 0.1, 0.5, and 1.0 km buffer zones, are presented in Table 2. An alternate specification was estimated that included the three buffer zones in the same model, but was found to have high levels of multicollinearity. Consequently, we follow Holmes et al. (2006) and estimate three separate models, each including a single MBP buffer variable (MPB-0.1, MPB-0.5 and MPB-1). The variable ρ indicates the degree of spatial correlation between sales prices. It is highly significant, in all three models, indicating that spatial correlation is an important price determinant.

Estimated coefficients on the structural variables are mostly significant and exhibit the expected signs. Across the three models, results indicate that housing prices are positively correlated with square footage, lot size, number of bedrooms, having a finished basement, and having a deck or patio. Construction style and quality also affect housing prices. Specifically, homeowners are willing to pay more for frame homes, log homes, custom homes, and above average construction. In contrast, housing prices are negatively correlated with the age of the house and prefabricated homes.

With respect to land cover variables, all three models indicate that housing prices are positively correlated with the percentage of water (i.e. lakes and reservoirs) and forest within a 1 km radius of the house. Although both variables are significant, the percentage of water has substantially more impact on housing prices than the percentage of forests. On average, estimated coefficients on WATER and FOREST indicate that water is 7.4 times more influential than forested area. In addition, housing prices are negatively correlated with the percentage of industrial area (INDUSTRY) within a 1 km radius of the house. Estimated coefficients for industrial area are larger than those for water and forests; however, given the limited number of industrial sites in Grand County the average housing property is less affected by industry than water and forests.

With respect to the MPB damage, estimation results indicate that housing prices are negatively correlated with the number of trees killed by beetle infestation. In particular, estimated coefficients, while small, are significant at the 0.01 level for each of the three buffer zones. Estimated coefficients for the MPB-0.1, MPB-0.5 and MPB-1.0 km buffer zone variables are, respectively: −1.186E−03, −7.919E−05, and −3.091E−05. Notably, these coefficients increase as the radius of the buffer zone increases. This indicates that the closer a damaged tree is to a house the greater impact it will have on utility and price.

Finally, we calculate the marginal implicit price for MPB damage. The general formula for this calculation is presented in Eq. (5) (Small and Steimetz, 2007).

$$\frac{\partial P}{\partial q_{MPB}} = \left[\frac{1}{1-\rho}\right] B_{MPB} P. \tag{5}$$

Here P is the average sales price from the sample population, ρ is the spatial autocorrelation parameter, q_{MPB} is a vector of MPB damage, and B_{MPB} is the coefficient from the appropriate MPB damage variable. Findings from the S-2SLS estimation suggest that the marginal implicit price of a tree killed within 0.1 km radius of a home is approximately \$648. Likewise, the marginal implicit price for the 0.5 and 1.0 km radiuses are approximately \$43 and \$17. These values can also be interpreted as the homeowners maximum WTP to avoid utility loss from MPB damage. By comparison, the stumpage value for an average lodgepole pine in the Rocky Mountain region ranged from \$4.43 in 2005 to \$0.48 in 2010 (G. Roper and M. Etzenhouser, personal communication, March 2, 2010). The dramatic change in price is due to a sudden increase in the supply of timber — a consequence of salvaging MPB killed trees.

9. Discussion and conclusions

The relationship between drought, overcrowded forests and the MPB epidemic, along with other concomitant beetle infestations in the Rocky Mountain region, suggest that fire suppression practices are damaging to forest ecosystems. Moreover, the dynamics of the current MPB epidemic suggest the presence of threshold effects, where ecosystems services collapse once a certain level of natural capital is depleted (Pearce and Barbier, 2006). Specifically, drought and the dominant policy practice, over many decades, of fire suppression have led to drastic reductions in forest service flows (Donovan and Brown, 2005 and 2007). Given prolonged drought and ongoing fire suppression policies, the beetle epidemic might be argued to be an expected ecological response that may ultimately move forest ecosystems towards more natural density levels.[6] However, we would still argue that from a sustainability perspective, continued human actions (e.g., fire suppression policies, exacerbated by drought) that induce beetle infestations and epidemics reduce the stock of natural capital for future generations, at least in the short term (e.g., see Turner et al., 1995). Such a human-induced reduction would be inconsistent with the notion that the present generation has an obligation to pass down healthy forests, not those sickened by decades of fire suppression. Further, as shown here, the impact of these policies are leaving behavior trails as they are being capitalized into economic damages in current real estate markets.

Funding considerations for forest restoration activities are complicated by the checkerboard or mosaic pattern of multi-jurisdictional, public and private land ownership in the WUI (Prante et al., 2007). Further, increments in forest health and wildfire risk reduction (because of the risk externalities between proximal properties) can have public good characteristics (Berrens et al., 2008). Economic theory predicts that public goods will be underprovided in the absence of either clearly defined property rights or some type of regulatory intervention and revenue generation (e.g. taxes or fees).

Addressing potential free-riding, and solving coordination problems can be aided by an understanding of the types, magnitudes and incidence of benefits and costs. The range of social benefits generated by forest restoration includes a variety of on-site benefits (e.g. production values and recreation [Morris and Walls, 2009]), non-use values, as well as off-site benefits to homeowners and residents in the WUI (Hand et al., 2008a,b; Izon et al., 2010). As evidence of the off-site benefits of forest restoration, our results indicate that housing prices are negatively affected by MPB damage occurring beyond property boundaries. In particular, results indicate marginal prices of \$648, \$43, and \$17 for the 0.1, 0.5, and 1.0 km radiuses respectively.

In terms of exploring potential revenue generation, in the case of Grand County, evidence from the hedonic pricing model indicates that residents are willing to pay \$17 to prevent the death of each tree within 1 km of their home. If the average number of trees killed by

[6] See Fox et al. (2009) for a discussion of sustainability and the link between ecology, socio-economics, and ecosystem services. With respect to the MPB, Fox et al. (2009) offer a framework for evaluating the action/reaction mechanism of beetle infestations, drought, and fire suppression practices.

MPB per home is 367, then the average total WTP is approximately $6200 per household. Given that there are 10,894 households in Grand County, the total revenue theoretically available from property owners (with perfect capture) for all forest and ecosystem management programs is $67,542,800. In comparison, the Grand County Assessor's Office reports property tax revenue of $46,759,027 for 2007. Of this revenue, $203,516 is designated for water and soil conservation. No revenue is designated explicitly for forest management programs.

Given the benefits of forest restoration, and recent research concerning the causes and prevention of beetle infestations, an appropriate solution to the MPB problem may be to establish public programs to maintain healthy forest conditions. This study suggests that at least partial funding for these programs is available from the residents of the WUI, possibly through taxation, or through participation in a variety of cost-share programs (from federal, state and local government agencies) to restore forest health and mitigate wildfire risks in the WUI. Two examples of cost-share programs are: (i) the Colorado Forest Restoration Act (State of Colorado, 2007), a state program; and (ii) the Collaborative Forest Restoration Program, a federal program which currently operates only in New Mexico (Prante et al., 2007). These are examples of prominent programs that provide partial funding for community-based, and multi-jurisdictional, forest restoration projects. Between April 2008 and April 2009 the Colorado Forest Restoration Act provided partial funding for 12 projects, including a project to remove MPB killed trees in Grand County (Jahnke, 2009). The 12 projects reduced hazardous fuels on a total of 3115 acres. These projects were accomplished using $876,450 in grant funding and $1,355,000 in matching funds from community contribution (Jahnke, 2009). Currently, an additional 29 projects, which are scheduled for completion in April 2010, have received funding. Likewise, the Collaborative Forest Restoration Program has provided over $42 million in grants for 131 projects since its inception in 2000 (Friederici et al., 2009). These projects treated 17,000 acres of New Mexico's forests, woodlands, and riparian areas. Ultimately, with a better understanding of the full range of benefits generated through implementation, forest restoration programs may be able to protect property values in the WUI and help ensure that an adequate level of natural capital, in the form of healthy forest ecosystems, is available to future generations.

Acknowledgements

We thank Carolyn Sieg for research support. Funding for this research was provided under Joint Venture Agreements (05-JV-257 and the 06-JV-199) between the Department of Economics, University of New Mexico and the U.S. Department of Agriculture's Forest Service, Rocky Mountain Research Station, Flagstaff, AZ and Fort Collins, CO (USA).

References

Amman, G., McGregor, M., Dolph Jr., R., 2007. Forest Insect and Disease Leaflet: Mountain Pine Beetle. [on-line document] Accessed 15 November. . <http://www.barkbeetles.org/mountain/fidl2.htm>.

Anselin, L., 1988. Spatial Econometrics: Methods and Models. Kluwer Academic Publishers, Boston.

Berrens, R., McKee, M. Jones, Talberth, J., 2008. Using economic experiments in evaluating mitigation decisions. In: Martin, W., Raish, C., Kent, B. (Eds.), Wildfire Risk: Human Perceptions and Management Implications. Washington DC, Resources for the Future/Johns Hopkins University Press, pp. 226–243.

British Columbia Ministry of Forests and Range (BCMOFR), 2008. Facts About B.C'.s Mountain Pine Beetle. [on-line document] Accessed 15 February 2009. < http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/MPB_Facts.pdf>.

Carroll, A., 2007. The mountain pine beetle *Dendroctonus ponderosae* in Western North America: potential for area-wide integrated management. In: Vreysen, M., Robinson, A., Hendrichs, J. (Eds.), Area-Wide Control of Insect Pests. Springer, New York, pp. 297–307.

Cho, S., Bowker, J., Park, W., 2006. Measuring the contribution of water and green space amenities to housing values: an application and comparison of spatially weighted hedonic models. Journal of Agricultural and Resource Economics 31 (3), 485–507.

Colorado State Forest Service, 2009. Colorado's Major Tree Species. Colorado State Forest Service, Colorado State University, Fort Collins, Colorado. [on-line document] Accessed 22 February 2010. <http://csfs.colostate.edu/pages/major-tree-species.html>.

Dennis, F., Burke, J., Duda, J., Green, C., Hessel, D., Kaufmann, M., Lange, D., Lee, B., Rinke, H., Sheppard, W., Sturtevant, B., Thinnes, J., Underhill, J., Woodmansee, B., 2009. Lodgepole Pine Management Guidelines for Land Managers in the Wildland-Urban Interface. Colorado State Forest Service, Colorado State University, Fort Collins, Colorado. [on-line document] Accessed 22 February 2010. <csfs.colostate.edu/pages/documents/lpp-guide-LS-www.pdf>.

Donovan, G., Brown, T., 2005. An alternative incentive structure for wildfire management on national forest land. Forest Science 51 (5), 387–395.

Donovan, G., Brown, T., 2007. Be careful what you wish for: the legacy of Smokey Bear. Frontiers in Ecology and the Environment 5 (2), 73–79.

Fox, W., McCollum, D., Mitchell, J., Swanson, L., Kreuter, U., Tanaka, J., Evans, G., Heintz, H., Breckenridge, R., Geissler, P., 2009. An Integrated Social, Economic, and Ecologic Conceptual (ISEEC) framework for considering rangeland sustainability. Society and Natural Resources 22 (7), 593–606.

Freeman, A., 1998. Hedonic pricing method. In: Bromley, D. (Ed.), The Handbook of Environmental Economics. Blackwell, Oxford, pp. 672–686.

Friederici, P., Fisher, L., Romero, R., Williams, R., Dunn, W., 2009. Collaborative Forest Restoration Program: Lessons Learned. [on-line document] Accessed 1 March 2010. <http://www.fs.fed.us/r3/spf/cfrp/>.

Grand County Division of Natural Resources, 2008. Grand County Forest Management Plan for County Road Rights of Way. [on-line document] Accessed 20 February 2010. <http://co.grand.co.us/DNR.html>.

Hand, M., Thacher, J., McCollum, D., Berrens, R., 2008a. Forest amenities and location choice in the Southwest. Journal of Agricultural and Resource Economics 33 (2), 232–253.

Hand, M., Thacher, J., McCollum, D., Berrens, R., 2008b. Intra-regional amenities, wages and home prices: the role of forests in the Southwest. Land Economics 84 (4), 635–651.

Holmes, T., Murphy, E., Bell, K., 2006. Exotic forest insects and residential property values. Agricultural and Resource Economics Review 35 (1), 155–166.

Izon, G., Hand, M., Fontenla M., Berrens, R., 2010. The economic value of protecting inventoried roadless areas: A spatial hedonic price study in New Mexico. Contemporary Economic Policy. doi:10.1111/j.1465-7287.2009.00190.x.

Jahnke, J., 2009. Final One-Year Report on HB07–1130: The Pilot Forest Restoration Program. [on-line document] Accessed 1 March 2010. <http://csfs.colostate.edu/pages/forestry-legislation-2009.html>.

Johnson, E., Ross, J., 2006. USDA Forest Service Rocky Mountain Region Forest Health Aerial Survey Accuracy Assessment 2005 Report. [on-line document] Accessed 3 December 2007. <http://www.fs.fed.us/r2/resources/fhm/aerialsurvey/download/docs/AAreport_2005_final.pdf>.

Kim, C., Phipps, T., Anselin, L., 2003. Measuring the benefits of air quality improvement: a spatial hedonic approach. Journal of Environmental Economics and Management 45, 24–39.

Kim, Y., Wells, A., 2005. The impact of forest density on property values. Journal of Forestry 103 (3), 146–151.

Leatherman, D., 2009. Report on the Health of Colorado's Forests 2008: Special Issue on High Elevation Forests. Colorado State Forest Service, Colorado State University, Fort Collins, Colorado. [on-line document] Accessed 22 August 2009. <http://csfs.colostate.edu/pages/documents/894651_08FrstHlth_www.pdf>.

Leatherman, D., Aguayo, I., Mehall, T., 2007. Mountain Pine Beetle. Trees and Shrubs no. 5.528. [on-line document] Accessed 15 November 2007. <http//www.ext.colostate.edu/pubs/insect/05528.html>.

Loomis, J., 2004. Do nearby forest fires cause a reduction in residential property values? Journal of Forest Economics 10, 149–157.

Morris, D., Walls, M., 2009. Climate Change and Outdoor Recreation. Resources for the Future, Washington, DC.

Natural Resources Canada, 2007. The Mountain Pine Beetle in British Columbia. [on-line document] Accessed 18 November 2007. <http://mpb.cfs.nrcan.gc ca/index_e.html>.

Paterson, R., Boyle, K., 2002. Out of Sight, Out of Mind? Using GIS to Incorporate Visibility in Hedonic Property Value Models. Land Economics 78 (3), 417–425.

Pearce, D., Barbier, E., 2006. Blueprint for a Sustainable Economy. Earthscan, London.

Poor, J., Pessagno, K., Paul, R., 2007. Exploring the hedonic value of ambient water quality: a local watershed-based study. Ecological Economics 60, 797–806.

Prante, T., Thacher, J., McCollum, D., Berrens, R., 2007. Building social capital in forest communities: revealed preference analysis of New Mexico's collaborative Forest Restoration Program. Natural Resources Journal 47 (4), 867–915.

Radeloff, V., Hammer, R., Stewart, S., Fried, J., Holcomb, S., McKeefry, J., 2005. The wildland–urban interface in the United States. Ecological Applications 15 (3), 799–805.

Romme, W., Clement, J., Hicke, J., Kulakowski, D., MacDonald, L., Schoennagel, T., Veblen, T., 2006. Recent Forest Insect Outbreaks and Fire Risk in Colorado Forests: A Brief Synthesis of Relevant Research. Colorado Forest Research Institute.

Schowalter, T., Withgott, J., 2001. Rethinking insects: what would an ecosystem approach look like? Conservation Biology in Practice 2 (4), 10–16.

Schmid, J., Mata, S., 2005. Mountain Pine Beetle-Caused Tree Mortality in Partially Cut Plots Surrounded by Unmanaged Stands. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-54.

Schmid, J., Mata, S., Kessler, R., Poop, J., 2007. The Influence of Partial Cutting on Mountain Pine Beetle-caused Tree Mortality in Black Hills Ponderosa Pine Stands. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-68.

Small, K., Steimetz, S., 2007. Spatial Hedonics and Willingness to Pay for Residential Amenities. Working Paper no. 050631, University of California-Irvine.

State of Colorado, 2007. The Colorado Forest Restoration Act. House Bill No. 07-1130. on-line document] Accessed 18 June 2009. <http://www.state.co.us/gov_dir/leg_dir/olls/sl2007a/sl_311.htm>.

Taylor, L., 2003. The hedonic method. In: Champ, P., Boyle, K., Brown, T. (Eds.), A Primer on Nonmarket Valuation. Kluwer Academic Publishers, Boston, pp. 331–393.

Taylor, S., Carroll, A., 2003. Disturbance, forest age, and mountain pine beetle outbreak dynamics in BC: a historical perspective. In: Kelowna, B., Shore, T., Brooks, E., Stone,

J. (Eds.), Mountain pine beetle symposium: Changes and Solutions. : Canadian Forest Service. Pacific Forestry Centre, Victoria, British Columbia, pp. 41–51.
Turner, R., Doktor, P., Adger, N., 1995. Sea-level rise and coastal wetlands in the U.K.: mitigation strategies for sustainable management. In: Jansson, A., Hammer, M., Folke, C., Costanza, R. (Eds.), Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Washington D.C, Island Press, pp. 266–281.
U.S. Census Bureau, 2000. United States Census 2000. [on-line document] Accessed 23. November 2007. < http://www.census.gov/main/www/cen2000.html>.
U.S. Department of Agriculture, U.S. Department of the Interior, Jan. 4, 2001. Urban wildland interface communities within vicinity of federal lands that are at high risk from wildfire. Federal Register 66, 751–777.
U.S. Geological Survey, 2008. Land Use Land Cover. [on-line document] Accessed 7 June 2008. <http://water.usgs.gov/GIS/dsdl/ds240/index.html>.
van Mantgem, P., Stephenson, N., Byrne, J., Daniels, L., Franklin, J., Fule, P., Harmon, M., Larson, A., Smith, J., Taylor, A., Veblen, T., 2009. Widespread increase of tree mortality rates in the western United States. Science 323 (5913), 521–524.
Walton, A., 2009. Provincial-Level Projection of the Current Mountain Pine Beetle Outbreak: Update of the Infestation Projection Based on the 2008 Provincial Aerial Overview of Forest Health and Revisions to the “Model” (BCMPB.v6). [on-line document] Accessed 18 February 2010. <http://www.for.gov.bc.ca/hre/bcmpb/Year6.htm>.
Witcosky, J., 2007. Status of Mountain Pine Beetle Populations in Lodgepole Pine Stands in Northern Colorado and Southern Wyoming. USDA Forest Service, Rocky Mountain Region, Forest Health Management, Lakewood Service Center, LSC-07-06.