Essays on the Non-market Valuation and Optimal Control of Bio-invasions in Urban Forest Resources

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Forestry

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December, 2016
Blacksburg, Virginia

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(Abstract)

This dissertation consists of three essays, of which, two involve assessing the value of tree cover in urban communities and the other evaluates cooperative management of an invasive species by urban communities. The first chapter summarizes the three topics and briefly describes the motivation, methods applied and main conclusions in each study.

Chapter 2 presents a meta-analysis of hedonic property value studies on the value of tree cover. A meta-regression was performed using implicit value estimates for tree cover at property-level from various locations in the U.S. along with auxiliary data of county-level tree cover to investigate the relationship between tree cover and implicit-price estimates for residential properties. The study found that on average 35 percent and 40 percent tree cover respectively at property-level and county-level optimize the benefits to the property owners in urban areas. These results provide insights to forward-looking communities to adapt their tree planting and protection efforts to lessen climate-induced impacts.

Chapter 3 applies a first-stage Hedonic property price model to estimate preference for tree cover in urban communities using single-family house sales data from multiple property markets across the U.S. The study analyses how home owners' preference for tree cover vary across the landscape and across cities. Further, it identifies what factors affect these variations via the general inferences obtained from an internal meta-analysis. The study confirms the heterogeneity of preferences as affected by the differences in the abundance of tree cover in study locations, regional differences and household characteristics. These findings add to the hedonic literature and provide useful information for future urban planning.

Chapter 4 focuses on cooperative management of invasive species in landscapes with mixed land ownerships. This study analyzes the effect of the land ownership on the management efforts between an infested municipality and an uninfested municipality when a transferable payment scheme is involved in the cooperative agreement. A dynamic optimization problem was set up to evaluate the case of Emerald ash borer (EAB) control in multiple jurisdictions in the Twin Cities, Minnesota. The results suggest that when the infested municipality has more public lands and when the transfer payments are efficiently used to implement greater control, the municipalities are more likely to commit to bargaining, and smaller transfer payments paid over a longer span of time are sufficient for optimal control of the spread of invasive species across the municipalities.

The last chapter concludes the three studies and discusses the insights for future research.

Essays on the Non-market Valuation and Optimal Control of Bio-invasions in Urban Forest Resources

Shyamani D. Siriwardena

(General Audience Abstract)

Urban trees have become a key resource in building sustainable communities. Knowledge of preferences for trees, costs and benefits of trees, and how trees are managed by private and public landowners, is indispensable in making targeted planning that would fulfill the economic, social and environmental objectives of the urban communities This dissertation explores on these topics in three papers. Chapter 1 summarizes the three topics and briefly describes the motivation, methods applied and main conclusions in each study. Chapter 2 presents a meta-analysis that combines the non-market value estimates for tree cover from previous hedonic studies from various locations in the U.S. along with auxiliary data to investigate the relationship between the level of tree cover and value estimates. The study found that on average 35% and 40% tree cover respectively at property-level and county-level optimize the benefits to the property owners. Chapter 3 analyses how home owners' preferences for trees vary across the landscape in multiple cities in the U.S., and the results are systematically summarized via an internal-meta analysis. The study confirms the preference heterogeneity across the landscape and found that the relative abundance of tree cover in study locations, regional differences and household characteristics affect the preferences. Chapter 4 develops a dynamic optimization model to study how private and public land ownership in local municipalities affects the cooperative management of urban trees to control the Emerald ash borer (EAB) infestation in Twin Cities, Minnesota. The results suggest that when an infested municipality has more public lands and when the transfer payments are efficiently used to implement greater control, the municipalities are more likely to commit to bargaining agreements that last for longer period of time. Results from the three studies provide insights to forward-looking communities to adapt their tree planting and protection efforts to lessen climate-induced impacts. The last chapter concludes the three studies and discusses the insights for future research

ACKNOWLEDGEMENTS

I am indebted to my advisors, Dr. Kevin J. Boyle and Dr. Kelly Cobourn, for their invaluable advice, mentorship, patience and concerns throughout this research. They have mentored me and helped me for the professional development throughout these past few years; they gave me the motivation to keep exploring the environmental economic topics. I am sincerely grateful for their friendship and I am honored to have them as my advisors.

I am also grateful to my committee members, Dr. Thomas P. Holmes, Dr. Gregory Amacher, Dr. Eric Wiseman and Dr. Andrew McCoy for their help, valuable insights and comments on my research. It was a great opportunity and experience to work with them, and their guidance enabled me to grasp new ideas and develop a logical perception of real-life environmental economic problems.

A special thanks to all my colleagues and friends for their friendship and advice. They made Blacksburg a wonderful place for me.

I thank wholeheartedly to my husband, Sampath Karunarathne, for being with me through this journey, and helping me stay motivated. I could not have made it this far without him.

I thank my parents for their love and support in everyday of my life. I am grateful for the sacrifices they made for me and for the guidance they provided throughout my life.

I dedicate this dissertation to my parents and all my teachers.

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Chapter 1

Introduction

Urban trees have become a key resource in building sustainable urban communities due to the various eco-system benefits (e.g., landscape aesthetics, wildlife habitat, improving air quality, stormwater control) they provide to local communities. Landscape composition, land use, land use policies related to the urban trees, climate and disturbance regimes (eg. Invasive forest pests and wildfire) and socioeconomic conditions determine the level of tree cover in urban areas, the costs and benefits associated with urban trees. Urban planners should make sure that trees are managed at suitable locations at sufficient amounts so that the residents can obtain the desired benefits from trees.

The decision of where to locate trees within the landscape and how to manage the tree canopy cover within private properties and public lands largely depends on how much costs and benefits associated with trees are to be borne by private land owners and the local governments in urban areas. Knowledge about what preferences the urban communities have for trees in the urban landscape, and what are the objectively measured costs and benefits of tree cover in urban areas is critical for proper planning and designing of urban systems. Moreover, understanding on how tree cover in urban areas is managed as a transboundary resource across private and public lands or across local jurisdictions is indispensable to community planners in making targeted planning that would fulfill the economic, social and environmental objectives of the urban community. This dissertation explores on these topics by: (1) application of Hedonic property price models in Chapter 2 and 3 for non-market valuation of tree cover in urban residential areas in the U.S.; (2) developing a dynamic optimization model to study the cooperative management of urban tree resources to control a bio-invasion in the Twin Cities, Minnesota.

Tree canopy cover is a non-market good whose value is not directly priced, however its value can be implicitly estimated using non-market valuation methods such as Hedonic property price model and contingent valuation method. These approaches use observed behavior or stated preferences of urban residents to elicit the value of consumptive and non-consumptive use of tree cover in urban areas. Hedonic price models (Rosen, 1974) are commonly used to implicitly estimate the value of trees by observing the revealed behavior of home owners in response to price changes of housing properties associated with a change in the tree canopy cover on or near their properties. These estimates represent the preferences of home owners on where to locate trees and in what amounts. In Chapter 2 and 3, this approach is used to assess the value of tree canopy cover in urban communities across the U.S.

Using the Hedonic price model, dozens of studies have estimated the marginal implicit value of trees (forested areas) in multiple study areas in the US and other countries; however, the findings are not systematically summarized in a manner to provide general guidance to policy makers. Using results from 15 hedonic studies in the U.S, a meta-analysis is performed in Chapter 2 to infer the relationship between tree cover and implicit-price estimates for residential properties. The meta-analysis utilizes greater variation of tree canopy cover, implicit value estimates of tree cover, property characteristics and other location-specific factors in multiple study areas than can typically be accomplished within individual hedonic studies, and provide better estimates on the value of trees. This analysis finds that property owners prefer tree cover at distant neighborhoods than on or near the property. Home owners' benefits are maximized at 30 percent of on-property tree cover and at 38 percent in county tree cover. These findings inform and justify the tree planting and protection programs implemented in urban areas in response to development and climate change.

Previous hedonic studies provide mixed results for preferences for tree cover and imply these preferences have a spatial variation across study areas. Further they suggest that implicit prices for tree cover may not be constant across the landscape within a study area because home owners may have heterogeneous preferences for tree cover at different locations. However, Hedonic studies are not consistent in the data, model specifications and methods they used to recover implicit price for tree cover. Therefore, it is difficult to compare the results across the study locations or obtain broad conclusions based on their results. External-meta analysis similar to the study presented in the Chapter 2 may summarize the results from previous studies, but the estimation is restricted due to lack of studies that evaluates trees using similar methods. Therefore, in Chapter 4, a hedonic price model is applied to recover more informative estimates on how home owners value trees as a private good on the property and as a public good on neighboring lands in 10 cities in the U.S. The data sets used and the methods applied to recover implicit prices in this study are similar across the cities. This enables comparisons of the preferences across the cities and generalization of the results via an internal meta-analysis (Banzhaf and Smith, 2007).

In this study, it is assumed that tree cover within 0-100m buffer area of each property provides private benefits (therefore these trees are considered a private good) while tree cover beyond 100m and within 1km buffer provides external benefits to land owners (therefore these trees are considered a public good). To recover more accurate estimates, we utilize a suite of high resolution data of property sales and land cover from multiple cities in the U.S. Sales data are obtained from multiple listings that report all transaction in the study areas. High resolution data (1m) of tree cover and other neighborhoods amenities that may affect the property values are used as they better delineate the spatial information and improve the quantification of these variables.

The results provide new evidence for differential effect of tree cover on property value at various distances from the property implying that home owners have heterogeneous preferences for tree cover across the urban landscape. Further this study confirms the non-linear relationship between the implicit price and tree cover within different neighborhoods as suggested by the meat-analysis in

Chapter 2 and other Hedonic studies (eg. Netusil et al., 2010). Interestingly, this non-linear relationship varies across the landscape within a city and between locations where trees are considered amenity or disamenity. In study locations with positive implicit prices, an increase in tree cover within 100m and in the buffer area of 501-1000m increases property values, but after a threshold tree cover level property prices decrease. These optimal values were found to be 50 percent and 45 percent respectively. Opposite results are found for trees in 501-1000m. In locations where implicit prices are negative, increasing tree cover decreases the benefits. Further, this study indicates that regional differences and socio-demographic variables are significant determinants of the preference heterogeneity. These findings are of highly importance for future planning and designing of urban systems as consideration of tree canopy cover and decision making by both private and public land owners may become complex with anticipated changes in urban system due to rapid urbanization and climate change.

Chapter 4 focuses on cooperative management of invasive species in landscapes with mixed land ownerships. This study extends the previous applications of cooperative control of invasive species by evaluating how the private and public land ownership affects the decision making by local governments in relation to controlling a bio-invasion. The efficacy of invasive species control is influenced by how much of the public and private lands are subject to control activities and to what extent and at which efficiency the local governments invest on control activities. These effects are studied by evaluating the level of control by an infested municipality when more public lands become available to implement control activities.

A dynamic model of bilateral-bargaining is used to study the cooperative control of the spread of an invasive species from an infected municipality to a near-by uninfested municipality and a fixed transfer payment is used as incentives for greater control by the infested municipality. As opposed to complex models with complicated dynamics of invasive species and multi-lateral bargaining (Epanchin-Niell and Wilen, 2014; Kovacs et al., 2014), application of this simple bilateral bargaining model to study the case of Emerald ash borer (EAB) (*Agrilus planipennis Fairmaire*) invasion in multiple jurisdictions in the Twin Cities, MN provides a unique opportunity to explore in detail how bargaining outcomes and social costs of bargaining are influenced by the land ownership. The results from this study confirm that cooperation between the neighboring land owners is critical to reach socially optimal management of invasive species, and land ownership plays a vital role in negotiation between the neighboring land owners. When more lands are subjected to control efforts and when the transfer payments are efficiently used to implement greater control, the municipalities are more likely to commit to bargaining, and smaller transfer payments paid over a longer span of time are sufficient for optimal control of the spread of invasive species across the municipalities. These findings provide new insights for future invasive species management efforts.

The following chapters make contributions to the knowledge on management of urban forest resources by providing general guidelines to urban planners on preferences for tree canopy cover in urban areas via meta-analysis, by providing new evidence for preference heterogeneity in urban communities across the U.S via application of hedonic model, and by characterizing the cooperative behavior of local governments with heterogeneous land ownership to control an invasive forest pest via a bargaining model.

Chapter 2

The implicit value of tree cover in the U.S.: A meta-analysis of hedonic property value studies

Abstract

Trees in residential neighborhoods and communities provide benefits for homeowners that are capitalized into residential property values. The implicit value of trees in locations of interest is recovered in hedonic price studies. A single study that values tree cover is restricted to statistical insights that can be drawn from the amount of variation observed at a specific study location. Using research results obtained from multiple original studies, meta-analysis can investigate greater variation in property characteristics than can be accomplished within individual studies. Going beyond individual study characteristics, available spatial data on characteristics in each study area can enrich the analysis.

In this paper a meta-regression of hedonic price studies from various locations in the U.S. is estimated to investigate the relationship between tree cover and implicit-price estimates for residential properties. This type of assessment is timely in light of anticipated climate changes that may alter the distribution, abundance and health of tree species during the coming decades. The subsequent losses of tree canopy cover can impact property values via degradation of landscape aesthetics and the costs associated with the removal and maintenance of dead and dying trees. Forward-looking communities can adapt their tree planting and protection efforts to lessen these climate-induced impacts and information on the economic value of tree canopy cover can be used to help inform such efforts.

Keywords: hedonic valuation, climate change, community forestry, invasive species, forest matrix, Heckman model

2.1. Introduction

Tree cover, the land area covered by tree crowns, in residential neighborhoods is an environmental attribute that provides a suite of ecosystem services (e.g., landscape aesthetics, wildlife habitat, energy conservation, stormwater control) to homeowners and communities (Nowak et al., 2010). Most trees in urban and suburban neighborhoods are located on private property where the costs of tree planting and maintenance are borne by homeowners, while the benefits of trees can be enjoyed by the greater community. The disparity between who pays the costs (homeowners) and who receives the benefits from trees on privately-owned property (homeowners and the community) suggests that the level of tree cover on privately-owned land may be socially sub-optimal. A better understanding of the costs and benefits of trees, within the context of multiple social-ecological settings (Pickett et al., 2011), can help community planners design tree planting and protection programs to improve the quality of life for people and justify the costs of such programs.

Although the economic benefits of tree canopy cover (tree cover hereafter) are not directly priced, one component of their economic value, the implicit value to property owners, can be estimated using hedonic property value models. Hedonic models decompose the total price paid for a property into the "implicit" prices of property characteristics. The implicit price of a characteristic, such as the amount of tree cover, is the amount home buyers pay for a small change in the level of the characteristic, holding all other property characteristics constant (Taylor, 2003).

Previous hedonic studies have found that the value of forested areas varies with the degree of forest fragmentation and urbanization. For example, larger forest patches are valued more in the urban core, while a more fragmented and diverse landscape is preferred in rural-urban interfaces (Cho et al., 2008). Trees are valued more in areas where they are scarce and less so in heavily forested areas (Netusil et al., 2010). Large trees with full canopies have been shown to enhance retail settings (Wolf, 2004) and large shade trees are preferred by residents in areas with hot summers (Schroeder et al., 2006). Temporal variations of the value of trees has also been observed by Cho et al. (2009) where the amenity value of trees increased over time with declining forest patch size and density.

Forested areas can also present real or perceived risks that lower property values. Locations that have experienced or where there are perceived risks from forest fires or invasive pests attacking trees may result in homes located near forested areas having lower values (Holmes et al., 2006; Hugget, 2003; Kim and Wells, 2005; Stetler et al. 2010). The effects on property prices from risks due to forest pest infestations may be widespread in the United States: the hemlock wooly adelgid in the northeast, the emerald ash borer in the Midwest, and the mountain pine beetle in the west. The forest-fire effect may be more geographically concentrated in the western United States where there are frequent large forest fires that pose risks to residences. In addition, a suite of socio-economic, cultural, and lifestyle factors may influence the diversity and spatial extent of trees in urban and suburban landscapes (Hope et al., 2003; Troy et al., 2007).

In this paper, we present a meta-analysis of hedonic property value studies that have estimated the relationship between tree cover and residential property values across the U.S. A meta-analysis is the systematic examination of research results from multiple studies to learn what the results of the studies collectively imply. In addition, meta-analyses allow insights that may not be possible from a single study. For any given study, the range of an attribute that is observed to support estimation may be limited while greater variation may be observed across multiple studies. For example, in the context of the current application, a limited range of tree cover might be observed for any individual study and larger variation in tree cover might be observed over multiple studies. In addition, a meta- analysis can consider geographic and demographic differences in studies that are fixed for any single study, e.g., tree cover and the local population in the area where the studies were conducted. Thus, the meta-data from previous hedonic studies of tree cover are augmented with auxiliary county-level tree cover and tree age data from the U.S. Forest Service. Spatial variation across studies is also controlled by including U.S. Bureau of Census data on population and income.

The meta-analysis includes two measures of tree cover: (1) *tree cover* on and near residential properties and (2) *county-level cover* in the county where the residential properties are located. Linear and square terms for these variables allow for nonlinear relationships between implicit prices and tree cover. The empirical results indicate that both measures of tree cover have positive, nonlinear, and statistically significant effects on residential property values. The results reveal that the density of *county-level tree cover* that maximizes implicit prices (38 percent) is greater than the density of property-level *tree cover* on or near residential properties that maximizes implicit prices (30 percent). This pattern of results supports the intuition that the investment of tree cover on private land may be sub-optimal from a social perspective.

We suggest that this type of assessment and the consequent knowledge of the implicit value of tree cover are of timely importance in light of two trends that can acutely affect the extent, composition, and productivity of urban and peri-urban forests in the coming decades: climate change and urbanization. It is thought that climate-induced migration and redistribution of tree species might extirpate some tree species in some areas as well as cause shifts in tree diversity, stand age, species predominance, and the overall number of trees (Iverson and Prasad, 2001; Prasad et al., 2009; Woodall et al., 2009). In addition, changes in climate may increase the frequency and severity of forest fires, insect and disease outbreaks, and extreme weather events that can affect tree health and abundance and ultimately the extent of tree cover (Dale et al., 2001; Bentz, 2008; Frankel, 2008). Compounding climate change effects is the loss of trees to development and urbanization. Nowak and Greenfield (2012) looked at 20 major U.S. cities during the mid to late 2000s and found that tree cover was declining at a rate of about 0.27 percent per year while impervious surface cover was increasing at about 0.31 percent per year. When the researchers extrapolated the loss rate across urban areas of the conterminous United States, they determined that aggregate annual loss of tree cover is substantial, about 7,900 ha or roughly 4 million trees. Communities attempting to stabilize and enhance tree cover, particularly on private residential property where the bulk of existing tree cover and tree planting opportunities exist, need objective information on the economic value of tree cover to help justify their efforts.

2.2. Conceptual Framework

Hedonic price functions of residential property sales represent the sale prices of properties, agreed to by willing sellers and buyers, as functions of property characteristics:

$$HP = f(PC, SC, LC, EC{:}\,\beta) + e \tag{2.1}$$

where *HP* is the sale price of properties, *PC* is property characteristics (e.g., acreage), *SC* is structure characteristics (e.g., square feet of living are in a residence), *LC* is location characteristics (e.g., proximity to schools), *EC* is environmental characteristics (e.g., tree cover), β is a vector of coefficients to be estimated, and *e* is a random error term. The implicit price (IP_i) of any individual characteristic (c_i) is:

$$IP_i = \frac{\partial HP(\cdot)}{\partial c_i} \tag{2.2}$$

The implicit price for tree cover is the dependent variable used in the meta-analysis reported here. The dependent variable in a meta-equation is often referred to as the *effect size.* Although the standard practice is to explain variation in effect sizes using only data on characteristics reported in the original study, recent meta-analyses have used characteristics describing the spatial context in the area surrounding the original study sites to enhance explanatory power (Ghermandi and Nunes, 2013; Johnston et al., 2014). In the current study, the effect size is the implicit price for tree cover on and near a residential property; the implicit price constitutes the effect on property sale prices from a change in tree cover. Because the implicit value of tree cover may be influenced by the condition and abundance of trees in the broader geographic area where people work, shop, and recreate, we also include a vector of contextual ancillary variables in the meta-analysis. Following this logic, a general specification for the meta-equation is:

$$IP = g(Study\_Char,\ Context\_Char; \theta) + \varepsilon \tag{2.3}$$

where *Study_Char* is a vector of characteristics that describes original studies, *Context_Char* is a vector of characteristics that describes the spatial context surrounding the original study locations, θ is a vector of coefficients to be estimated, and ε is a random error term.

When reviewing the hedonic studies that included tree cover as a property characteristic, we found some studies that estimated positive implicit prices, some that revealed negative implicit prices, and some that found both positive and negative implicit prices. Thus, the first step in the analysis is to estimate a selection model to see if a set of study and context characteristics influence whether positive or negative implicit prices are observed for tree cover (Heckman, 1979). The selection model is:

$$\Pr(IP > 0) = h(Study\_Char',\ Context\_Char';\ \gamma) + \omega \tag{2.4a}$$

$$IP^{+} = g^{+}(Study\_Char,\ Context\_Char;\ \theta^{+}) + \varepsilon^{+} \tag{2.4b}$$

where ω is a random error term in the selection equation (2.4a) to predict if studies report positive or negative implicit prices, the apostrophes in the selection equation indicate different characteristics are included in the selection equation (2.4a) and meta-equation (2.4b), the plus symbol in equation 4b indicates the meta-equation is estimated solely for positive implicit price estimates (*IP*>0), and γ and $\theta^{+}$are vectors of coefficients to be estimated. Equation (2.4a) predicts the probability that a positive implicit price is estimated (versus negative) and equation (2.4b) is the meta-equation for positive implicit prices. The selection model allows a test of whether including only positive implicit price estimates will affect coefficient estimates in the meta-equation.

2.3. Data

An extensive search of the literature identified 56 hedonic property value studies that included measurements of either forest or tree characteristics as explanatory variables.[1] Most of these studies (44) were conducted in the U.S., although we also identified studies conducted in Canada, China, Denmark, Finland, France, and the United Kingdom. The studies included peer-reviewed journal articles, MS and Ph.D. theses, and working papers. There was no date restriction on the search, and the search identified studies that were conducted over a span of 35 years.

From the global set of studies, we selected studies to be included in the meta-analysis using the following criteria:

1st. Hedonic price functions must be based on sales of residential properties (i.e., studies based on commercial sales, rental rates, tax assessments, etc. were excluded.)

2nd. Studies must have been conducted in the U.S. This criterion facilitated the compilation of ancillary variables. In addition, there are only a small number of studies conducted outside of the United States and these studies were conducted in a number of different countries.

3rd. The unit of measurement for trees must be tree cover on or surrounding each sold property, while excluding studies based on other forest metrics (e.g., distance from homes to the nearest forest).[2]

4th. Studies must include adequate information to permit calculation of the implicit price and mean level of tree cover for the study area.

These conditions reduced the number of usable studies to 15. Of these studies, 13 included multiple implicit-price estimates resulting in a total of 106 observations for the meta-analysis[3]. All implicit-price

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[1] The study identification process included a search of relevant databases including AgEcon Search, CABDirect, and Google Scholar. We appreciate a reviewer brings one study to our attention that was not revealed in this search.

[2] None of the other forest metrics were represented in a sufficient number of studies to support separate meta-analyses.

estimates from each study are included in the data used to estimate the meta-equation with one exception. Any observation related to unhealthy trees due to disturbances such as forest fires or invasive pest outbreaks is not included in the analysis (e.g., observations for defoliated and dead hemlocks in Holmes et al. (2010) are excluded). Thus, the negative implicit prices would not be the result of trees with compromised structure or health.

The hedonic studies gleaned from the literature and those selected for the meta-analysis are broadly distributed across the United States (Figure 2.1). As noted above, the data include observations on the implicit value of tree cover as an amenity (positive implicit price estimates; n=68) and as a disamenity (negative implicit price estimates; n=38). Eight studies reported both positive and negative implicit price estimates.

To satisfy the condition that the estimated meta-equation must be based on a dependent variable measuring a common effect size, the marginal implicit prices (*IP*) for all included observations was measured as the change in property prices due to a one percent change in tree cover. Studies used a variety of functional specifications of the hedonic equation (see "MODEL" column in Table 2.1). For the studies that specified a linear hedonic model as a function of the percentage of land area covered by tree cover, the coefficient estimate for this variable is simply the marginal implicit price (e.g., Dimke, 2008). Whenever other functional forms or other measures of tree cover were used in the hedonic model, an alternative approach was used to compute the implicit prices for a one percent change in tree cover.

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[3] Multiple observations come from studies that estimated more than one functional form of the hedonic price model, studies that estimated separate models for tree cover in multiple neighborhoods, and studies that estimated separate models for different forest types. For example, the Netusil et al. (2010) study provided 12 observations from quadratic and log-log models for tree cover at property and 5 sub-regions within the study area. Holmes et al. (2006) estimated four separate models for tree cover (parcel level, 0.1km buffer, 0.5 km buffer, and 1 km buffer) for four different forest types, which resulted in 16 implicit-price estimates.

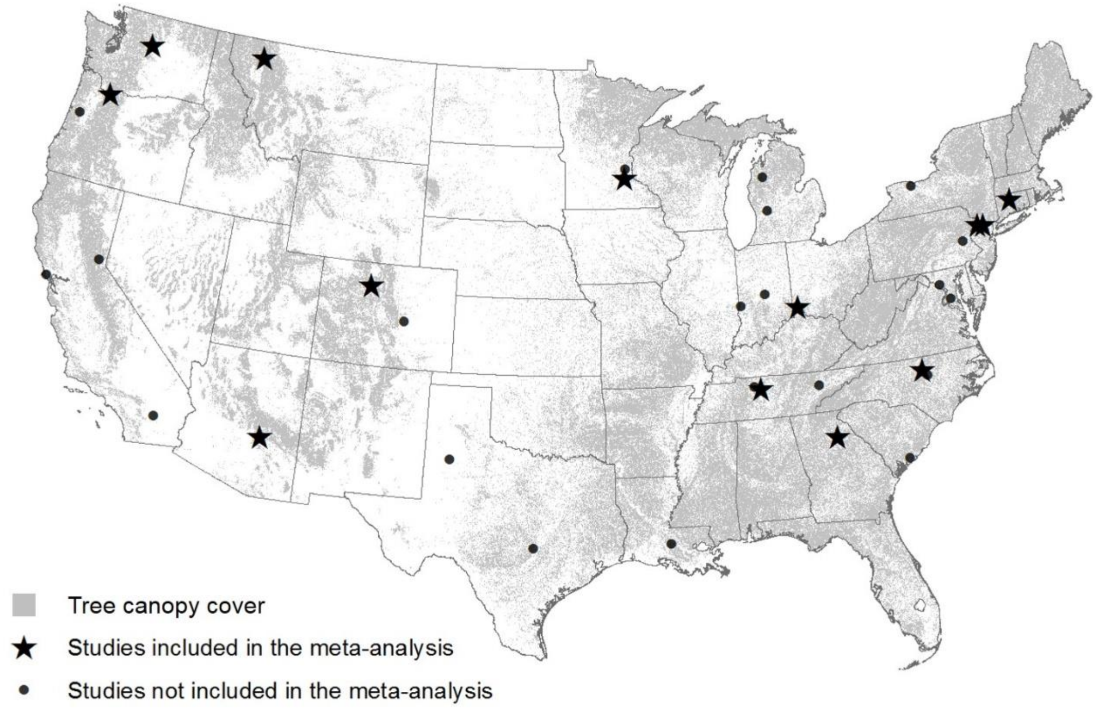

Figure 2.1 Geographic distribution of hedonic property value studies conducted in the United States that include tree variables as property characteristics. Note: a star or dot on the map may represent the location of more than one study. Tree canopy cover data from Homer et al. (2007).

Using a specification with the natural log of the sale price as the dependent variable in the hedonic equation as an example, let $ln(P) = \beta_0 + \beta_1 tc$, where P is the sale price of properties, tc is the tree cover measure, β_1 is the parameter estimate on tree cover, and β_0 is a "grand constant" that captures the influence of all other variables in the model specification. The steps to compute the implicit prices are:

Step 1: Calculate $\widehat{\beta_0} = ln(\bar{P}) - \beta_1\overline{tc}$, where $\bar{P}$ is the average sale price and $\overline{tc}$ is the average tree cover from observations used to estimate the study-specific hedonic equation.

Step 2: Using the computed value of $\widehat{\beta_0}$, calculate an adjusted housing price (P^A) for a 1% increase in tree cover: $P^A = exp\big(\widehat{\beta_0} + (\beta_1\overline{tc} * 1.01)\big)$.

Step 3: Calculate the marginal implicit price as the difference between the adjusted and mean housing prices: $IP = P^A - \bar{P}$

This process is also applied to log-log models (e.g., Netusil et al., 2010) and quadratic functional forms (e.g., Stetler et al., 2010), while making appropriate adjustments to the calculation where necessary. The calculated implicit prices are then converted to 2013 dollars using the Consumer Price Index (U.S. Department of Labor, Bureau of Labor Statistics, 2015).

Percent tree cover (*treecover*) is the key independent variable in the meta-equation, but this variable was not measured as a percentage for all studies (see "UNIT" column in Table 2.1). The majority of studies reported tree cover as a percentage or proportion (e.g. Holmes et al., 2006; Dimke, 2008; Netusil et al., 2010), while others measure tree cover in area units (e.g., hectares, square meters or square feet). For latter studies, the tree cover measures are converted to percentages in the following manner:

Step 1: Calculate $A = \pi r^2$ where A is the area of neighborhood with radius r within which the tree cover is measured.

Step 2: Calculate $treecover = (B/A)*100$ where B is the mean tree cover within the respective neighborhood given in the original study.

This process is applied to calculate tree cover associated with differing buffer sizes used across and within studies (e.g. 250 m and 500 m buffer areas in Stetler et al, 2010).

Ancillary data used in estimating the meta-equation were obtained from five sources[4]:

1. County-level data on the percent of tree cover were obtained from the U.S. Forest Service's Urban Forest Data (http://www.nrs.fs.fed.us/data/urban/ , accessed 04.15. 2013).

[4] For studies that used a county as the study area, ancillary data were collected for the county. For community-based studies, ancillary data for the county where the community is located were obtained. For studies that encompassed multiple counties, county level averages of ancillary data were used in the analysis.

2. The presence of forest invasive species or pathogens was obtained from the U.S. Forest Service's "Annual Insect and Disease Conditions Reports" (http://wwwtest.fs.fed.us/r8/foresthealth/publications/pubs_conditions.shtml , accessed 08.13.2013).
3. The proportion of total county acreage in forest land partitioned into three age groups (young stands (<40 years), medium-aged stands (40 to 119 years) and old stands (> 120 years) were obtained from U.S. Forest Service's Forest Inventory Data Online (FIDO) (http://www.fia.fs.fed.us/tools-data/, accessed 04.16.2013).
4. County-level data on the annual number of days with temperatures exceeding 90°F were obtained from NOAA's National Climatic Data Center (http://www.ncdc.noaa.gov/cdo-web/, accessed 08.13.2013).
5. Data on socio-economic variables (population density and income) were obtained from the US Census Bureau (http://quickfacts.census.gov/qfd/index.html, accessed 06.12.2013).

The inclusion of these data in the meta-equation helps to control for spatial differences across the original hedonic studies that might influence estimated implicit prices beyond the characteristics of the hedonic studies themselves. These locational characteristics would likely be fixed (invariant) for any individual study.

This auxiliary data is important because previous studies have found evidence that tree cover in the vicinity of properties influences property values (e.g., Holmes et al., 2006, 2010; Sander et al. 2010, 2010; Netusil et al., 2010). For example, Cho et al. (2011) found that forest cover at a distance of 1.5 miles from a property had significant effects on property values. That is, thinking broadly of the community where people work, shop, and recreate, tree cover from a larger area than immediately around a property may affect property values.

The presence of forest pests can affect the quality of tree cover and are included to control for the potential negative effect on implicit prices. As implicit prices are excluded from studies that specially focused on the effects of forest pests on property values, this variable is best thought of as representing the risk that trees might be exposed to forest pests in the study areas.

The age of trees and temperature data are included to represent the amenity value of tree cover: older stands would have more tree cover and thus more shade, which might be more desirable in hotter climates. At the same time, older trees may develop structural defects, which might pose a risk (disamenity) of property damage or personal injury in the event of inclement weather.

Population and income can potentially affect whether trees are an amenity or disamenity and thereby affect the value that property purchasers place on tree cover. These socioeconomic variables and the other ancillary variables discussed above are likely to be fixed for any given hedonic study, but vary spatially across studies and provide the potential for a meta-analysis to provide insights on the value of tree cover beyond what can be observed in any single hedonic study.

2.4. Model Specification

The first model to be estimated is the selection model (equations 2.4a and 2.4b). The selection equation (2.4a) is specified as:

$$h(Z;\gamma) = \Upsilon_0 + \Upsilon_1 onprop + \Upsilon_2 onprop*medtrees + \Upsilon_3 onprop*oldtrees + \Upsilon_4 onprop*invasive + \Upsilon_5 onprop*temp + \Upsilon_6 popdensity + \Upsilon_7 medianincome + \omega \quad (2.5a)$$

where Z is a vector of study and context characteristics, and γ is a vector of coefficients to be estimated. Each of the variables listed in equation 2.4a is defined in Table 2.2. The dependent variable is binary and indicates if an implicit price is positive (=1) or negative (=0), and the selection equation is specified as a probit. The selection equation includes an explanatory variable (*onprop*) delineating whether the tree cover measure is on a property (=1) or includes tree cover near a property (=0), and this variable is interacted with other variables that may influence whether tree cover is viewed as an amenity or disamenity (*medtrees*, *oldtrees, invasive*, and *temp*). As noted previously, older trees may provide shade, but also potentially pose a greater risk of damage or injury. Invasive tree pests may affect the amenity value of trees and may increase the risk of tree breakage. Higher temperatures may create a desire for more tree shade for outdoor comfort and air conditioning savings, while lower temperatures may create a desire for less tree shade to allow winter sunlight to heat the home and hasten melting of ice and snow. Population density and median income are included to consider if these demographic characteristics affect whether tree cover is viewed as an amenity.

The meta-equation (2.4b) is specified as:

$$g^{+}(X,\theta^{+}) = \theta_0^{+} + \theta_1^{+} treecover + \theta_2^{+} treecover^2 + \theta_3^{+} ctreecover + \theta_4^{+} ctreecover^2 + \theta_5^{+} houseprice + \theta_6^{+} eastern + \theta_7^{+} pacificnw + \theta_8^{+} medtrees + \theta_9^{+} oldtrees + \theta_{10}^{+} signif + \theta_{11}^{+} popdensity + \theta_{12}^{+} medianincome + \varepsilon^{+} \qquad (2.5b)$$

where all variables are defined in Table 2.2 and the θ_i^{+} are coefficients to be estimated. The dependent variable is the consistent measure of the implicit price (effect size) explained in the previous section. The *treecover* variable represents the tree cover variable from the original hedonic models, and *ctreecover* is included to consider if tree cover in the greater study area where people work, shop, and recreate also affects the implicit value of tree cover on or near a property. Both of these variables are included as linear and squared terms (*treecoversq* and *ctreecoversq*) to allow for nonlinear relationships between the implicit value and the tree cover measures.

The mean value of house prices (*houseprice*) from the original hedonic studies is included to see if implicit values of tree cover are affected by selling prices of properties. Binary variables for studies conducted in the eastern U.S. and Pacific Northwest are included to control for spatial fixed effects in different areas of the country (e.g., the risk of forest fires). The omitted category includes studies conducted in the mountain west. Tree age is included because the age of trees affects the size of the crown and could affect the implicit price of tree cover. The omitted category is young trees (<40 years of age). Finally, a variable is included to see if the significance of implicit price estimates in the original hedonic studies affects the magnitudes of the estimates in meta-equation; all implicit price estimates, statistically significant and insignificant, from the hedonic studies are included in the meta-data.

The selection model estimates equations (2.5a and 2.5b) jointly (Wooldridge, 2002), and we conducted a test for the presence of selection from only using studies with positive implicit prices in the estimation of equation (2.5b).

$$H_o: \rho = 0 \ \ vs \ H_a: \rho \neq 0 \qquad (2.6)$$

where ρ is the correlation between the error terms in equations (2.5a and 2.5b) (ω and ε^{+}, respectively) If the null hypothesis cannot be rejected, then the meta-equation (2.5b) can be estimated solely, without the selection equation.

A number of robustness analyses are conducted to provide insight into how much confidence can be placed in the meta-equation coefficient estimates and thus conclusions drawn from the meta-analysis. Given that most studies provided multiple implicit-price estimates and these multiple estimates from individual studies cannot be assumed to be independent observations, the meta-equation is estimated using OLS, study fixed effects, random effects and multilevel mixed-effects. In addition, horizontal robustness checks, excluding individual observations or studies (groups of observations) are also conducted (Boyle et al., 2013). The primary focus of these robustness analyses is to consider if the exclusions of observations from the data affects the estimates of the coefficients on *treecover* and *ctreecover*. The results of these robustness analyses are reported below.

2.5. Results and Discussion

Summary statistics for the variables used in the estimation are reported in Table 2.2. These data indicate that 64 percent of the observations have positive implicit prices. Of the studies with positive implicit prices, the average implicit price for a 1 percent change in tree cover is \$239, and the comparable figure for negative implicit prices is -\$156. Values of the variable *treecover* for the positive implicit prices range from 0.1 percent to 61 percent and the comparable range for negative implicit prices is zero to 40 percent.

2.5.1 Heckman selection equation

Estimation of the Heckman sample selection model (equations 2.5a and 2.5b) resulted in the conclusion that the null hypothesis of no correlation (equation 2.6) could not be rejected (p=0.93). As there is no sample selection, the primary focus of the analyses reported in this paper is the meta-equation. The results from the estimation of the Heckman selection equations are reported in the Appendix 2. A1.

Table 2.1 Summary of hedonic property value studies used in the meta-analysis

Publication	Study Characteristics[a]									
	YEAR	POSITIVE	NEGATIVE	POSITIVE & SIGNIFICANT	NEGATIVE & SIGNIFICANT	UNIT	MODEL	AVERAGE TREE COVER	AVERAGE COUNTY COVER	AVERAGE SELLING PRICE
Cho et al.	2011	0	1	0	0	Area (acres)	$\ln P=\beta_0+\beta_1 \ln X$	24%	36%	\$233,588
Coley	2005	1	0	1	0	Area (ft^2)	$\ln P=\beta_0+\beta_1 X$	2%	50%	\$137,658
Dimke	2008	6	0	5	0	Percentage	$P=\beta_0+\beta_1 X$	26%	27%	\$186,947
Drake-McLaughlin and Netusil	2011	3	3	3	3	Proportion	$\ln P=\beta_0+\beta_1 X+\beta_1 X^2$	25%	45%	\$24,576
		4	2	2	2	Proportion	$\ln P=\beta_0+\beta_1 X+\beta_1 X^2+\beta_3 XZ$			
Holmes et al.	2006	10	6	7	2	Percentage	$\ln P=\beta_0+\beta_1 X$	8%	66%	\$494,894
Holmes et al.	2010	9	7	2	0	Percentage	$\ln P=\beta_0+\beta_1 X$	8%	66%	\$230,176
Huggett	2003	0	6	0	2	Percentage	$\ln P=\beta_0+\beta_1 X$	9%	41%	\$128,470
Kim and Wells	2005	1	1	1	1	Area (m^2)	$P=\beta_0+\beta_1 X$	16%	13%	\$236,608
Mansfield et al.	2005	4	0	4	0	Proportion	$P=\beta_0+\beta_1 X$	30%	54%	\$196,699
Netusil et al.	2010	2	4	1	4	Percentage	$\ln P=\beta_0+\beta_1 X+\beta_1 X^2$	14%	45%	\$236,961
		5	1	3	1	Percentage	$\ln P=\beta_0+\beta_1 \ln X$			
Paterson and Boyle	2002	3	0	0	0	Percentage	$\ln P=\beta_0+\beta_1 X$	61%	52%	\$295,048
Price et al.	2010	3	0	3	0	Percentage	$\ln P=\beta_0+\beta_1 X$	37%	42%	\$482,959
Sander et al.	2010	9	3	4	1	Percentage	$\ln P=\beta_0+\beta_1 X$	15%	17%	\$343,098
Sander and Haight	2012	5	1	4	0	Percentage	$\ln P=\beta_0+\beta_1 X$	14%	16%	\$380,596
Stetler et al.	2010	3	3	2	1	Area (ha)	$\ln P=\beta_0+\beta_1 X+\beta_1 X^2$	14%	50%	\$310,132

[a]Column label definitions are as follows: YEAR=publication year, POSITIVE=# of positive implicit prices, NEGATIVE=# of negative implicit prices, POSITVE & SIGNIFICANT=# of POSITIVE significant at 10% level, NEGATIVE & SIGNIFICANT=# of NEGATIVE significant at 10% level, UNIT=tree cover measurement, MODEL=functional form of hedonic equation, AVERAGE TREE COVER= average percent of tree cover on or near property, AVERAGE COUNTY COVER = average percent of tree cover in the county where the properties are located, and AVERAGE SELLING PRICE=average sale prices (\$2013).

Table 2.2. Definitions and summary statistics of variables used in the meta-analysis

Variable	Description	Positive observations (*IP*>0) Mean (min, max) [a]	Negative observations (*IP*<0) Mean (min, max)
Dependent variable in selection equation			
amenity	1 if *implicit price (IP)* is positive and 0 if *IP* is negative	0.64 (0.00, 1.00)	NA
Dependent variable in meta-equation			
IP	Implicit price of tree cover for a 1% increase ($2013)	$239.41 ($0.32, $2696.15)	-$156.26 (-$895.94, -$0.04)
Independent variables			
onprop	1 if *treecover* on property, 0 otherwise	0.35 (0.00, 1.00)	0.40 (0.00, 1.00)
treecover	% tree cover on or near property	14 (0.10, 61)	12 (0.00, 40)
ctreecover	% county-level tree cover	44 (13,66)	48 (13, 66)
houseprice	Mean sale price of properties ($2013)	$285,138 ($24,576, $494,894)	$249,200 ($24,576, $494.894)
eastern [b]	1 if study area is east of Mississippi River, 0 otherwise	0.69 (0.00, 1.00)	0.47 (0.00, 1.00)
pacificnw [b]	1 if study area is in Oregon or Washington, 0 otherwise	0.21 (0.00, 1.00)	0.42 (0.00, 1.00)
signif	1 if tree cover significant at 10% level, 0 otherwise	0.66 (0.00, 1.00)	0.47 (0.00, 1.00)

[a] Minimum and maximum of the variables are given in parenthesis.
[b] Omitted category includes the following study locations in the mountain west: Greater Flagstaff area, Arizona; Grand County, Colorado; and Flathead, Lake, Sanders, Lincoln and Missoula Counties, Montana.

Table 2.2. Definitions and summary statistics of variables used in the meta-analysis *contd.*

Variable	Description	Positive observations (*IP*>0) Mean (min, max) [a]	Negative observations (*IP*<0) Mean (min, max)
medtrees [c]	% of county forests aged 40 to 119 years	69 (8, 91)	64 (45, 91)
oldtrees [c]	% of county forests aged 120 years or older	11 (0.00, 44)	16 (0.00, 44)
invasive	1 if invasive species or pathogen, 0 otherwise	0.80 (0.00, 1.00)	0.70 (0.00, 1.00)
temp	Annual days with temperature above 90°F	15 (0.00, 76)	14 (3, 45)
popdensity	County population density (people/square mile)	886 (7, 2,715)	1,245 (7, 2,715)
medianincome	County median income	\$56,084 (\$34,000, \$81,330)	\$53,911 (\$35,613, \$81,330)

[a] Minimum and maximum of the variables are given in parenthesis.
[c] Percent of county forest below 40 years of age is the omitted category.

2.5.2 Meta-equation

The meta-equation is estimated with White's consistent standard errors (Nelson and Kennedy, 2009).[5] In this estimation, we found that *popdensity* and *medianincome* were insignificant. This is driven in large part by the study-specific auxiliary data being correlated, which reduces the efficiency of the estimation of all coefficient estimates. Thus, we test the null hypothesis that the coefficients on *popdensity* and *medianincome* are jointly insignificant in the meta-equation:

$$H_o\!: \theta_{11}^{+} = \theta_{12}^{+} = 0 \; vs \; H_o\!: \theta_{11}^{+} \neq 0, \theta_{12}^{+} \neq 0 \qquad 2.7)$$

We could not reject this null hypothesis (F= 2.11, p=0.13). Given this result, the estimation results reported here are for equation (2.5b) with the *popdensity* and *medianincome* variables excluded.[6]

The *treecover*, *treecoversq*, *ctreecover* and *ctreecoversq* variables all have significant coefficient estimates (Table 2.3). The linear terms of these variables have positive coefficient estimates and the squared terms have negative coefficients. This supports the intuition from previous research that people value tree cover up to a point, but beyond this point tree cover declines in value. This could occur for a variety of reasons, including:

- some shade is good, but too much shade blocks sunlight for lawns and passive solar heating;
- tree cover provides privacy, but too much cover may hamper home security or obscure vistas;
- trees make a home more attractive, but too much tree cover may lead to buildup of mildew and algae on exterior structures and excessive cleanup of leaves and litter;
- trees attract watchable wildlife, but too much tree cover may attract nuisance wildlife;

[5] To account for multiple observations from most studies, we estimated the meta-equation using fixed-effects, random-effects, and mixed-effects estimation. The fixed-effects estimation did not work because of collinearity issues. The random-effects and mixed-effects estimations did not change the quantitative and qualitative results for the meta-equation coefficient estimates.

[6] We estimated the meta-equation using negative implicit prices as the dependent variable and none of the explanatory variables were significant.

- trees provide cover from harsh wind and rain, but may break apart in inclement weather or create a wildfire hazard;

There could be a variety of other explanations, but these considerations are consistent with what other investigators have found.

It is interesting to note that the implicit prices of tree cover are higher for eastern study sites (*eastern*) than for mountain west study sites (the omitted category in the estimation), and implicit prices for Pacific Northwest studies are not significantly different from mountain west studies. This difference could be due to a higher risk of forest fires in the mountain west and Pacific Northwest, a preference for more vistas in the west, a preference for more privacy in the east, or other explanations.

The coefficient for older forests (*oldtrees*) is positive and significant, indicating significantly higher implicit prices for study sites with older versus younger forests (the omitted category) in the county where the studies were conducted. This suggests people value living in areas of mature forests that provide more shade and may be visually appealing.[7]

Using the results shown in Table 2.3, the levels of *treecover* (*tc*) and *ctreecover* (*ctc*) that maximize implicit prices were computes as:

$$\frac{\partial IP^{+}}{\partial tc} = 0 \; and \; \frac{\partial IP^{+}}{\partial ctc} = 0 \qquad (2.8)$$

The level of *treecover* that maximizes implicit prices is 30 percent with a standard error of 15 percent and the comparable level for *ctreecover* is 38 percent with a standard error of 3 percent.[8]

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[7] This is an interesting outcome when compared to the result from the selection equation reported in the Appendix. Older trees increase the probability of a negative implicit price, but also increase the magnitude of positive implicit prices. These results suggest the concurrent amenity/disamenity of older trees; more shade and a desirable aesthetic, but higher perceived risks with more maintenance costs.

[8] The standard errors were approximated using the Marcov Chain Monte-Carlo (MCMC) approach using the Gibbs sampler (Plassman and Khana, 2007). This method generates a large number of samples from posterior distributions of coefficient estimates for *treecover* and *ctreecover* and posterior distributions of turning points of *treecover* and *ctreecover* that maximize the implicit prices. Posterior means and standard deviations are calculated for these finite sample approximations of the sampling distribution of the levels of *treecover* and ctreecover that maximize implicit prices.

Table 2.3. Meta-equation coefficient estimates (positive implicit prices, IP+).

Variables	Coefficient Estimates
treecover	22.32*[a]
	(12.64)[b]
treecoversq	-0.37**
	(0.18)
ctreecover	84.10**
	(35.94)
ctreecoversq	-1.11**
	(0.47)
houseprice	-0.0002
	(0.0007)
eastern	1393.97**
	(681.76)
pacificnw	351.75
	(239.73)
oldtrees	41.07**
	(17.66)
medtrees	5.08
	(4.63)
signif	100.54
	(98.15)
intercept	-2971.9**
	(1176.81)
n	68
R^2	0.27

[a] Single asterisk indicates significance at the 10 percent level and double asterisk indicates significance at the 5 percent level.
[b] Robust standard errors are given in parentheses.

It is worth noting that *treecover* ranges from 0.1 percent to 61 percent in the data used to estimate the meta-equation and the comparable range for *ctreecover* is 13 percent to 66 percent (see

Table 2.2). Thus, the levels of *treecover* and *ctreecover* that maximize implicit prices are within the observed data on tree cover. Increasing tree cover beyond these levels does not result in a negative implicit price; it is just that the implicit prices decline from their maximum values.

An additional consideration is that the mean value of *treecover* is 14 percent (Table 2.2), while the value that maximizes implicit price for this variable is 30 percent (more than one standard deviation below the value that maximizes implicit prices). Further, 14 percent tree cover on or near a property is much less for tree cover in the county where the properties are located (44 percent, Table 2.2). These relationships support the notion that individual property owners underinvest in trees on their property from both the perspective of individual property owners and a societal perspective.

2.5.3 Horizontal robustness

Conducting robustness checks in any empirical analysis is always important, but it is particularly important for this analysis when estimation is done with only 68 observations. With a small sample size, a single observation or group of observations (study) has the potential to influence estimation results.

Removal of single observations and re-estimation of the meta-equation did not induce major changes in the estimates of the key coefficients for *treecover*, *treecoversq*, *ctreecover* and *ctreecoversq.* None of these coefficient estimates changed sign, the average change in the magnitude of the estimated coefficients for these variables is only 4 percent, and there were three occurrences where *treecover* and *treecoversq* became insignificant (Table 2.4). The only variable that exhibited substantial sensitivity to removing observations is *houseprice* with an average effect of 19 percent, but this variable is insignificant in the original meta-equation reported in Table 2.3 and only becomes significant in two instances in the observation-removal robustness analysis.

Table 2.4. Observation robustness (removing one observation at a time from estimation).

Variables	Number of times sign of coefficient changed	Number of times significance of coefficient changed (at 10% level)	Absolute, percent changes in coefficient magnitudes
			Average (min, max)[a]
treecover	0	3	4% (0, 52)
treecoversq	0	3	4% (0, 39)
ctreecover	0	0	4% (0, 21)
ctreecoversq	0	0	4% (0, 19)
houseprice	2	0	19% (0, 177)
eastern	0	1	5% (0, 52)
pacificnw	0	6	5% (0, 40)
oldtrees	0	1	4% (0, 31)
medtrees	0	2	7% (0, 179)
signif	0	0	7% (0, 55)

[a] Minimum and maximum of the variables are given in parentheses.

In contrast, all coefficient estimates for *treecover*, *treecoversq*, *ctreecover* and *ctreecoversq* exhibited more variability when studies (sets of observations) are removed from the estimation. Recall, there are thirteen studies with positive implicit price estimates and the number of observations range from one to ten per study (Table 2.1). Here the coefficient estimates for *treecover*, *treecoversq*, *ctreecover* and *ctreecoversq* sometimes changed significance or sign up to two times; the average change in coefficient estimates ranges 35 percent (*treecover*) to 56 percent (*ctreecover*) (Table 2.5).

Table 2.5. Study robustness (removing one study at a time from estimation).

Variable	Number of times sign of coefficient changed	Number of times significance of coefficient changed (at 10% level)	Absolute, percent changes in coefficient magnitudes
			Average (min, max)[a]
treecover	0	3	35% (1, 97)
treecoversq	2	2	46% (3, 167)
ctreecover	1	1	56% (1, 291)
ctreecoversq	1	1	55% (0, 294)
houseprice	5	1	225% (4, 930)
eastern	2	2	65% (6, 272)
pacificnw	1	2	66% (2, 315)
oldtrees	1	2	59% (7, 244)
medtrees	2	3	88% (0, 443)
signif	0	0	19% (0, 95)

[a] Minimum and maximum of the variables are given in parentheses.

Given these study sensitivity results, it is logical to ask which studies are affecting the estimation. This analysis is conducted by looking at the changes in the level of tree cover that maximizes implicit prices (Table 2.6). Recall the level of *treecover* that maximizes implicit prices, based on the full estimates with all observations, is 30 percent and the comparable value for *ctreecover* is 38 percent. The good news is that only three studies resulted in changes of the level of *treecover* by more than 10%, but the bad news is that the effects were quite large: 51 percent (Holmes et al., 2006), -26 percent (Netusil et al., 2010) and -11 percent (Drake-McLaughlin and Netusil, 2011). The effects on the level of *ctreecover* were generally smaller; again, two studies resulted in greater than 10 percent changes in the maximum implicit price (-13 percent for Holmes et al., 2006 and 15 percent for Holmes et al., 2010). It is important to note that studies with the largest percentage deviations in the levels of *treecover* that maximize implicit prices, when their observations are removed from the estimation, have some of the largest numbers of observations in the data (9 in Holmes et al., 2006; 10 in Holmes et al., 2010; 7 in Netusil et al., 2010; 7 in Drake-McLaughlin and Netusil, 2011). The key insight from the study robustness checks is that while coefficient estimates varied, in most cases the linear and square term coefficient estimates moved in a relationship that does not change the levels of *treecover* and *ctreecover* that maximize implicit prices.

Table 2.6. Changes in implicit prices by study for study robustness.

	Percent changes	
Study	*treecover*	*ctreecover*
Coley (2005)	4%	-2%
Dimke (2008)	NA [a]	-2%
Drake-McLaughlin and Netusil (2011)	-11%	1%
Holmes et al. (2006)	51%	-13%
Holmes et al. (2010)	2%	15%
Kim and Wells (2005)	2%	-1%
Mansfield et al. (2005)	0%	5%
Netusil et al. (2010)	-26%	0%
Paterson and Boyle (2002)	NA	-3%
Price et al. (2010)	-1%	1%
Sander et al. (2010)	2%	-2%
Sander and Haight (2012)	1%	-1%
Stetler et al. (2010)	7%	-4%

[a] NA indicates coefficient estimate of *treecoversq* and *ctreecoversq* have the wrong signs and are insignificant so tree cover that maximizes implicit prices could not be calculated.

The violations of robustness do not imply that the influential studies should be removed from the analysis, nor do they imply that the meta-analysis results are invalid, but they do suggest that the findings reported here should be interpreted as preliminary and with caution. More studies are needed to add spatial breadth and location-specific depth of implicit price estimates to confirm the preliminary findings presented here. It is crucial that the future studies focus on percent tree cover as the key variable so that the new empirical estimates can be merged with the empirical estimates used here to estimate a new meta-equation.

2.6. Conclusions

This study finds a nonlinear relationship between the implicit value of tree cover and two types of tree canopy cover: tree cover on or near a property, and tree cover in the county where a property is located. This nonlinear relationship allows the computation of the amount of property-level and county-level tree cover that maximizes the implicit value of tree canopy cover: 30 percent for tree cover on or near a property, and 38 percent at the county level. This pattern of results suggests that property owners prefer more tree cover in the general area where they work, shop and recreate, as a public good, than on their own property, as a private good. This discrepancy may be due to the fact that homeowners generally pay all of the planting and maintenance costs and bear most of the perceived risks (i.e., wildfire and storm damage) for trees located on their property. When these costs and risks are either borne by other private landowners, or are shared by all taxpayers for trees located on public land, higher levels of county-level tree cover are preferred.

The finding that the implicit value of tree cover is maximized at about 38% for county-level cover is consistent with the often-cited 40 percent tree cover espoused by American Forests as an ecological goal for communities on the East Coast and Pacific Northwest of the United States. The average urban tree cover in the U.S. is currently about 35 percent (Nowak et al., 2010). Therefore, in many areas, overall tree cover could be rightly increased with a concomitant positive effect on residential property values.

The preference for old trees (more than 120 years old) found in this meta-analysis is another interesting result. A simplistic view of land development may be to cut down old trees and then plant new ones upon completion of construction rather than invest in protection and restorative care of old trees; here again, this may be indicative of underinvestment in community tree cover. These veteran trees are much more ecologically valuable than young trees for carbon storage, air pollution abatement, stormwater interception, and energy conservation, and these results provide evidence that they have more amenity value too. Thus, communities might wish to consider public outreach programs, zoning policies, and tax incentives to protect and maintain older tress. Although such endeavors come at a cost for the community, these costs might be recouped in part through additional real estate tax revenues on higher-appraising residential property.

While the findings of this study may be helpful to local officials involved in planning community forestry programs, we expect that decision-making by both community planners and households will become more complex in the future due to various outcomes anticipated from a changing climate. On the one hand, a hotter climate may increase the value of tree cover for its ability to shade and cool homes. This preference may be most acute in urban areas that are vulnerable to "heat island" effects. Further, tree canopy and forested riparian buffers intercept stormwater, helping to mitigate the flooding and water quality effects of runoff. On the other hand, climate change may increase the frequency and severity of extreme weather events, which could lead to an increase in storm damage to trees, causing increased power outages and debris cleanup costs. This may push communities to think twice about maintaining large, mature trees in residential areas. Consequently, the future may bring complex challenges to residential property owners and community forest planners alike. Because tree-cover considerations may vary by geographic location, preferences for property-level and county-level tree cover may become even more nuanced and, over time, local planners may find it useful to engage residents to discuss and refine the goals of community forestry programs.

References

Barbosa, A.E., J.N. Fernandes, and L.M. David. 2012. "Key issues for sustainable urban stormwater management." *Water Research*, 46 (20): 6787-6798.

Bentz, B. 2008. *Western U.S. Bark Beetles and Climate Change*. U.S. Department of Agriculture, Forest Service, Climate Change Resource Center (http://www.fs.fed.us/ccrc/topics/bark-beetles.shtml , accessed 11.02.2014).

Boyle, K.J., C.F. Parmeter, B.B. Boehlert, and R.W. Paterson. 2013. "Due-diligence in meta-analyses to support benefit transfers." *Environmental Resource Economics*, 55 (23): 357–386.

Cho, S-H., N.C. Poudyal, and R.K. Roberts. 2008. "Spatial analysis of the amenity value of green open space." *Ecological Economics*, 66 (2): 403-416.

Cho S-H., S.G. Kim, R.K. Roberts, and S. Jung. 2009. "Amenity values of spatial configurations of forest landscapes over space and time in the Southern Appalachian Highlands." *Ecological Economics*, 68 (10): 2646-2657.

Cho, S.H., D. Lambert, S. Kim, R. Roberts, and W. Park. 2011. "Relationship between value of open space and distance from housing locations within a community". *Journal of Geographical Systems*, 13 (4): 393-414.

Coley, M.C. 2005. "House and landscape value: an application of hedonic pricing technique investigating effects of lawn area on house selling price." MS Thesis, The University of Georgia.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L, C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks, and B.M. Wotton. 2001. "Climate change and forest disturbances." *BioScience,* 51 (9): 723-734.

Dimke, K.C. 2008. "Valuation of tree copy on property values of six communities in Cincinnati, Ohio." PhD Dissertation, The Ohio State University.

Drake-McLaughlin, N., and N.R. Netusil. 2011. "Valuing walkability and vegetation in Portland, Oregon." In Twenty-Second Interim Report and Proceedings from the Annual Meeting, W2133. R.H von Haefen (ed.): 173-201.

Frankel, S.J. 2008. "Forest plant diseases and climate change." U.S. Department of Agriculture, Forest Service, Climate Change Resource Center. (http://www.fs.usda.gov/ccrc/topics/plant-diseases.shtml , accessed 11.02.2014).

Getz, D.A., A. Karow, and J.J. Kielbaso. 1982. "Inner city preferences for trees and urban forestry programs." *Journal of Arboriculture,* 8 (10): 258-263.

Ghermandi, A., and P.A. Nunes. 2013. "A global map of coastal recreation values: results from a spatially explicit meta-analysis." *Ecological Economics*, 86: 1-15.

Hart, M.A., and D.J. Sailor. 2009. “Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island.” *Theoretical and Applied Climatology*, 95 (3-4): 397-406.

Heckman, J.J. 1979. “Sample selection bias as a specification error.” *Econometrica*, 47 (1): 153-161.

Holmes, T.P., E.A. Murphy, and K.P. Bell. 2006. "Exotic forest insects and residential property values." *Agricultural and Resource Economics Review*, 35 (1): 155-166.

Holmes, T.P., E.A. Murphy, K.P. Bell, and D.D. Royle. 2010. "Property value impacts of hemlock woolly adelgid in residential forests." *Forest Science*, 56 (6): 529-540.

Homer, C., J. Dewitz, J. Fry, M. Coan, N. Hossain, C. Larson, N, Herold, A. McKerrow, J. N. VanDriel, and J. Wickham. 2007. “Completion of the 2001 national land cover database for the conterminous United States.” *Photogrammetric Engineering and Remote Sensing*, 73 (4): 337-341.

Hope, D., C. Gries, W. Zhu, W.F. Fagan, C.L. Redman, N.B. Grimm, A.L. Nelson, C. Martin, and A. Kinzig. 2003. “Socioeconomics drive urban plant diversity.” *Proceedings of the National Academy of Science*, 100 (15): 8788-8792.

Huggett Jr, R.J. 2004."Fire in the wildland-urban interface: an examination of the effects of wildfire on residential property markets." PhD Dissertation, North Carolina State University.

Iverson, L.R., and A.M. Prasad. 2001. “Potential changes in tree species richness and forest community types following climate change.” *Ecosystems,* 4 (3): 186-199.

Johnston, R.J., E.Y. Besedin, and R. Stapler. 2014. “Enhanced geospatial data for meta-analysis and environmental benefit transfer: an application to water quality improvements.” Presented at the *Meta-Analysis of Economics Research Network, MAER-Net 2014 Athens Colloquium*, Athens, Greece.

Kim, Y.S., and A. Wells. 2005. "The impact of forest density on property values." *Journal of Forestry*, 103 (3): 146-151.

Mansfield, C., S.K. Pattanayak, W. McDow, R. McDonald, and P. Halpin. 2005. "Shades of green: measuring the value of urban forests in the housing market." *Journal of Forest Economics*, 11 (3): 177-199.

Nelson, J.P. and P.E. Kennedy. 2009. “The use (and abuse) of meta-analysis in environmental and natural resource economics: an assessment.” *Environmental and Resource Economics,* 42 (3): 345-377.

Netusil, N.R., S. Chattopadhyay, and K.F. Kovacs. 2010. "Estimating the demand for tree canopy: a second-stage hedonic price analysis in Portland, Oregon." *Land Economics*, 86 (2): 281-293.

Nowak, D.J., and E.J. Greenfield. 2012. “Tree and impervious cover change in US cities.” *Urban Forestry & Urban Greening*, 11 (1): 21-30.

Nowak, D.J., S.M. Stein, P.B. Randler, E.J. Greenfield, S.J. Comas, M.A. Carr, and R.J. Alig. 2010. “Sustaining America’s urban trees and forests: a forests on the edge report.” Gen. Tech. Rep. NRS-62, U.S. Department of Agriculture, Forest Service, Northern Research Station.

Paterson, R.W., and K.J. Boyle. 2002. "Out of sight, out of mind? using GIS to incorporate visibility in hedonic property value models." *Land Economics*, 78 (3): 417-425.

Pickett, S.T., M.L. Cadenasso, J.M. Grove, C.G. Booned, P.M. Groffman, E. Irwin, S.S. Kaushal, V. Marshall, B.P. McGrath, C.H. Nilon, R.V. Pouyat, K. Szlavecz, A. Troy, and P. Warren, 2011. “Urban ecological systems: Scientific foundations and a decade of progress.” *Journal of Environmental Management*, 92 (3): 331-362.

Plassmann, F., and N. Khanna. 2007. “Assessing the precision of turning point estimates in polynomial regression functions.” *Econometric Reviews*, 26 (5): 503–528.

Prasad, A., L.S. Iverson, S. Matthews, and M. Peters. 2009. “Atlases of tree and bird species habitats for current and future climates.” *Ecological Restoration*, 27 (3): 260-263.

Price, J.I., D.W. McCollum, and R.P. Berrens. 2010. "Insect infestation and residential property values: A hedonic analysis of the mountain pine beetle epidemic." *Forest Policy and Economics,* 12 (6): 415-422.

Sander, H., S. Polasky, and R.G. Haight. 2010. "The value of urban tree cover: a hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA." *Ecological Economics*, 69 (8): 1646-1656.

Sander, H. and R.G. Haight. 2012. "Estimating the economic value of cultural ecosystem services in an urbanizing area using hedonic pricing.” *Journal of Environmental Management*, 113: 194-205.

Schroeder, H., G. Flannigan, and R. Coles. 2006. “Residents’ attitudes toward street trees in the UK and US communities.” *Arboriculture and Urban Forestry*, 32 (5): 236-246.

Stetler, K.M., T.J. Venn, and D.E. Calkin. 2010. "The effects of wildfire and environmental amenities on property values in northwest Montana, USA." *Ecological Economics*, 69 (11): 2233-2243.

Taylor, L.O. 2003. "The Hedonic Method." In *A Primer on Nonmarket Valuation*, P. Champ, K. Boyle and T. Brown (eds.). New York: Kluwer Academic Publishers.

Troy, A.R., J.M. Grove, J.P. O’Neil-Dunne, S.T. Pickett, and M.L. Cadenasso. 2007. “Predicting opportunities for greening and patterns of vegetation on private urban lands.” *Environmental Management*, 40 (3): 394-412.

U.S. Department of Labor, Bureau of Labor Statistics.2015. “Consumer price index data from 1913 to 2016.” (http://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/, accessed July 2013).

Wolf, K.L. 2004. “Trees and business district preferences: A case study of Athens, Georgia, US.” *Journal of Arboriculture*, 30 (6): 336-346.

Woodall, C.W., C.M. Oswalt, J.A. Westfall, C.H. Perry, M.D. Nelson, and A.O. Finley. 2009. "An indicator of tree migration in forests of the eastern United States." *Forest Ecology and Management,* 257 (5): 1434-1444.

Wooldridge, J. 2002. "Econometric analysis of cross section and panel data". Cambridge: MIT Press.

Appendix 2A: Results of Heckman selection model

Table 2. A1. Joint estimation of selection equation and meta-equation

	Variable	Coefficient
Selection equation	*onprop*	3.27[a]
		(4.03)[b]
	onmed	0.003
		(0.06)
	onold	-0.19**
		(0.07)
	oninvasive	-2.87
		(2.69)
	ontemp	0.01
		(0.05)
	popdensity	0.0004**
		(0.0002)
	medianincome	0.00002*
		(0.00001)
	intercept	-1.03
		(0.71)
Meta-equation	*treecover*	19.09
		(11.92)
	treecoversq	-0.33*
		(0.17)
	ctreecover	49.23
		(40.06)
	ctreecoversq	-0.70
		(0.51)
	houseprice	-0.002
		(0.002)
	eastern	735.87
		(1132.8)
	pacificnw	397.96
		(667.9)
	medtrees	11.72
		(8.55)
	oldtrees	19.53
		(23.83)
	signif	112.53
		(94.06)
	popdensity	-0.21
		(0.15)
	medianincome	0.005
		(0.02)
	intercept	-1696.32
		(1151.4)
	ρ	-0.05
		(0.52)

[a] Single asterisk indicates significance at the 10 percent level and double asterisk indicates significance at the 5 percent level.
[b] Robust standard errors are given in parentheses.

Chapter 3

Preference for urban tree cover: A hedonic price analysis in multiple cities in the U.S.

Abstract

Hedonic price models are commonly used to value the home owner preference for trees on or near property. The “first-stage” hedonic model, estimating the hedonic price function, analyses the preferences in terms of the welfare measures associated with a marginal change in the tree cover. Estimates from previous studies provide mixed conclusions and show a considerable variation across study locations, demographic groups and also across the landscape. In this study, we apply the first-stage hedonic model to assess whether the home owners prefer trees as a private good or a public good by valuing tree cover in different distances (0-100m, 101-500m, 501-1000m) from property. We extend the analysis to study these differential effects at multiple study locations in the U.S., and perform an internal meta-analysis to examine what the results from different location collectively imply about the value of tree cover.

Results from the study suggests that home owners’ preference for tree cover vary across geographical locations and across the landscape of an urban community, and found that location characteristics and socio-demographic characteristics attribute to these heterogeneous preferences. In locations where trees are considered an amenity, increasing tree cover within 0-100m and 101-500m buffer areas from property increase the benefits to home owners, and increasing tree cover beyond that decreases the benefits. In locations where trees are considered a disamenity, increasing tree cover in these buffer areas decreases benefits. The findings from this study on both the location-specific preferences and general inferences are useful for urban planning and designing.

Key words: hedonic valuation, marginal implicit price, urban tree cover, internal meta-analysis

3.1 Introduction

Tree canopy cover, providing a wide range of benefits to local communities, has become a key resource in designing urban systems that are resilient and adaptable to changes in climate, development, and socio-economic factors in urban areas. Objective economic values of trees are critical to plan and design the urban cities and these values are obtained by assessing how home owners benefit from trees in urban areas. Home buyers sort into their optimal choice of property which contains their preferred attributes including the trees. This implies that the amount of money the home buyer is willing to pay for the trees adds into the property price. Ideally any difference in price between two houses that are identical except for their tree cover must be solely due to the trees (Anderson and Cordell, 1988). Therefore, the variations in property prices and tree cover in an urban area can be used to estimate the value of trees. In practice, these variations are utilized in Hedonic property price (HP) models (Rosen, 1974; Palmquist, 2006) to estimate how marginal and/or non-marginal changes of tree cover affect the property prices, thereby the welfare of property owners.

Hedonic price models are commonly used to value the trees in urban areas where the property markets are assumed to be well-developed. These models specify the property price as a function of attributes associated with the property, such as property characteristics and neighborhood characteristics including tree cover. This price equation is estimated using property sales data to obtain the marginal implicit price of tree cover or the marginal effect of tree cover on property price. These estimates represent households' preference for tree cover at margin in terms of how much the sale value of property changes when tree cover on or near property changes by one unit. A majority of the hedonic property value studies report the marginal implicit price estimates of tree cover obtained in this manner. When the changes associated with the tree cover are non-marginal, Hedonic second-stage estimation is desirable, however the applications are limited as estimation is complex and data intensive[9].

Previous hedonic studies that value tree cover conclude that home values are affected by the level of urban tree cover (Anderson & Cordell,1988; Dombrow et al., 2000; Morales et al., 1976; Morales, 1980; Mansfield et al. 2005; Holmes et al., 2006; Donavan and Butry, 2010; Netusil et al., 2010; Holmes et al., 2010; Irwin, 2002; Price et al., 2010; Stetler et al., 2010; Sander et al., 2010), proximity of forests to residential properties (Tyrvainen and Miettinen, 2000; Mansfield et al., 2005; Thorsnes, 2002) and view of forests (Tyrvainen and Miettinen, 2000). These studies focus on different geographic locations, use different definitions of tree cover measure (for example, number of trees on property, percent of tree cover on property, distance to nearest forest etc.), and apply different model specifications and estimation methods to estimate implicit values. Evidence provided by these studies for the effects of tree cover on property value and the home owners' preferences for tree cover are mixed and varies across study locations. The locational differences as explained by scarcity of trees, landscape composition, socio-economic and climatic factors and urban policy may attribute to these heterogeneous preferences.

Previous first-stage hedonic studies further suggest that implicit prices for tree cover may not be constant across the landscape because home owners may have heterogeneous preferences for tree cover at different locations. For example, Cho et al. (2010) found that implicit value of trees is positive but has diminishing effects with distance from the property, and the tree cover adds very little to the sale price at threshold distance of 1.6 miles. Netusil (2005) found that presence of trees on property

[9] There only a few studies performed the second-stage analysis to estimate demand for tree cover. Garrod and Willis (1992) estimated demand for broadleaved woodlands and confer trees in Forestry Commission lands in multiple property markets Britain. In the U.S., Netusil et al. (2010) estimated demand for tree canopy within ¼ mile from single-family residential properties in 4 submarkets in Portland, Oregon. Similarly, a few second-stage analyses exist for other open spaces. For example, Mahan et al. (2010) estimated the demand for urban wetlands; Boyle et al. (1999) and Zhang et al. (2015) derived demand for water quality; demand for air quality was estimated by Chattopadhyay et al. (1999).

reduces the sale value of property while trees within 200 feet from the lot and 200 feet to ¼ mile from the lot increase the property value. Holmes et al., (2010) sound that implicit price of coniferous trees is not significant at property level and in the 100m vicinity but significantly positive at a distance of 500m from the property. Price et al. (2010) concluded that tree cover at 100 m, 500 m and 1 km distances significantly increase the property value while Sadler et al. (2010) found significant effects at 90 m and 250 m. Sander and Zhao (2015) also found that trees are not valued on property but in the close neighborhood within 250m. Sander et al. (2010) value the tree cover with 100, 250, 500, 750 and 1000m from the properties and found that tree cover of 44 percent within 100m and 60 percent within 250m from the property maximize the property value. These studies provide evidence for differential effect of tree cover at various distances from the property on the sale value of property, and the results are mixed in the threshold distance. This implies the need of more research to explore these topics.

Our study extends the evaluation of the preference for tree cover by (1) estimating the private land owners' preferences for tree cover in well-defined multiple property markets in the U.S and identifying how trees affect the property values in these markets; (2) providing new evidence on how the preferences for the trees in close and distant neighborhoods of properties differ across the landscape and across the cities; (3) evaluating how the tree cover in public lands and socio-demographic variables affect the home owner preference for tree cover on private properties.

Preferences of home owners are obtained by estimating the price function for each market and calculating the marginal implicit prices. The study areas are geographically spread across the U.S. Therefore, we assume there is no integration between markets and there is no movement of home owners across markets due to high moving costs. This means that individuals in one market do not consider housing in other markets when they make the purchasing decision. Therefore, hedonic price function for a particular market arise only due to the interaction of buyers and sellers in that market, thus separate hedonic price functions can be estimated for each market. A significant variation in quantity of tree cover and other location factors such as supply of housing and amenity characteristics and distribution of socio-demographic characteristics of individuals is observed across these markets. The hedonic price functions may vary across markets due to this variation and the estimates of implicit prices for tree cover may vary across markets independently of the level of property characteristics. This enables the estimation of the preference heterogeneity of home owners in these communities.

Further, our analysis is augmented by estimating the price functions using high resolution data which yields more informative and accurate estimates. Property sales data were obtained from multiple-listings for the sales years of 2005-2014 in each city. These records provide information of most of the actual property tractions in the housing markets and augment the estimates of the hedonic price model than data collected from random sample of buyers in the market. Tree cover and other environmental amenity variables in the neighborhood of each property were obtained from high resolution spatial data (1m resolution) of land cover types. This data accurately delineates the land cover classes than low resolution land cover data commonly used in previous studies and greatly improve the quantification of the relative abundance of amenities in the vicinity of each property. Thereby, they facilitate incorporating important and relevant amenity variables in the model along with tree cover, thus reduce the potential bias in the model estimates.

We consider tree cover within three neighborhoods of each property to evaluate the preference for trees within private properties (private trees) and the trees in vicinity or distant locations which provide external benefits to home owners (public trees). Tree cover within a buffer area of 0-100m around each property are considered to represent private trees, and trees within the neighborhoods of 101-500m and 501-1000m from the property represent the public trees. Inclusion all these tree cover variables in the empirical model permits estimating the differential effects of trees in private properties and public lands. These estimates help understand the heterogeneous preferences of home owners.

We summarize the estimates obtained from various study areas by performing an internal meta-analysis (Banzhaf and Smith, 2007; Kuminoff et al., 2010a; Klemick et al., 2015). Specifically, we study the relationship between the implicit price of tree cover on private properties with itself and the tree cover in public lands. Similar datasets and method were used to derive the implicit prices. Thus identifying which factors determine the variation of implicit prices in our study areas is feasible than when using estimates from different studies.

Results from the study suggests that home owners' preference for tree cover vary across geographical locations and across the landscape of an urban community, and found that location characteristics and socio-demographic characteristics attribute to these heterogeneous preferences. In locations where trees are considered an amenity, increasing tree cover within 0-100m and 101-500m buffer areas from property increase the benefits to home owners, and increasing tree cover beyond that decreases the benefits. In locations where trees are considered a disamenity, increasing tree cover in these buffer areas decreases benefits. The study provides more informative estimates of the location-specific preferences and more general rules regarding the preference structure of urban communities that are useful in urban planning and designing.

3.2 Hedonic property value model for estimating preferences for tree cover

Hedonic models implicitly estimate the demand of tree cover and other characteristics of residential property via modeling the property sales in housing markets. In this modeling framework, a house (Z) is considered as a differentiated product with a vector of attributes ($\underline{z} = z_1, z_2, z_3, ..., z_n$) including tree cover on property (z_1) and tree cover in public lands (z_2, z_3). Sale price of the house $(P(\underline{z}))$ is decomposed into the implicit prices of each attribute (p_{z_i}) and the demand parameters for each attribute are recovered by solving the utility maximization problem of each household over this differentiated product.

Suppose residential properties are sold in perfectly competitive market where buyers and sellers in well-defined housing market are price takers (supply of houses in the market are exogenous to consumers). Each consumer with demographic characteristics α and income *y* purchases a property and seeks to maximize utility by choosing the model of *Z* with $\underline{z}$ and the amount x, a composite commodity representing all other goods, subject to budget constraint[10].

$$\max_{\underline{z},x} U(\underline{z}, x; \alpha) \text{ s.t } y = P(\underline{z}) + x \tag{3.1}$$

First order conditions are:

$$\partial U(\cdot)/\partial z_i = \lambda_i \partial P(\underline{z})/\partial z_i \qquad i = 1,2,3,\ldots..n$$

$$\partial U(\cdot)/\partial x = \lambda_i$$

$$y = P(\underline{z}) + x \tag{3.2}$$

where λ_i is the Lagrange multiplier. A home owner choses levels of property characteristic z_i such that marginal rate of substitution between the property characteristic and numeraire good is equal to the marginal implicit price of that property characteristic. Then, for tree cover on private property (z_1), we can write this relationship as follows.

$$\frac{\partial U(.)/\partial z_1}{\partial U(.)/\partial x} = \frac{U_{z_1}}{U_x} \equiv \frac{\partial P(\underline{z})}{\partial z_1} = p^*_{z_1} \tag{3.3}$$

Above relationship reveals the marginal implicit price for private trees. Similarly, we can derive the implicit prices for trees in public lands. These implicit prices can be interpreted as the WTP for a one-unit change in tree cover in private and public lands.

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[10] Prices and income are normalized by dividing by the price of numeraire good x, and x is Hicksian composite good.

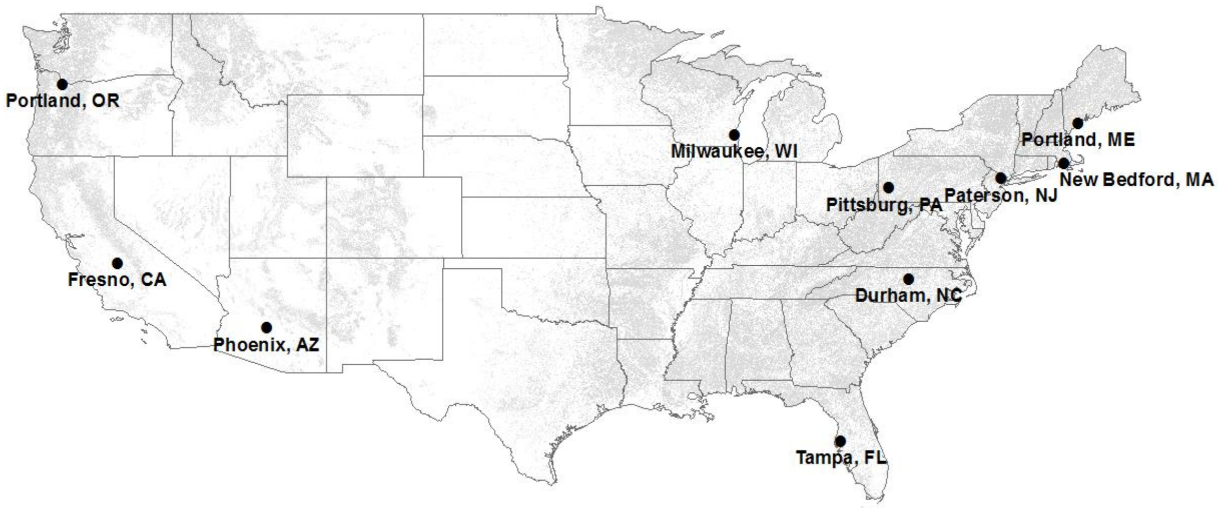
3.3. Data and methods

3.3.1 Property sales data

We collected property sales data, tree cover and other environmental attributes, location and neighborhood characteristics from 12 cities in the U.S (Durham, NC; Phoenix, AZ; Fresno, CA; Portland, ME; Portland, OR; Pittsburgh, PA; New Bedford, MA; Milwaukee, WI; Patterson, NJ; Tampa, FL; Green Bay, WI; and Woodbine, IA) (See Figure 3.1). Sales transactions data are obtained from multiple-listings (MLS) data. This data provides a subset of property characteristics that may affect the sale value of properties, therefore, other relevant property characteristics were obtained from several other data sources. We obtained high resolution (1m) GIS data of land cover types for each city from the EPA's EnviroAtlas (https://www.epa.gov/enviroatlas)[12] and created the tree cover and other land cover types in the vicinity of each property. Also, we collected GIS information on census block boundaries within each city (U.S. Census, 2010) and merged with the property sales data. Each city boundary was defined based on the community boundary GIS layers from the EPA's EnviroAtlas[13]. These communities spread across the U.S. and are geographically segregated. No consumers would consider two communities as substitutes, thus, all the communities can be considered as separate markets (Palmquist, 2003).

[12] EnviroAtlas provides a suite of ecological parameters in various urban communities across the U.S. For our study we obtained raster data (1 m) that categorize land cover types within each city. These land cover categories have been created using aerial imagery from the National Agricultural Imagery program (NAIP) in 2010 (See EnviroAtlas for more information). The GIS layers provide presence of each land cover category within 1m^2 area. We used this data to calculate the percentage of land cover types in the vicinity of each property.

[13] EnviroAtlas's community boundaries are based on the U.S. Census 2010 definition of urban statistical areas.



■ Tree canopy cover
● Urban communities included in the Hedonic analysis

Figure 3.1 Geographical distribution of cities used in the Hedonic analysis

Sales data of single-family houses from 2005 to 2014 were obtained from multiple-listings data. This data includes buyers and sellers' information for residential sales and each property location is identified by its address, FIPS codes and latitude and longitude information. The data include house attributes of sale price, size of living area, lot size, number of bathrooms and bedrooms and year built and sale date. Sales are categorized in to sale types of new sales, regular resale, REO sale and foreclosures and sale transaction types of single-parcel and multi-parcel transactions. This data was cleaned for incorrect spatial location of properties, duplicates, missing values and incongruous data in house attributes. Point location of each house was identified via latitude and longitude information provided in the MLS data and sales records located within respective study boundaries and zip codes were selected. All single-parcel transactions including the repeated sales were selected while multiple-parcel transactions, REO sales and foreclosures were excluded from the analysis. Sales prices were normalized to 2010 prices using seasonally adjusted housing price index from the U.S. Federal Housing Finance Agency at the state level. Further trimming was done using the upper and lower 5 percent of price per unit area of living area. (See appendix 3.A for more information on data cleaning protocol). Two cities were dropped from the analysis due to smaller sample size (92 observations in Woodbine, IA) and lack of data on property characteristics (Green Bay, WI).

Table 3.1 summarizes the house attributes used in the analysis and shows that property characteristics vary within and across cities significantly. The average sale price ranges from $151,959 to $293,394 while residential properties in the Portland (OR) are sold at the highest price followed by those in the cities of Patterson (NJ) and Portland (ME) and New Bedford, (MA). Durham (NC) and Portland (ME) have relatively larger houses in larger lots selling at higher prices. In densely populated cities such as Patterson (NJ), Fresno (CA), Portland (OR) and Phoenix (AZ), larger houses in small lots are sold at higher prices. These variations make the price functions differ across cities and permit estimating the price functions for each city.

3.3.2 Tree cover and other land cover data

GIS data of land cover types include trees and forests, impervious surface, water bodies, agricultural lands, grass and herbaceous lands, soil and barren lands, shrub land, orchards, woody wetlands and emergent wetlands (See Appendix 3.B for definitions and summary statistics of these 9 land cover categories for the study areas). Land cover types vary across from location to location, and, impervious surface, tree cover, grass and herbaceous lands and agricultural lands cover most of the landscape. For example, overall tree cover is higher in cities in the East Coast (eg. Durham (NC), Portland (ME) and Pittsburgh (PA)) compared to others. Tree cover is the lowest in cities in arid regions (eg. Fresno (CA) and Phoenix (AZ)). Densely populated cities have higher level of impervious surface and lower levels of tree cover (eg. Patterson (NJ) and Portland (OR)). Agricultural lands cover about one third of Fresno (CA)

Table 3.1 Summary statistics of house attributes in each city

City	Number of observations	*census_blocks*[a]	*price* mean (min-max)[b]	*living_sqft* mean (min-max)	*lot_acres* mean (min-max)	*age* mean (min-max)
Durham, NC	30,592	185	237,691 (27,847-1,698,562)	2,090 (540-10,340)	0.35 (0.02-20.04)	21 (0-258)
Phoenix, AZ	250,726	2260	203,357 (20,050-3,743,675)	2,056 (500-14,042)	0.22 (0.02-13.49)	16.72 (0-122)
Fresno, CA[c]	50,659	403	207,263 (25,187-2,355,814)	1,901 (504-10,102)	0.22 (0.01-19.66)	. .
Tampa, FL	145,420	1099	164,980 (11,912-3,200,000)	1,869 (500-11,382)	0.25 (0.02-18.99)	24 (0-125)
New Bedford, MA	6,343	128	241,387 (42,697-1,862,814)	1,548 (538-9,038)	0.34 (0.02-18.68)	60 (0-289)
Portland, ME	1,373	145	248,659 (63,715-992,094)	1,678 (502-7,544)	0.49 (0.05-12.6)	55 (0-253)
Patterson, NJ[c]	5,396	106	257,533 (37,065- 772,607)	2,026 (528-6,116)	0.09 (0.01-0.8)	. .
Portland, OR	152,362	930	293,394 (41,752-2,617,822)	1,921 (500-11,269)	0.19 (0.02-18.73)	38 (0-155)
Pittsburgh, PA	75,894	1060	151,959 (18,570-1,915,400)	1,678 (500-12,824)	0.31 (0.01-19.01)	59 (0-214)
Milwaukee, WI	40,466	1148	168,692 (19,530 -1,449,786)	1501 (512-11,009)	0.26 (0.02-14)	54 (0-177)

[a] Column label definitions are as follows: *census_blocks*=Number of census block groups in each city, *price*=Sale price of property (converted to $2010 using the seasonally-adjusted quarterly HPI index from the Federal Housing Finance agency), *living_sqft*=Size of living area of house (ft^2), *lot_acres*=Lot size (acres) and *age*=Age of housing property (years).

[b] The range of the variables are given in the parenthesis

[c] For these cities, age information of residential properties were not available.

while about 70 percent of Phoenix (AZ) are covered by shrublands. Water bodies cover about 25 percent of the cities in east coast (Portland, ME and Tampa, FL). These variations in land cover types are expected to affect the property values differently across the study areas.

We used these GIS land cover data layers to calculate the relative abundance of tree cover and other land cover types in the vicinity of each residential property in the study areas. Previous literature provide evidence for significant effects of land cover types in the neighborhood of property on its sale value, however the findings are not consistent on the size of the neighborhood within which these land cover types affect the property value. We used 3 buffer distances to define 3 neighborhoods around each residential property[14]. These include the buffer areas within 0-100m, 101-500m and 501-1000m around each property. We specify that these neighborhoods respectively represent the tree cover on property, tree cover within the walking distance from property and tree cover in the general area where people drive to work. We calculated the percent of each land cover category within each of these buffer areas around each property.

Figure 3.2 presents the summary of the tree cover and impervious surface variables created for the three neighborhoods in each city (See Appendix 3.C for summary statistics of other environmental amenity variables). Relative abundance of tree cover and impervious surface within these neighborhoods varies across the urban communities as suggested by the differences in overall land

[14] Buffer distances are specified based on the definitions of the neighborhoods in previous hedonic literature and the significance of the amenities within these buffers to influence property values. Most of the previous hedonic studies considered buffer distance up to 1km. Cho et al (2010) found significant effects of tree cover even at 5 km radius neighborhood. Calculating zonal statistics of GIS data to create these variables is time-consuming and sample size for several of our cities is large. Therefore, we considered neighborhoods only up to 1 km. The decision of this threshold buffer distance was also determined by availability of EnviroAtlas GIS data to calculate land cover type variables at each property. When land cover data was not available for a property within the buffer considered, we excluded that property from the analysis. We performed this exercise to assess how the sample size changes with the buffer distance. For our study locations, more than 90 percent of property locations had adequate GIS data within 1km buffer.

cover types discussed above. It is noted that tree cover and impervious surface also vary across the neighborhoods within each community. For example, in most of the cities in the East Coast (eg. Durham (NC), Portland (ME) and Pittsburgh (PA)) that are highly forested, percent of tree cover exceeds 40 percent of the area at all neighborhood levels. However, tree cover levels vary across the 3 neighborhoods in these cities. In Durham (NC) and Pittsburgh (PA) tree cover is the lowest in the immediate vicinity of residential property (within 100m) and tree cover increases with the distance from house indicating that on average property owners in these cities prefer more tree cover in public lands than having them in their own property. In contrast, in the cities of Fresno (CA) and Phoenix (AZ) where the overall tree cover is less abundant, more trees are maintained in the immediate vicinity of the properties. This variation in the distribution of tree cover with the distance from residential properties within and across the cities allows capturing the differential effects of trees on property value.

3.4 Empirical model

Price equation specified below was estimated separately for each market. The dependent variable of the model is the log value of the sale price of each property (in $2010) and specified as a function of property characteristics (structural characteristics and tree cover) and neighborhood characteristics (neighborhood amenities and location characteristics).

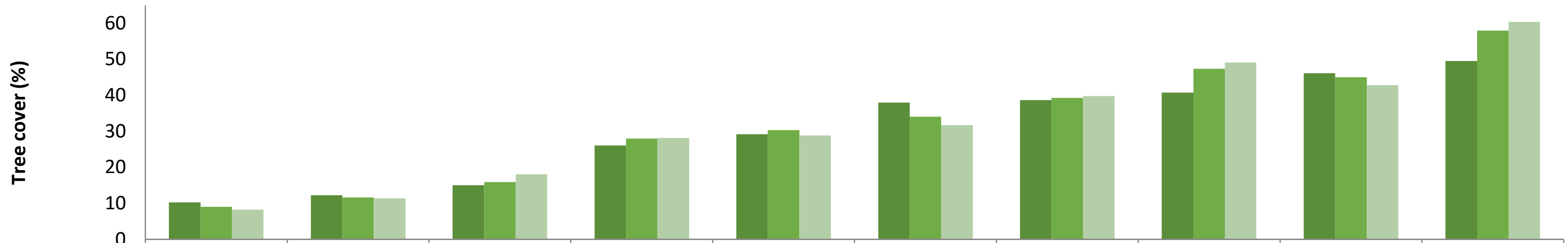
$$\begin{aligned}\ln(saleprice) = \beta_0 + \sum_{h=1}^{6} \delta_h H_h + \sum_{d=1}^{3} (\beta_{1d} treecover_d + \beta_{2d} treecoversq_d) \\ + \sum_{m=1}^{9} (\gamma_{1dm} ENV_{dm} + \gamma_{2dm} ENVsq_{dm}) + \sigma_j sale\_year_j + \rho_k block_k + \epsilon \qquad (3.7)\end{aligned}$$

where *H* is a vector of structural attributes of each property, $treecover_d$ and $treecoversq_d$ are vectors of the linear and squared percent of tree cover within the three neighborhoods, $ENVd_m$ and $ENVsqd_m$ *vectors* respectively are linear and squared environmental amenities, and $sale\_year_j$ and $block_k$ are vector containing the fixed effects for the sale year of property and census block group to which the property belongs to.

Structural characteristics of houses include the size of living area, lot size and the age of property at the time of sale. Each of these attributes is expected to have positive but diminishing effects on the sale value of the property (Saphores and Li, 2012; Price et al, 2010). Therefore, squared size of living area, squared lot size and squared age of property were included in the model.

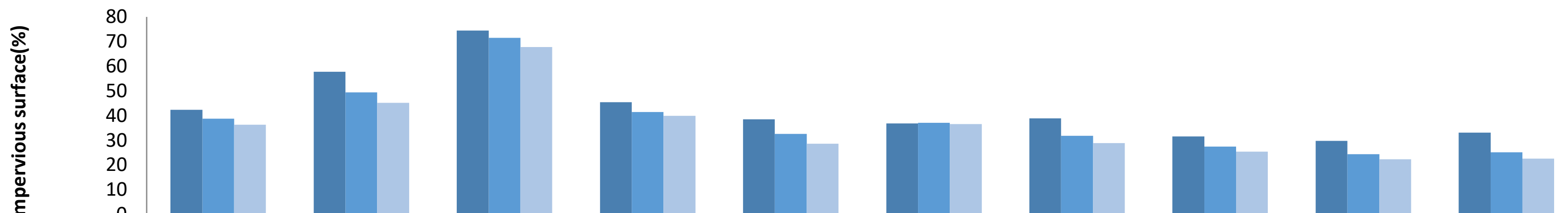
Relative abundance of tree cover within the buffers of 0-100m, 101-500m, 501-1000m for each housing property was included in the model and is represented by the vector $treecover_d$ (d=3). Property prices and tree cover are found to have non-linear relationship (Netusil et al., 2010; Stetler et al., 2010; Sander et al., 2010) thus a quadratic functional form was specified with squared percent of tree cover ($treecoversq_d$) within these buffers. We hypothesize that home owner's preference for tree cover may differ across the immediate and distant neighborhoods of the property.

Omitted relevant variables such as "neighborhood amenities" are more likely to be correlated with the tree cover resulting in biased first-stage coefficient estimates. Quasi-experiment estimators (Kuminoff et al., 2010b) are recommended but such a setting is not available for our study as our data only consists of one observation of tree cover during the multiple years of study period. Therefore, we included as many as relevant neighborhood variables and spatial fixed effects at census block level to control for unobserved heterogeneity in our model.



	Phoenix (AZ)	Fresno (CA)	Patterson (NJ)	Portland (OR)	New Bedford (MA)	Milwaukee (WI)	Tampa (FL)	Pittsburgh (PA)	Portland (ME)	Durham (NC)
100m	10.28	12.31	15.04	26.08	29.26	38.01	38.71	40.78	46.13	49.57
101-500m	9.10	11.71	15.96	27.99	30.32	34.08	39.33	47.42	45.02	58.02
501-1000m	8.27	11.37	18.11	28.22	28.86	31.76	39.80	49.15	42.82	60.45

(a) Percentage of tree cover



	Phoenix (AZ)	Fresno (CA)	Patterson (NJ)	Portland (OR)	New Bedford (MA)	Milwaukee (WI)	Tampa (FL)	Pittsburgh (PA)	Portland (ME)	Durham (NC)
100m	42.37	57.74	74.52	45.43	38.51	36.86	38.91	31.53	29.79	33.19
101-500m	38.84	49.45	71.55	41.49	32.67	37.17	31.89	27.44	24.44	25.11
501-1000m	36.36	45.16	67.80	39.97	28.66	36.64	28.93	25.49	22.31	22.60

(b) Percentage of impervious surface

Figure 3.2 Percentage of tree cover and impervious surface within 0-100m, 101-500m and 501-1000m buffers in each city

The first set of relevant variables includes the tree cover at distant neighborhoods of each property described above. In this study, our objective is to estimate the households' preference for tree cover within the nearest neighborhood of each housing property (0-100m in this case). However, sale value of property may be influenced by the trees at distance as households may prefer trees for their aesthetic value or appreciate trees as public goods rather than private goods. Excluding the tree cover at the distant buffers of 101-500m or 501-1000m in the regression model may results in biased estimates for tree cover within 100m.

The second set of variables is the amenities in the surrounding neighborhoods (ENV_m and $ENVsq_{m)}$ which may affect the property values. For example, price of properties in the close proximity to the city centers, roads or retail settings may be high while having agricultural fields in the neighborhood may reduce the property value (Cho et al, 2011). To capture these effects, we included in the model the neighborhood amenities variables such as percent of impervious surface, agricultural lands and water bodies that we created using the land cover data set explained above. Similar to the tree cover variables, we expect these neighborhood variables at different distance from property to have different and non-linear effects on property value. Therefore, linear and quadratic terms of these variables within the three neighborhoods were considered.

Also, we applied spatial fixed effects at census block level to control for the unobserved heterogeneity[15]. If the unobservable variables are constant across all observations within a census block,

[15] Spatial fixed effects have been widely used in hedonic property models to value open space amenities. These include Census tracts/blocks (Kuminoff et al. 2010b; Tuttle and Heintzelman,2015; Pope, 2008b), School districts (McMillen, 2010), Subdivisions (Abbott and Kaliber, 2011), City /county/Municipality (Kovacs et al., 2011), and Horsch and Lewis (2009), Submarkets: Sander and Polasky (2009), and Tax districts (Pope, 2008b). When the spatial fixed effects areas are large (eg. tax district dummies) the marginal price is overstated. When the fixed effect areas are smaller (eg. census tracts or blocks), the estimates begin to converge towards the quasi-random experiment estimates (Pope, 2008b).

and vary among observations across different census block, the fixed effects of the census block will control for the effects of the missing variables (Palmquist, 2005; Kuminoff, Parmeter and Pope, 2009; McMillen, 2010; Abbott and Klaiber, 2010). In addition, dummy variables for the sale years (base case is 2005) were included to capture the time trends. All the variables included in the hedonic model and their descriptions are given in Table 3.2 below.

3.5 Results

3.5.1 Results for first-stage estimation

Summary of the first-stage estimation for tree cover variables in the study areas and marginal implicit price estimates are given in Table 3.3[16]. Most of the coefficient estimates are significant at 10 percent level and suggest that tree cover is a significant factor that determines the sale values of properties in all the housing markets we studied. Further they confirm the non-linear relationship between the tree cover and property sale values. First stage estimates however vary across the cities and across the neighborhoods of the properties, indicating distinct characteristics of these markets. These differences are explained using the marginal implicit price estimates in Table 3.2 that were calculated using the first-stage coefficients.

[16] Here we do not report the results for the house attributes and other neighborhood variables. Most of these variables are significant at 10 percent level and indicate having non-linear relationship with property price. Living area and lot size have significant and positive but diminishing effects on the house price while age of house has negative and increasing effects. The qualitative results for the house attributes are consistent across the cities. However, the results indicate that the marginal effects of neighborhood amenities differ across the neighborhoods and across the cities, as expected. The coefficient estimates for these variables are given in Appendix 3D.

Table 3.2. Variables and variable descriptions used in the hedonic models

	Variable	Variable description
Property characteristics	*saleprice*	Sale price of property ($2010) (Sale prices are converted to $2010 values using the HPI index - seasonally adjusted quarterly price indices-from Federal Housing Finance agency)
	lnP	Log value of *saleprice*
	living	Size of living area (ft^2)
	livingsq	Squared size of living area
	lotsize	Lot size (acres)
	lotsq	Squared lot size
	age	Age of house at the time of sale (years)
	agesq	Squared age of house
Land cover types variables	*treecover1*	% tree cover within 0-100m buffer
	treecover2	% tree cover within 101-500m buffer
	treecover3	% tree cover within 501-1000m buffer
	treecover1sq	squared % tree cover within 0-100m buffer
	treecover2sq	squared % tree cover within 101-500m buffer
	treecover3sq	squared % tree cover within 501-1000m buffer
	water1	% water bodies within 0-100m buffer
	water2	% water bodies within 101-500m buffer
	water3	% water bodies within 501-1000m buffer
	water1sq	squared % water bodies within 0-100m buffer
	water2sq	squared % water bodies within 101-500m buffer
	water3sq	squared % water bodies within 501-1000m buffer
	impervious1	% impervious surface within 0-100m buffer
	impervious2	% impervious surface within 101-500m buffer
	impervious3	% impervious surface within 501-1000m buffer
	impervious1sq	squared % impervious surface within 0-100m buffer
	impervious2sq	squared % impervious surface within 101-500m buffer
	impervious3sq	squared % impervious surface within 501-1000m buffer
	grass1	% grass and herbaceous lands within 0-100m buffer
	grass2	% grass and herbaceous lands within 101-500m buffer
	grass3	% grass and herbaceous lands within 501-1000m buffer
	grass1sq	squared % grass and herbaceous lands within 0-100m buffer
	grass2sq	squared % grass and herbaceous lands within 101-500m buffer
	grass3sq	squared % grass and herbaceous lands within 501-1000m buffer
	agriculture1	% agricultural lands within 0-100m buffer
	agriculture2	% agricultural lands within 101-500m buffer
	agriculture3	% agricultural lands within 501-1000m buffer
	agriculture1sq	squared % agricultural lands within 0-100m buffer
	agriculture2sq	squared % agricultural lands within 101-500m buffer
	agriculture3sq	squared % agricultural lands within 501-1000m buffer

Table 3.2. Variables and variable descriptions used in the hedonic models *contd.*

	Variable	Variable description
Land cover types variables	*wetland11*	% woody wetlands within 0-100m buffer
	wetland12	% woody wetlands within 101-500m buffer
	wetland13	% woody wetlands within 501-1000m buffer
	wetland11sq	squared % woody wetlands within 0-100m buffer
	wetland12sq	squared % woody wetlands within 101-500m buffer
	wetland13sq	squared % woody wetlands within 501-1000m buffer
	wetland21	% emergent wetlands within 0-100m buffer
	wetland22	% emergent wetlands within 101-500m buffer
	wetland23	% emergent wetlands within 501-1000m buffer
	wetland21sq	squared % emergent wetlands within 0-100m buffer
	wetland22sq	squared % emergent wetlands within 101-500m buffer
	wetland23sq	squared % emergent wetlands within 501-1000m buffer
	shrub1	% shrub lands within 0-100m buffer
	shrub2	% shrub lands within 101-500m buffer
	shrub3	% shrub lands within 501-1000m buffer
	shrub1sq	squared % shrub lands within 0-100m buffer
	shrub2sq	squared % shrub lands within 101-500m buffer
	shrub3sq	squared % shrub lands within 501-1000m buffer
	orchard1	% orchards within 0-100m buffer
	orchard1sq	% orchards within 101-500m buffer
	orchard2	% orchards within 501-1000m buffer
	orchard2sq	squared % orchards within 0-100m buffer
	orchard3	squared % orchards within 101-500m buffer
	orchard3sq	squared % orchards within 501-1000m buffer
Fixed effects	*yr2005*	yr2005=1 if sale year==2005, else zero
	yr2006	yr2006=1 if sale year==2006, else zero
	yr2007	yr2007=1 if sale year==2007, else zero
	yr2008	yr2008=1 if sale year==2008, else zero
	yr2009	yr2009=1 if sale year==2009, else zero
	yr2010	yr20010=1 if sale year==2010, else zero
	yr2011	yr2011=1 if sale year==2011, else zero
	yr2012	yr2012=1 if sale year==2012, else zero
	yr2013	yr2013=1 if sale year==2013, else zero
	yr2014	yr2014=1 if sale year==2014, else zero
	block	Dummy variables indicating the block in where the house is located

Implicit price estimates for tree cover within the three neighborhoods are positive in most cases suggesting that home owners in urban areas consider tree cover is an amenity. Two exceptions are noted; increasing tree cover within 100m and 101-501m buffers in Fresno (CA) and within 100m in Portland (ME) causes the property price to decline. In cities where tree cover adds value to the housing properties, increasing tree cover by 1 percent within 100m, 101-500m and 501-1000m respectively increases the average property values by $5543, $7892 and $8770 respectively. Each of these marginal increases respectively attribute to about 2.5, 3.3 and 4 percent of the average sale price in these markets.

In Phoenix (AZ) and Tampa (FL), property values increase consistently with the distance where level of tree cover is expected to increase. In both the communities, home owners consider trees as an amenity; however, they prefer to have more trees in neighboring lands than in their own property. This provides evidence for home owner's tendency to free-ride on their neighbors to maintain greater tree cover that provides external benefits and tendency to avoid tree planting and maintenance costs. For example, Phoenix (AZ) is located in Southwestern of US which has a subtropical desert climate with long, extremely hot summers and short, mild to warm winters. The landscape consists of relatively less tree cover compared to the impervious surface and current tree cover levels within and in vicinity of the residential properties are the lowest among the communities we studied. Therefore, more trees are preferred to improve the microclimate and aesthetics. As expected, results from the hedonic model show home owners prefer trees in all the neighborhoods in this community; however, trees located in greater distance from houses are more preferred. Further, the results revealed that property values increase by 1.1 percent when the tree cover within the 101-500m increases by one unit; when tree cover is increased within the 501-1000m area, the property prices increase by 4.9 percent. These benefits can be maximized if the tree cover in the immediate neighborhood and beyond is doubled.

In Pittsburgh (PA) and Durham (NC) we found that tree cover in distant neighborhoods add more value to the property while tree cover within 100m does not significantly affect the property values. This may be because these communities are located in highly-forested areas, thus home owners are indifferent on the private benefits provided from tree cover on their property, but they receive ecosystem benefits from trees in distant locations such as aesthetic landscapes.

Table 3.3. Coefficient estimates from the first-stage model and marginal implicit price of tree cover by city

	Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
Coefficient estimates	treecover1	-0.0001[a]	0.0020***	-0.0018**	-0.0024***	0.0216***	-0.023***	0.0174	0.0418***	0.0023	0.0506***
		(0.0005)[b]	(0.0006)	(0.0008)	(0.0004)	(0.004)	(0.004)	(0.0113)	(0.0037)	(0.0021)	(0.007)
	treecover1sq	4.6E-05***	0.0001***	0.0001**	0.00004***	2.8E-05***	3.4E-05	0.0002***	3.9E-06	1.9E-05***	2.05E-05***
		(5.2E-06)	(1.8E-05)	(2.3E-05)	(3.1E-06)	(1.4E-05)	(3.6E-05)	(0.0001)	(3.2E-06)	(5.7E-06)	(5.6E-06)
	treecover2	0.0329***	0.0204***	-0.0105***	0.0210***	0.085***	0.065**	0.0241**	0.0518***	0.0181***	0.026***
		(0.0019)	(0.0013)	(0.0015)	(0.0012)	(0.004)	(0.011)	(0.0119)	(0.0041)	(0.0084)	(0.004)
	treecover2sq	-0.0001***	-0.0005***	0.0004***	-5.5E-06	-8.9E-05***	-0.0001**	0.0002	9.2E-06**	-0.0001***	-5.3E-05
		(1.5E-05)	(4.2E-05)	(4.7E-05)	(5.9E-06)	(2.8E-05)	(5.2E-05)	(0.0002)	(4.8E-06)	(1.3E-05)	(1.2E-05)
	treecover3	0.1519***	0.1045***	0.0210***	0.0546**	0.014***	0.096***	0.0050	0.0255***	0.0281*	0.029***
		(0.0025)	(0.0031)	(0.0061)	(0.0023)	(0.004)	(0.011)	(0.0232)	(0.0019)	(0.0156)	(0.004)
	treecover3sq	-0.0007***	-0.0033***	-0.0006***	0.0001**	-1.2E-05	-0.0001***	0.0005	-9.4E-06**	-7.8E-06	2.3E-05
		(2.2E-05)	(0.0001)	(0.0002)	(8.6E-06)	(3.9E-05)	(5.3E-05)	(0.0004)	(3.8E-06)	(3.2E-05)	(1.9E-05)
Average marginal implicit price ($)	IP_100m	NA	822.38	-102.58	145.36	5608.73	-5788.93	NA	12335.68	NA	8805.95
			[0.4]	[-0.05]	[0.09]	[2.3]	[-2.3]		[4.2]		[5.2]
	IP_500m	5072.37	2302.58	-238.09	3472.12	19149.11	13916.22	6196.81	15345.09	1312.78	4260.07
		[2.1]	[1.1]	[-0.1]	[2.1]	[7.9]	[5.6]	[2.4]	[5.2]	[0.9]	[2.2]
	IP_1000m	16122.74	10071.68	1374.51	10488.88	3393.53	20991.42	NA	7338.09	4270.41	4878.35
		[6.8]	[4.9]	[0.7]	[6.4]	[1.4]	[8.4]		[2.5]	[2.8]	[2.9]
	No. of Observations	30,592	250,726	50,659	145,420	6,343	1,373	5,396	152,362	75,894	40,466

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are in parenthesis, and marginal implicit price as a percent of house price are in brackets.
NA indicates that marginal implicit values were not calculated as the coefficient estimates in Table 3.3 were not significant.

In most of the cities, benefits provided to private land owners from trees increases consistently with the distant to tree cover from houses. However, this pattern is not observed in New Bedford (MA) and Portland (OR). In these cities, tree cover within 0-100m and 101-500m buffer areas are more valued by home owners than the trees beyond 500m. This may be because; these two cities are among the densely-populated communities where residential properties are located on smaller lots. Home owners may prefer to have more trees at close distance for shade, privacy and aesthetic benefits. Similar factors may lead to the significant effects of tree cover within 100-500m in Paterson (NJ).

Comparison of the marginal price effects of tree cover across the buffer distances in the city of Portland (ME) revealed that increased levels of tree cover within 100m of properties reduces the property value while an increase of tree cover beyond 100m brings greater appreciation of property values. This implies that home owners in this community would not like to have more trees on their properties as they are more likely to avoid the cost of maintaining trees, and rather would like to enjoy trees in neighboring lands as a public good.

Fresno (CA) is located in semi-arid region in the U.S. where water resources are limited and efficient water use is encouraged in managing vegetation in residential landscapes. Current level of tree cover is relatively low, thus increasing trees is expected to increase property values. However, we found that home owners do not prefer increasing tree cover within 0-100mand 100-500m but the tree cover beyond 500m is highly valued. This may be attributed to home owners' incentives to avoid costs of watering trees in their property while receiving external benefits from trees maintained in public lands.

3.5.2. Internal meta-analysis

The hedonic model suggests that the preferences for tree cover have a spatial variation within and across study locations. This implies that property value impacts may vary across cities based on various sources of observed and unobserved heterogeneity including tree cover and other neighborhood amenities, geographic factors and socio-demographic factors of property owners. In order to examine what the results from various study locations collectively imply about the estimates tree cover, an internal meta-analysis was performed. Specifically, we assessed what is the relationship between the estimated implicit prices of tree cover in each buffer area with the quantity of tree cover in the respective buffer and other location and socio demographic factors.

We used property- level estimates of implicit price for tree cover in the three buffer areas in the meta-analysis. These values were calculated using the coefficient estimates for tree cover in Table 3.3, quantities of tree cover in each property within each buffer area and sale price of properties. We used observations from 10 cities, thus, altogether, 759234 observations were used in the analysis. Table 3.4 shows the number of positive and negative observations provided by each study location for each buffer area. Several cities provided positive implicit price observations only; some provided negative implicit prices only; others provided both positive and negative observations. Therefore, we estimated a Heckman selection model (Heckman, 1979) for each buffer area to check if a set of study locations affect the results of the meta-equation.

Table 3.4. Number of positive and negative implicit price observations for each buffer area by city

City	0-100m buffer		101-500m buffer		501-1000m buffer	
	POS [a]	NEG	POS	NEG	POS	NEG
Durham (NC)	30,385	207	30,592	0	30,592	0
Phoenix (AZ)	250,726	0	226,768	23,958	226,250	24,475
Fresno (CA)	16,269	34,390	25,658	25,001	41,845	8,814
Tampa (FL)	103,799	41,621	145,420	0	145,420	0
New Bedford (MA)	6,343	0	6,343	0	6,343	0
Portland (ME)	0	1,377	0	1,377	0	1,377
Patterson (NJ)	5,396	0	5,396	0	5,396	0
Portland (OR)	152,362	0	152,362	0	152,362	0
Pittsburgh (PA)	75,894	0	75,894	0	75,894	0
Milwaukee (WI)	40,466	0	40,466	0	40,466	0

[a] Column label definitions are as follows: POS = Positive implicit value of tree cover within the buffer area, NEG= Negative implicit value of tree cover within the buffer area

The Heckman selection model consists of two equations: selection equation and meta-equation. The selection equation defines the probability of observing positive implicit price (versus negative) as a function of study characteristics, study location characteristics and socio-demographic variables as follows.

$$\Pr(IP_d > 0) = \theta_0 + \sum \theta_{1k}\boldsymbol{y_k} + \theta_3 eastern + \theta_4 pacificnw + \vartheta \quad (3.8a)$$

where IP_d is the implicit price of tree cover within the d^{th} buffer area (d=3), *eastern* and *pacificnw* are two dummy variables indicating the regional location of study area, $\boldsymbol{y_k}$ is a vector of socio-demographic characteristics of home owners that may affect perceiving trees as an amenity or a disamenity. The meta-equation is specified for positive implicit price observations as follows.

$$IP_d^+ = \gamma_0 + \gamma_1 treecoverd + \gamma_2 treecoverdsq + \gamma_3 saleprice + \gamma_4 signif + \gamma_5 eastern$$

$$+\gamma_6 pacificnw + \sum \gamma_{7k}\boldsymbol{y_k} + \omega \quad (3.8b)$$

The dependent variable (effect size) is the implicit price of tree cover within the d^{th} buffer area. This equation specifies the magnitude of positive implicit price as a function of study characteristics, study location characteristics and socio-demographic variables. Linear and squared quantity of tree cover in d^{th} buffer area (*treecoverd* and *treecoverdsq)* are included in the meta-equation to allow for non-linear relationship between the implicit value and tree cover; sale value of properties is included to see if implicit value of tree cover is effected by selling price. All implicit price estimates, statistically significant and insignificant, were included in the meta-analysis. In order to see if the significance of implicit price in original studies affect the magnitude of implicit price, a variable (*signif*) is included in the meta-equation.

Two dummy variables indicating the regional location of the cities were used to control for spatial heterogeneity in broader area. These include the variable *east*ern which is equal to 1 if the city is located in the eastern U.S. and *pacificnw* which is equal to 1 if the city is located in the Pacific North West. There are 6 cities in the Eastern U.S. and 2 cities in the West Coast. The others include Phoenix (AZ) located in Southwestern U.S. and Milwaukee (WI) in Midwestern U.S. Additionally; a suite of census-block level socio-demographic variables (U.S. Census, 2010) were included to assess how these variables affect the implicit price of tree cover. These variables median household income ($2010), median age of households (years), percent of people of 25 years and older with bachelor’s degree or higher, population density in the census block (persons/mile2), average family size, and percent of houses vacant in the census block group in which the residential property is located. Summary statistics of the variable used in the meta-analysis are given in Table 3.5.

Table 3.5. Summary statistics of variables for positive and negative implicit price observations

Variable	0-100m buffer		101-500m buffer		501-1000m buffer	
	POS [a]	NEG	POS	NEG	POS	NEG
Dependent variable in selection equation						
amenity [b]	0.90	.	0.94	.	0.96	.
Dependent variable in meta-equation						
IP_100m [c]	3,871.07	-270.62	.	.	.	.
IP_500m	.	.	5,658.09	-1349.90	.	.
IP_1000m	.	.	.	.	8,661.62	-3,192.61
Independent variables						
treecover1	26.75	13.52	.	.	.	.
treecover2	.	.	27.24	12.39	.	.
treecover3	.	.	.	.	26.61	18.62
saleprice	$212,756	$18,1080	$206,955	$246,718	$208,174	$238,845
medincome	$69,478	$64,071	$68,083	$81,154	$68,483	$78,589
popdensity	4,431.94	3,586.11	4,372.86	3,948.51	4,329.40	4,696.62
medage	38.33	36.68	38.34	35.53	38.08	39.78
avefam	3.14	3.30	3.14	3.39	3.16	3.11
edu	36.51	27.89	35.45	38.27	35.37	41.44
vacant_rate	8.37	10.75	8.67	7.89	8.69	7.07
eastern	0.17	0.02	0.17	0.00	0.16	0.00
pacificnw	0.25	0.44	0.25	0.51	0.27	0.26
signif	0.84	1.00	0.84	1.00	0.85	1.00
No. of observations	681,640	77,595	710,276	48,959	725,945	33,289

[a] Column label definitions are as follows: POS = Positive implicit value of tree cover within the buffer area, NEG= Negative implicit value of tree cover within the buffer area.

[b] *amenity=1 if the implicit price is positive, else zero*

[c] *IP_100m= implicit price of tree cover within 0-100m buffer area; IP_500m= implicit price of tree cover within 101-500m buffer area; IP_1000m= implicit price of tree cover within 501-1000m buffer area.*

The selection equation (3.8a) and the meta-equation (3.8b) are jointly estimated (Wooldridge, 2002), and the following test was conducted to check for the selection effects of only using positive observations in the estimation of equation (3.8b).

$$H_o\!: \rho = 0 \;\; vs \; H_a\!: \rho \neq 0 \qquad (3.9)$$

where ρ is the correlation between the error terms in selection and meta equations (ϑ and ω, respectively). If the null hypothesis is rejected, then the selection and meta equations should be estimated jointly; if the null hypothesis cannot be rejected, then the meta-equation can solely be estimated.

3.5.2.1. Results for selection equation

Equations (3.8a and 3.8b) were estimated for tree cover in each buffer area (Model (1), (3) and (5)), and the results concluded that the null hypothesis of no correlation could not be rejected (p=0.00) in any of these models. Therefore, the meta-analysis was performed with joint estimation of the selection equation and the meta-equation. This exercise was repeated for each buffer, but now specifying the meta-equation solely for negative observations (Model (2), (4) and (6)).

Results for the selection equations are reported in Table 3.6. Model (1) specifies the probability of observing a positive implicit price for the tree cover within 0-100m buffer area while Model (2) evaluates the probability of observing negative implicit price for the tree cover in this buffer. The results indicate significant selection effects in these models (p value=0.00), and the socio-demographic variable and region variables significantly affect perceiving trees within 0-100m buffer as an amenity or a disamenity. In locations where implicit price of tree cover in this buffer is positive (Model (1)), the probability of perceiving trees as an amenity decreases when median income, average family size and vacancy rate increases. In contrast, probability of perceiving trees as an amenity in these locations increases when median age of households and education attainment increases. Further, tree cover within 0-100m area is less preferred in the study locations in Eastern and Pacific North West of U.S. compared to other regions where the overall tree cover is low, thus more tree cover on property would increase benefits to home owners. Socio-economics variables have opposite effects in perceiving trees as a disamenity except for median income and median age of households, per the results in Model (2). Moreover, this model suggests that probability of perceiving trees as a disamenity is low in the study locations in the Eastern U.S and high in the Pacific North West compared to other regions.

Model (3) and Model (4) respectively assess the effects of socio-demographic and region variables on observing positive and negative implicit prices of tree cover within 101-500m buffer area. Model (5) and Model (6) considers tree cover within 501-1000m buffer area. Results for most of the socio-economic variables in these models are qualitatively similar to those for the tree cover in 0-100m buffer. However, comparison of the results across the buffers suggests that the region variables have different effects on the valuation of tree cover in the three buffer areas. For example, in the eastern region, home owners are more likely to consider trees in 101-500m and 501-1000m buffers as an amenity compared to trees in 0-100m buffer. In Pacific North West, trees within 0-100m and 101-500m are more likely to considered as a disamenity compared to trees within 501-1000m.

3.5.2.2. Results for meta-equation

Table 3.7 shows the results for the meta-equations. All the tree cover variables we considered in these models are statistically significant at 1 percent level and confirms the non-linear relationship between the implicit price and quantity of tree cover. Magnitude of positive and negative implicit prices increase when tree cover within 0-100m and 101-500m increases until up to a threshold level, and then decrease from their maximum value. In contrast, increasing tree cover within 501-1000m decreases the implicit values. Various reasons could explain these results. For example, home owners may prefer trees within 0-100m buffer for shade and privacy, but too much trees may block sunlight and obscure vistas;

they may prefer trees in walking distance of 101-500m buffer area and distant locations for aesthetic landscapes, but too much trees may attract invasive pest species.

In locations where trees are considered an amenity (Model (1), (3), (5)), sale price of property and value of tree cover have a positive relationship. Preference for tree cover decreases when median income and average family size increase. More educated home owners living in densely populated areas prefer trees. In locations where trees are considered a disamenity (Model (2), (4), (6)), sale value of property and average family size decreases the magnitude of negative implicit prices while median income, population density and education level of households increases the negative implicit prices. These results confirm that socio-demographic variables have a differential effect on the home owners' preference for tree cover in different locations.

Using results from above models, we calculated the amount of tree cover in the three buffer areas that optimize the benefits to home owners. We found these optimal levels to be 50 percent of tree cover within 100m, 45 of percent tree cover within 101-500m and 24 percent of tree cover within 501-1000m in the locations where trees are considered an amenity. In these locations, home owners prefer to have more tree cover within 0-100m distance (50 percent) compared to that of 101-500m (45 percent). These optimal levels are comparatively higher than the current tree cover levels (26.75 and 27.24 percent respectively). This suggest that home owners underinvest in tree cover on property, and there is much potential to increase the tree cover in private properties to obtain maximum benefits. It is noted that increasing tree cover in distant locations within 501-1000m buffer area decreases benefits to home owners and the benefits reach a minimum at 24 percent of tree cover. For other study locations where trees are considered a disamenity, increasing tree cover increases the magnitude of negative implicit price, and the optimal tree cover levels are 25, 14 and 23 percent respectively for the immediate and distant buffers. The results highlight the heterogeneous preference of home owners for tree cover in different locations in the urban landscape.

Table 3.6. Results of selection equation for positive and negative implicit price observations for three buffers

	0-100m buffer		101-500m buffer		501-1000m buffer	
	POS [a]	NEG	POS	NEG	POS	NEG
Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
medincome	-1.2E-06***[b]	-7.3E-07***	-3.9E-06***	4.7E-06***	3.3E-06***	2.7E-06***
	(1.2E-07) [c]	(1.2E-07)	(1.4E-07)	(1.4E-07)	(2.0E-07)	(1.6E-07)
popdensity	1.1E-04***	-9.4E-05***	2.6E-05***	-2.1E-05***	-6.8E-05***	6.9E-05***
	(9.5E-07)	(1.0E-06)	(8.9E-07)	(9.1E-07)	(8.0E-07)	(8.8E-07)
medage	0.01***	0.0011***	-0.0040***	0.01***	-0.01***	0.01***
	(0.0003)	(0.0002)	(0.0007)	(0.0006)	(0.0004)	(0.0005)
avefam	-0.05***	0.21***	-0.71***	0.89***	0.13***	-0.08***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
edu	0.02***	-0.01***	-0.0046***	0.01***	-0.0020***	0.01***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0002)
vacant_rate	-0.02***	0.0036***	-0.0048***	0.01***	0.04***	-0.03***
	(0.0004)	(0.0004)	(0.0006)	(0.0005)	(0.0008)	(0.0009)
eastern	-0.13***	-1.18***	8.05***	-5.89***	8.02***	-8.17***
	(0.01)	(0.07)	(0.12)	(0.01)	(0.07)	(0.05)
pacificnw	-1.05***	0.12***	-0.83***	0.50***	0.65***	-0.58***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
intercept	0.11***	-1.30***	4.55***	-5.57***	0.98***	-2.27***
	(0.04	(0.02)	(0.06)	(0.06)	(0.05)	(0.05)
rho	0.84***	-0.98***	0.39***	0.29***	0.81***	0.84***
	(0.0039)	(0.0003)	(0.01)	(0.04)	(0.0047)	(0.01)
$\chi(1)$	8259.49	809.41	4504.07	60.18	6774.43	2357.54
p value	0.00	0.00	0.00	0.00	0.00	0.00

[a] Column label definitions are as follows: POS = Positive implicit value of tree cover within the buffer area, NEG= Negative implicit value of tree cover within the buffer area.

[b] Triple asterisks indicate significance at 1 percent level.

[c] Robust standard errors are in parenthesis, and marginal implicit price as a percent of house price are in brackets.

Table 3.7. Results of meta-equation for positive and negative implicit price observations

	0-100m buffer		101-500m buffer		501-1000m buffer	
	POS [a]	NEG	POS	NEG	POS	NEG
Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
treecover1	119.94*** [b]	30.12***	.	.	.	.
	(1.12) [c]	(4.65)	.	.	.	.
treecover1sq	-1.19***	-0.60***	.	.	.	.
	(0.01)	(0.15)	.	.	.	.
treecover2	.	.	266.08***	285.42***	.	.
	.	.	(0.89)	(3.81)	.	.
treecover2sq	.	.	-2.94***	-10.17***	.	.
	.	.	(0.01)	(0.17)	.	.
treecover3	.	.	.	.	-313.82***	-5650.51***
	.	.	.	.	(1.63)	(104.60)
treecover3sq	.	.	.	.	4.72***	121.38***
	.	.	.	.	(0.03)	(2.70)
saleprice10	0.02***	-0.0004***	0.04***	-0.01***	0.03***	-0.02***
	(0.0003)	(3.9E-05)	(0.0002)	(0.0002)	(0.0002)	(0.0006)
medincome	-0.02***	0.0005***	-0.03***	0.0043***	-0.0002	0.01***
	(0.0004)	(0.0001)	(0.0004)	(0.0004)	(0.0005)	(0.0015)
popdensity	0.36***	0.07***	0.21***	-0.0018	-0.29***	0.12***
	(0.0023)	(0.0028)	(0.0018)	(0.0022)	(0.0024)	(0.01)
avefam	-1086.96***	-147.02***	-307.86***	10.37	38.61**	-1228.26***
	(14.81)	(13.26)	(12.93)	(27.29)	(19.73)	(56.23)
Edu	55.62***	8.25***	20.28***	0.18	5.52***	18.73***
	(0.93)	(0.18)	(0.73)	(0.59)	(0.83)	(2.84)
Signif	3360.74***	-1402.01***	3409.35***	NA	655.87***	NA
	(16.01)	(56.96)	(17.39)		(23.89)	
intercept	-4171.71***	2021.71***	-7311.60***	-2304.13***	5538.34***	58027.26***
	(57.38)	(39.97)	(47.09)	(165.74)	(71.17)	(965.03)

[a] Column label definitions are as follows: POS = Positive implicit value of tree cover within the buffer area, NEG= Negative implicit value of tree cover within the buffer area.
[b] Double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[c] Robust standard errors are in parenthesis, and marginal implicit price as a percent of house price are in brackets.
NA indicates that marginal implicit values were not calculated as the coefficient estimates in Table 3.3 were not significant.

3.6. Conclusion

In this study estimated first-stage hedonic models in multiple study locations in the U.S. to assess how home owners in multiple property markets value tree cover as a private good or a public good by valuing tree cover in different distances from property. We found that, on average, home owners consider trees within 1km from residential properties as an amenity as trees add value to their properties. Further we found that the positive effect of trees on sale value of property varies across the study locations and the landscape within an urban community.

Exploiting the variation of implicit prices, tree cover and location characteristics, we examined what the results from multiple studied collectively imply about the value of trees in urban areas. This internal meta-analysis suggests that abundance of tree cover, regional differences and socio-demographic characteristics of home owners affect how they perceive trees as amenities or disamenities. Further it implies that the effect of these variables on the magnitude of the implicit price differ across locations where they are considered an amenity and locations where they are considered a disamenity. These findings indicate that urban planners need to adopt tree planting and management programs in urban communities in accordance with these heterogeneous preferences of home owners.

Further, the meta-analysis found that relative abundance of tree cover has a non-linear relationship with the implicit value of trees. This result is consistent with the findings in the external meta-analysis in Chapter 2 and other hedonic studies. We calculated what is the optimal level of tree cover that maximizes/minimizes benefits to property owners in terms of increased property value. For study locations where implicit prices are positive, we found that 50 percent of tree cover within 100m and 45 of percent tree cover within 101-500m maximize benefits to home owners. However, tree cover within 501-1000m decreases the implicit price of trees. These findings highlight the home owners' heterogeneous preference for tree cover across the landscape, as opposed to what is suggested in Chapter 2 which assumed home owners' preferences for tree cover are constant within 1km distance from home. This implies that urban planners might wish to consider tree planting programs, zoning policies and tax incentives to increase the overall tree cover on private properties and in nearby public lands (eg. street trees, parks) rather than tree cover located far away from residential locations. On the other hand, in study locations where trees are considered as a disamenity, increasing tree cover increases the negative implicit prices indicating that home owners in these locations may not prefer community programs that encourage planting more trees.

These findings on both the location-specific preferences and general inferences are more informative, and the knowledge from this assessment is of highly importance where urban planners are compelled to refine the goals of community forestry programs due to anticipated changes in urban systems due to climate change and urbanization. For example, changing demographics in the U.S. fuels in continuous urbanization and the suburban becoming more urbanized town centers. Between 2014 and 2060; the population age over 65 years is projected to increase from 15 percent to 24 percent of the total population and the millennials are becoming a significant part in the working force in coming years (U.S. Census, 2010). More residential developments are carried out to accommodate increasing number of young home buyers in urban areas and more development activities are carried out in walkable suburban town centers to provide amenities demanded by the older population. Along with these developments comes the reduced levels of tree cover in the residential areas, thus demand for tree cover may increases. For example, residents living in apartments in high rise buildings and smaller housing properties in congested city centers will highly value open spaces and are willing to pay premiums for residential properties with tree cover nearby. Older people in retirement are more likely to enjoy services and amenities in walkable distance and may value parks, street trees and landscape trees in the vicinity of their home for shade and view. These suggests that tree cover concerns and decision-making by property owners and community planners may become complex in future. We expect that the insights provided by our study will be useful for future urban planning and designing.

References

Abbott, J.K. and H.A. Kaliber, 2011. “An embarrassment of riches: confronting omitted variable bias ans multiscale capitalization in hedonic price models”. *The Review of Economics and Statistics*, 93(4): 1331–1342.

Anderson L.M., and H.K. Cordell, 1988. “Influence of trees on residential property-values in Athens, Georgia (USA) a survey based on actual sales prices”. *Landscape and Urban Planning*. 15 (12):153-164.

Banzhaf, H.S. and V.K. Smith, 2007. “Meta-analysis in model implementation: choice sets and the valuation of air quality improvements”. *Journal of Applied Econometrics*, 22(6):1013-1031.

Boyle, K.J., P.J. Poo, and L.O. Taylor, 1999. “Estimating the demand for protecting fresh water lakes from eutrophication”. *American Journal of Political economics*, 81(5): 1118-1122

Chattopadhyay, S., 1999. “Estimating the demand for air quality: new evidence based on the Chicago housing market”. *Land Economics*, 75(1):22-38.

Cho S.H., D. Lambert, S. Kim, R. Roberts, and W. Park, 2010. “Relationship between value of open space and distance from housing locations within a community”. *Journal of Geographical Systems*. 1-22.

Dombrow J., M. Rodriguez, C.F. Sirmans, 2000. “The market value of mature trees in single-family housing markets”. *Appraisal Journal*, 68 (1):39-43.

Donovan, G.H. and D.T. Butry, 2010. “Trees in the city: valuing street trees in Portland, Oregon.” *Landscape and Urban Planning*, 94 (2010) 77-83.

Garrod, G. and K. Willis. 1992. ‘‘The Environmental economic impact of woodland: a two-stage hedonic price model of the amenity value of forestry in Britain.’’ *Applied Economics*, 24 (7): 715-28.

Heckman, J.J. 1979. “Sample selection bias as a specification error.” *Econometrica*, 47 (1): 153-161.

Holmes T. P., E. A. Murphy, K. P. Bell., D.D. Royle, 2010. “Property value impacts of Hemlock woolly adelgid in residential forests”. *Forest Science*, 56(2):529-540.

Irwin E.G. 2002. “The effects of open space on residential property values”. *Land Economics*, 78(4):465-480.

Klemick, H., C. Griffiths, D. Guignet and P. Walsh, 2015. “Explaining variation in the value of Chesapeake Bay water quality using internal meta-analysis”. Working paper, National Center for Environmental Economics, U.S. Environmental Protection Agency, Washington, DC.

Kovacs, K., T.P. Holmes, J.E. Englin and J. Alexander, 2011. “The dynamic response of housing values to a forest invasive disease: evidence from a sudden oak death infestation”. *Environmental Resource Economics*, 49:445–471.

Kuminoff, N.V., C. Zhang, C. and J. Rudi, 2010a. “Are travelers willing to pay a premium to stay at a “Green Hotel”? evidence from an internal meta-analysis of Hedonic price premia”. *Agricultural and Resource Economics Review*, 55(4):1227-1250.

Kuminoff, N.V., C.F. Parmeter, and J.C. Pope, 2010b. “Which hedonic models can we trust to recover the marginal willingness to pay for environmental amenities”. *Journal of Environmental Economics and Management,* 60(3): 145-160.

McMillen, D.P. (2010). “Issues in spatial data analysis”. *Journal of regional science*, 50(1): 119-141.

Mahan, B. L., S. Polasky, and M.A. Richard,2000. ‘‘Valuing urban wetlands: a property price approach.’’ *Land Economics*, 76(1): 100-13.

Mansfield C., S.K. Pattanayak, W. McDow, R. McDonald., P. Halpin, 2005. “Shades of green: measuring the value of urban forests in the housing market”. *Journal of Forest Economics*, 11 (3):177-199.

Morales D.J., F.R. Micha and R.L. Weber, 1976. “The contribution of trees to residential property value: Manchester, Connecticut. *Valuation*, 23 (2):26-43.

Morales D.J. 1980. “The contribution of trees to residential property value”. *Journal of Arboriculture*, 6:305-308.

Netusil, N.R. (2005). “The effect of environmental zoning and amenities on property values: Portland, Oregon”. *Land Economics*, 81(2): 227-246.

Netusil, N. R., S. Chattopadhyay and K. F. Kovacs, 2010. "Estimating the demand for tree canopy: a second-stage hedonic price analysis in Portland, Oregon." *Land Economics*, 86 (2): 281-293.

Palmquist, R.B (2006). “Property value models”. In: *Handbook of Environmental Economics*, volume 2, Karl-Gran Miler and Jeffrey R. Vincent (eds.):763-8189.

Palmquist, R.B. (1984) "Estimating the demand for the characteristics of housing." *Review of Economics and Statistics*, 66:394-404.

Rosen, R. 1974. “Hedonic prices and implicit markets: product differentiation in pure competition”. *Journal of Political Economy*, 82:34-55.

Pope, J.C., 2008. “Fear of crime and housing prices: household reactions to sex offender registries”. *Journal of Urban Economics*, 64: 601-614.

Price, J. I., D. W. McCollum, and R. P. Berrens, 2010. "Insect infestation and residential property values: a hedonic analysis of the mountain pine beetle epidemic." *Forest Policy and Economics,* 12(6): 415-22.

Sadler J., A. Bates, J. Hale, P. James, 2010. “Bringing cities alive: the importance of urban green spaces for people and biodiversity”. In *Urban Ecology*, Ed. GastonK., Cambridge University Press, Cambridge, UK, 230-260.

Sander H., S. Polasky, R.G. Haight, 2010. “The value of urban tree cover: a hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA. *Ecological Economics*, 69(8):1646-1656.

Sander H.A. and C. Zhao, 2015. “Urban green and blue: who values what and where?” *Land Use Policy*. 42:194-209.

Saphores, J-D. and W. Li, 2012. “Estimating the value of urban green areas: a hedonic pricing analysis of the single-family housing market in Los Angeles, CA”. *Landscape and Urban Planning*, 104: 373–387.

Stetler K. M., T.J.Venn, D.E. Calkin, 2010. “The effects of wildlife and environmental amenities on property values in Northwest Montana, USA. *Ecological Economics*, 69:2233-2243.

Taylor, L.O. 2003. “The hedonic method.” In *A primer of non-market valuation*, P.A. Champ, K.J. Boyle and T.C. Brown (eds.), Kluwer Academic Publishers, 331-393.

Thorsnes P. 2002. “The value of a suburban forest preserve: estimates from sales of vacant residential building lots”. *Land Economics*, 78 (3):426-441.

US Census (2010). available at: http://www.census.gov/2010census/.

Tyrvainen L., and A. Miettinen, 2000. “Property prices and urban forest amenities”. *Journal of Environmental Economics and Management*, 39 (2):205-223.

Tuttle, C.M. and M.D. Heintzelman, 2015. “A loon on every lake: a hedonic analysis of lake water quality in the Adirondacks”. *Resource and Energy Economics*, 39: 1-15.

Wooldridge, J. 2002. “Econometric analysis of cross section and panel data”. Cambridge: MIT Press.

Zhang, C. K.J. Boyle, N.V. Kuminoff, N.V. 2015. “Partial identification of amenity demand functions”. *Journal of Environmental Economics and Management*, 71:180-197.

Appendix 3.A. Data Cleaning Protocols

1. Select observations by FIPS code of county/counties to which the study areas belong to.

2. Data selected above were processed in ArcGIS. Using latitude and longitude information each house was projected into a GIS map (geo-coordinate system: GSC_WGS_1984). Then house locations were projected to respective UTM projected coordinate system for study area and clipped to the study area boundary to remove observations with incorrect geographic locations.

3. From these data, single family houses (product_type= SINGLE FAMILY) were selected. Excluded category is condominiums, duplex, mobile home, high-rise condos.

4. From these selected houses, the new sales (SALE_TYPE= New Sale) and repeated sales (SALE_TYPE= Regular Resale) were selected. Excluded category is REO sale and foreclosures.

5. Further cleaning was done to select single-parcel transactions (parcel_transaction_type= Single-Parcel). Excluded category is multiple-parcel transactions.

6. Then zip code information in each house was matched with the ESRI zip code GIS layer (ESRI, 2014) to remove observations with incorrect zip codes.

7. Drop duplicates of houses if they were sold in the same day.

8. Implausible observations were removed based on the following conditions:
   - Square feet of living area > square feet of lot
   - Living area < 500 square feet for 1 bed room houses; for each additional bedroom 120 square feet was added to the 500 square feet assuming an average bedroom is 10 feet x 12 feet.
   - Ratio of number of bathrooms to number of bedrooms <0.3 or >1.5
   - The top and bottom 5 percent of price per square feet of living area

Appendix 3.B. Definition of land cover types and summary of overall land cover in study areas

Table3.B1 Definition of land cover types

Land cover type	Definition
Water	All surface waters: streams, rivers, canals, ponds, reservoirs, lakes, bays, estuaries, and coastal waters. For cases of ephemeral changes in water level and extent such as tidelands and some lakes, the waterline at the time of photo acquisition is used to define the extent of the water feature.
Impervious surface	Paved roads, parking lots, driveways, sidewalks, roofs, swimming pools, patios, painted surfaces, wooden structures, and most asphalt and concrete surfaces, dirt and gravel roads, railways
Soil & Barren	Bare fields, construction sites, quarries, gravel pits, mine lands, golf sand traps, stream and river sand bars, beaches and other bare soil and gravel surfaces.
Trees & Forest	Trees of any kind, from a single individual to continuous canopy forest. If a vegetation object casts a shadow longer than a few meters, it is usually classified as a tree. Large shrubs fall in this class.
Shrubland	Scrublands and brush (Shrubs are generally shorter than trees and bear multiple woody stems).
Grass & Herbaceous	Residential lawns, golf courses, roadway medians and verges, park lands, transmission line, natural gas corridors, recently clear cut areas, pasture, grasslands, prairie grass, and emergent wetlands vegetation.
Agriculture	Cultivated row crops and fallow fields that are being actively tilled (agricultural lands are treated primarily in a land cover sense as grass-herbaceous, trees, shrubs or soil, and secondarily as agriculture land use).
Woody Wetlands	Wetlands dominated by Tree and Forest species.
Emergent Wetlands	Wetlands dominated by Grass and Herbaceous species.

Source: EPA's EnviroAtlas

Table 3. B2 Summary of overall land cover types in each city

Land cover class	Water	Impervious surface	Soil & Barren land	Trees & forests	Shrubland	Grass and Herbaceous	Agriculture	Orchard	Woody wetlands	Emergent wetlands
Durham (NC)	2.27	14.15	2.04	67.24	.	14.30	.	.	.	.
Fresno (CA)	1.74	18.89	29.75	5.23	.	6.39	33.93	4.07	.	.
Green Bay (WI)	11.90	10.86	0.62	15.07	.	22.44	32.34	.	5.36	1.40
Milwaukee (WI)	7.84	19.53	0.67	28.71	.	25.31	8.79	.	6.50	2.64
New Bedford (MA)	23.01	7.48	0.94	38.90	.	13.94	.	.	12.94	2.79
Paterson (NJ)	2.33	52.62	1.29	29.17	.	14.59	.	.	.	.
Phoenix (AZ)	0.91	13.55	10.44	3.64	62.31	3.48	5.68	.	.	.
Pittsburgh (PA)	1.90	15.80	1.28	55.43	.	25.60	.	.	.	.
Portland (ME)	26.17	6.54	1.34	43.66	.	12.04	1.28	.	6.64	2.35
Portland (OR)	5.58	24.62	0.34	27.56	.	30.27	9.59	.	1.03	1.01
Tampa (FL)	26.16	14.86	1.87	32.30	.	16.21	0.72	.	6.38	1.49
Woodbine (IA)	1.17	2.36	1.37	12.41	.	13.58	69.11	.	.	.

Appendix 3.C. Summary statistics of tree cover and other land cover types within 100m, 101-500m and 501-1000m buffers

Table 3.C1. Summary statistics (mean) of percent of land cover within 0-100m buffer

City	Water	impervious surface	trees and forests	shrubland	grass and herbaceous	agriculture	orchard	woody wetlands	emergent wetlands
Durham (NC)	0.35	33.19	49.57	.	14.69	.	.	.	.
	(0, 59.37) [a]	(0, 97.68)	(0, 99.95)	.	(0, 80.50)	.	.	.	.
Phoenix (AZ)	0.31	42.37	10.28	7.26	8.11	0.31	.	.	.
	(0, 61.96)	(0, 99.18)	(0, 56.46)	(0, 100)	(0, 68.38)	(0, 89.53)	.	.	.
Fresno (CA)	0.39	57.74	12.31	.	16.35	0.52	0.08	.	.
	(0, 68.02)	(0, 94.21)	(0, 82.89)	.	(0, 62.39)	(0, 100)	(0, 44.66)	.	.
Tampa (FL)	2.49	38.91	38.71		16.49				
	(0, 100)	(0, 90.43)	(0, 99.72)	.	(0, 87.61)				
New Bedford (MA)	0.65	38.51	29.26	.	28.71	.	.	2.01	0.52
	(0, 45.37)	(0, 90.45)	(0.06, 94.32)	.	(0.53, 89.01)	.	.	(0, 78.36)	(0, 63.05)
Portland (ME)	0.34	29.79	46.13	.	20.67	.	.	.	.
	(0, 36.75)	(0, 92.86)	(0.23, 100)	.	(0, 76.49)	.	.	.	.
Patterson (NJ)	0.14	74.52	15.04	.	10.10	.	.	.	.
	(0, 30.17)	(10.62, 97.91)	(0.88, 69.87)	.	(0.3, 38.29)	.	.	.	.
Portland (OR)	0.10	45.43	26.08	.	28.05	0.10	.	0.11	0.10
	(0, 43.78)	(0, 99.84)	(0, 99.98)	.	(0.02, 91.85)	(0, 64.44)	.	(0, 43.47)	(0, 43.03)
Pittsburghh (PA)	0.04	31.53	40.78	.	27.25	.	.	.	.
	(0, 42.25)	(0, 97.57)	(0, 100)	.	(0, 99.89)	.	.	.	.
Milwaukee (WI)	0.04	36.86	38.01	.	24.24	0.12	.	0.57	0.13
	(0, 38.13)	(0, 85.33)	(0, 100)	.	(0, 78.67)	(0, 72.07)	.	(0, 100)	(0, 59.77)

[a] Minimum and maximum of the variables are given in the parenthesis

Table 3.C2. Summary statistics (mean) percent of land cover types within 101-500m buffer

City	Water	impervious surface	trees and forests	shrubland	grass and herbaceous	agriculture	orchard	woody wetlands	emergent wetlands
Durham (NC)	0.81	25.11	58.02	.	14.40	.	.	.	.
	(0, 33.89) [a]	(1.49, 69.65)	(17.31, 97.99)		(0.52, 48.78)	.	.	.	.
Phoenix (AZ)	0.55	38.84	9.10	9.42	9.62	2.21	.	.	.
	(0, 35.44)	(0, 90.31)	(0, 34.1)	(0, 98.99)	(0, 51.8)	(0, 77.78)	.	.	.
Fresno (CA)	1.24	49.45	11.71	.	15.04	3.14	0.69	.	.
	(0, 42.37)	(0.49, 79.36)	(0, 41.51)	.	(0.09, 55.82)	(0, 85.91)	(0, 38.82)	.	.
Tampa (FL)	4.76	31.89	39.33	.	17.45	.	.	.	.
	(0, 80.49)	(1.55, 81.66)	(0.61, 88.12)	.	(1.11, 62.8)	.	.	.	.
New Bedford (MA)	4.67	32.67	30.32	.	24.87	.	.	5.56	1.25
	(0, 78.82)	(0.59, 85.84)	(0.4, 83.02)	.	(3.55, 69.27)	.	.	(0, 47.82)	(0, 40.92)
Portland (ME)	3.40	24.44	45.02	.	19.10	.	.	.	.
	(0, 67.39)	(0.21, 65.1)	(2.24, 95.25)	.	(1.81, 49.56)	.	.	.	.
Patterson (NJ)	1.21	71.55	15.96	.	10.76	.	.	.	.
	(0, 12.4)	(28.66, 89.59)	(5.69, 55.31)	.	(4.66, 32.55)	.	.	.	.
Portland (OR)	0.59	41.49	27.99	.	28.62	0.65	.	0.29	0.22
	(0, 58.5)	(1.02, 91.43)	(1.72, 97.71)	.	(1.21, 76.03)	(0, 84.7)		(0, 16.87)	(0, 12.11)
Pittsburghh (PA)	0.64	27.44	47.42	.	23.99	.	.	.	.
	(0, 53.92)	(0.12, 84.24)	(3.68, 95.80)	.	(2.84, 71.82)	.	.	.	.
Milwaukee (WI)	0.40	37.17	34.08	.	25.06	0.55	.	2.01	0.58
	(0, 56.24)	(1.6, 74.68)	(4.9, 83.67)	.	(2.14, 63.35)	(0, 69.44)	.	(0, 52.69)	(0, 35.2)

[a] Minimum and maximum of the variables are given in the parenthesis

Table 3.C3. Summary statistics (mean) percent of land cover types within 501-1000m buffer

City	Water	impervious surface	trees and forests	shrubland	grass and herbaceous	agriculture	orchard	woody wetlands	emergent wetlands
Durham (NC)	0.83	22.60	60.45	.	14.52	.	.	.	.
	(0, 12.52) [a]	(1.15, 55.82)	(22.72, 92.34)		(1.77, 43.60)	.	.	.	.
Phoenix (AZ)	0.63	36.36	8.27	9.30	4.28	11.83	.	.	.
	(0, 29.12)	(0.48, 81.89)	(0,27.13)	(0, 33.31)	(0, 75.75)	(0, 99.39)	.	.	.
Fresno (CA)	1.52	45.16	11.37	.	14.21	5.59	1.18	.	.
	(0, 30.95)	(2.41, 73.77)	(0.15, 28.94)	.	(0.14, 31.75)	(0, 83.48)	(0, 34.49)	.	.
Tampa (FL)	5.64	28.93	39.80	.	17.80	.	.	.	.
	(0, 81.04)	(1.33, 73.23)	(1, 79.4)	.	(1.31, 56.65)	.	.	.	.
New Bedford (MA)	10.01	28.66	28.86	.	22.06	.	.	7.76	0.00
	(0, 85.74)	(0.46, 75.36)	(2.58, 74.57)	.	(2.50, 44.10)	.	.	(0, 44.76)	(0, 0)
Portland (ME)	6.90	22.31	42.82	.	18.12	.	.	.	.
	(0, 64.39)	(0.48, 46.01)	(8.68, 91.17)	.	(2.91, 44.95)	.	.	.	.
Patterson (NJ)	1.99	67.80	18.11	.	11.33	.	.	.	.
	(0, 9.61)	(33.51, 84.43)	(8.06, 43.73)	.	(6.33, 23.63)	.	.	.	.
Portland (OR)	1.51	39.97	28.22	.	28.03	1.48	.	0.38	0.27
	(0, 50.88)	(0, 82.88)	(0, 98.22)	.	(0, 75.09)	(0, 92.63)	.	(0, 10.3)	(0, 10.27)
Pittsburghh (PA)	1.72	25.49	49.15	.	22.93	.	.		.
	(0, 9.61)	(33.51, 84.43)	(8.06, 43.73)	.	(6.33, 23.63)	.	.	.	.
Milwaukee (WI)	1.10	36.64	31.76	.	25.67	0.89	.	2.81	0.88
	(0, 49.53)	(2.12, 67.16)	(7.25, 74.08)	.	(3.82, 52.45)	(0, 31.09)	.	(0, 39.58)	(0, 25.77)

[a] Minimum and maximum of the variables are given in the parenthesis

Appendix 3D. Coefficient estimates for house attributes, land cover types and sale year dummy variables

Table 3.D1. Coefficient estimates for house attributes

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
living	0.0007***[a]	0.0006***	0.0007***	0.0006***	0.0005***	0.0004***	0.0006***	0.0004***	0.0006***	0.0005***
	(1.2E-05) [b]	(9.5E-06)	(2.8E-05)	(6.2E-06)	(2.6E-05)	(2.9E-05)	(3.0E-05)	(3.3E-06)	(8.0E-06)	(1.9E-05)
livingsq	-5.5E-08***	-4.7E-08***	-6.5E-08***	-3.8E-08***	-3.3E-08***	-3.4E-08	-7.2E-08***	-2.6E-08***	-3.9E-08***	-4.4E-08***
	(2.3E-09)	(0.0365)	(5.6E-09)	(1.2E-09)	(6.0E-09)	(5.1E-09)	(6.1E-09)	(6.8E-10)	(1.5E-09)	(4.7E-09)
lot_acres	0.0767***	0.6851***	0.2558***	0.1903***	0.1477***	0.0724	1.2262***	0.2627***	0.0720***	0.0546***
	(0.0098)	(0.0365)	(0.0332)	(0.0078)	(0.0170)	(0.0280)	(0.2287)	(0.0169)	(0.0075)	(0.0117)
lot_sq	-0.0049***	-0.0747***	-0.0142***	-0.0127***	-0.0096***	-0.0056	-2.0994**	-0.0206***	-0.0050***	-0.0038***
	(0.0013)	(0.0125)	(0.0025)	(0.0012)	(0.0019)	(0.0026)	(0.4636)	(0.0033)	(0.0010)	(0.0012)
age	-0.0050***	-0.0101***	.	-0.0085***	-0.0049***	-0.0026	.	-0.0047***	-0.0086***	-0.0036***
	(0.0004)	(0.0003)	.	(0.0002)	(0.0003)	(0.0006)	.	(0.0001)	(0.0002)	(0.0003)
agesq	3.8E-05***	5.3E-05****	.	5.9E-05***	1.8E-05***	9.9E-06	.	3.7E-05***	2.0E-05***	3.9E-06
	(5.1E-06)	(3.7E-06)	.	(2.3E-06)	(1.6E-06)	(3.3E-06)	.	(9.2E-07)	(1.7E-06)	(2.4E-06)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.

[b] Robust standard errors are given in parenthesis.

Table 3.D2. Coefficient estimates for water bodies within 3 buffers

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
water1	0.0081***[a]	0.0102***	-0.0005	0.0063***	0.0353***	-0.0195	0.0434***	0.0475***	-0.0091*	0.0555***
	(0.0012) [b]	(0.0006)	(0.0012)	(0.0004)	(0.0060)	(0.0125)	(0.0134)	(0.0039)	(0.0049)	(0.0082)
water1sq	-3.1E-05	0.0001***	3.7E-05	-2.4E-05***	-0.0002*	0.0001	-0.0007*	0.0001**	0.0004***	0.0001
	(3.1E-05)	(1.6E-05)	(4.4E-05)	(6.8E-06)	(0.0001)	(0.0003)	(0.0004)	(0.0001)	(0.0001)	(0.0001)
water2	0.0100***	0.0121***	0.0027***	0.0223***	0.0828***	0.0522***	0.0201	0.0535***	0.0125	0.0255***
	(0.0025)	(0.0010)	(0.0010)	(0.0011)	(0.0046)	(0.0108)	(0.0121)	(0.0043)	(0.0084)	(0.0050)
water2sq	-0.0002	-0.0002***	-2.8E-05	4.3E-05***	-2.5E-05	1.4E-05	0.0009	2.6E-05	-4.4E-05	0.0001**
	(0.0002)	(0.0001)	(0.0001)	(9.9E-06)	(2.9E-05)	(0.0001)	(0.0009)	(2.3E-05)	(4.8E-05)	(1.1E-0.5)
water3	0.0590***	0.0341***	-0.0002	0.0640***	0.0113***	0.0819***	0.0176	0.0259***	0.0244*	0.0324***
	(0.0028)	(0.0016)	(0.0019)	(0.0024)	(0.0031)	(0.0115)	(0.0182)	(0.0020)	(0.0138)	(0.0045)
water3sq	0.0021***	-0.0001	0.0004***	3.7E-05***	4.6E-05**	0.0002***	0.0015	-8.2E-06	0.0001	0.0002***
	(0.0004)	(0.0001)	(0.0001)	(8.6E-06)	(2.3E-05)	(0.0001)	(0.0019)	(1.2E-05)	(0.0001)	(0.0001)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.

[b] Robust standard errors are given in parenthesis.

Table 3.D3. Coefficient estimates for impervious surface within 3 buffers

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
impervious1	0.0087*** [a]	0.0185***	0.0075***	0.0043***	0.0258***	-0.0169***	0.0327***	0.0463***	0.0064***	0.0554***
	(0.0008) [b]	(0.0008)	(0.0014)	(0.0005)	(0.0039)	(0.0053)	(0.0127)	(0.0037)	(0.0017)	(0.0074)
impervious1sq	-0.0001	-0.0002***	-0.0001***	-4.6E-05***	-3.1E-05**	-0.0001	-0.0001	-0.0001***	-4.8E-05***	-4.8E-05***
	(7.3E-06)	(8.4E-06)	(1.3E-05)	(3.4E-06)	(1.5E-05)	(4.1E-05)	(5.6E-05)	(4.7E-06)	(8.8E-06)	(8.8E-06)
impervious2	0.0041***	0.0256***	0.0191***	0.0218***	0.0727***	0.0570***	0.0467***	0.0513***	0.0064	0.0247***
	(0.0016)	(0.0010)	(0.0035)	(0.0012)	(0.0045)	(0.0115)	(0.0171)	(0.0043)	(0.0074)	(0.0047)
impervious2sq	0.0002***	-0.0003***	-0.0002***	-2.6E-05***	0.0001**	1.6E-05	-0.0001	-1.5E-05**	0.0001***	-7.3E-06
	(2.1E-05)	(1.1E-05)	(3.2E-05)	(6.2E-06)	(2.4E-05)	(0.0001)	(0.0001)	(6.4E-06)	(1.5E-05)	(1.3E-05)
impervious3	0.0336***	0.0446***	0.0353***	0.0754***	0.0100***	0.0617***	0.0988***	0.0241***	0.0249**	0.0349***
	(0.0019)	(0.0015)	(0.0053)	(0.0027)	(0.0030)	(0.0134)	(0.0263)	(0.0019)	(0.0106)	(0.0045)
impervious3sq	0.0007***	-0.0004***	-0.0003***	-0.0002***	2.3E-05	0.0004***	-0.0005***	4.8E-06	8.1E-06	-0.0001
	(2.9E-05)	(1.4E-05)	(4.4E-05)	(9.4E-06)	(2.9E-05)	(0.0001)	(0.0002)	(4.6E-06)	(5.0E-05)	(2.1E-05)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are given in parenthesis.

Table 3.D4. Coefficient estimates for grass and herbaceous lands within 3 buffers

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
grass1	-0.0023***[a]	0.0031***	-0.0038***	0.0016***	0.0273***	-0.0194***	0.0236**	0.0464***	0.0093***	0.0540***
	(0.0009)[b]	(0.0004)	(0.0009)	(0.0005)	(0.0042)	(0.0054)	(0.0120)	(0.0037)	(0.0018)	(0.0074)
grass1sq	0.0001***	0.0001***	0.0001	2.2E-06	-3.3E-05	-1.4E-05	0.0002	-0.0001***	-0.0001***	-2.3E-05**
	(1.9E-05)	(1.2E-05)	(2.1E-05)	(4.2E-06)	(2.4E-05)	(0.0001)	(0.0002)	(5.8E-06)	(1.1E-05)	(1.2E-05)
grass2	0.0062***	0.0122***	0.0196***	0.0273***	0.0956***	0.0489***	0.0395***	0.0540***	0.0114	0.0230***
	(0.0020)	(0.0009)	(0.0030)	(0.0013)	(0.0050)	(0.0137)	(0.0157)	(0.0041)	(0.0075)	(0.0048)
grass2sq	0.0004***	-0.0001***	-0.0003***	-0.0001***	-0.0002***	0.0001	0.0002	-1.7E-05*	4.4E-05**	4.3E-05**
	(4.8E-05)	(2.3E-05)	(0.0001)	(9.9E-06)	(4.7E-05)	(0.0002)	(0.0003)	(9.3E-06)	(2.1E-05)	(2.1E-05)
grass3	0.0393***	0.0735***	0.1021***	0.0761***	0.0181***	0.0765***	0.0395	0.0268***	0.0332**	0.0392***
	(0.0028)	(0.0023)	(0.0149)	(0.0028)	(0.0042)	(0.0142)	(0.0312)	(0.0020)	(0.0142)	(0.0051)
grass3sq	0.0008***	-0.0017***	-0.0029***	-0.0001***	-0.0002**	0.0002	0.0006	-2.8E-05***	-3.7E-05	-0.0001***
	(0.0001)	(0.0001)	(0.0004)	(1.5E-05)	(0.0001)	(0.0002)	(0.0010)	(7.3E-06)	(4.2E-05)	(4.1E-05)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are given in parenthesis.

Table 3.D5. Coefficient estimates for agricultural lands within 3 buffers

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
agri1	.	0.0022**[a]	-0.0002	0.0056***	.	0.2647	.	0.0388***	.	0.0539**
	.	(0.0006)[b]	(0.0009)	(0.0017)	.	(2.3980)	.	(0.0039)	.	(0.0078)
agri1sq	.	0.0001***	8.7E-06	-0.0001***	.	-0.0042	.	0.0001***	.	-0.0001
	.	(1.4E-05)	(2.2E-05)	(0.0001)	.	(0.0356)	.	(2.9E-05)	.	(0.0001)
agri2	.	0.0054***	0.0012**	0.0251***	.	0.0682*	.	0.0480***	.	0.0279***
	.	(0.0004)	(0.0006)	(0.0016)	.	(0.0385)	.	(0.0043)	.	(0.0049)
agri2sq	.	1.8E-05**	0.0001***	-0.0002***	.	5.5E-06	.	3.6E-05***	.	-0.0001
	.	(7.8E-06)	(2.1E-05)	(0.0001)	.	(0.0052)	.	(1.3E-05)	.	(0.0001)
agri3	.	0.0223***	0.0157***	0.0847***	.	0.1207***	.	0.0258***	.	0.0362***
	.	(0.0007)	(0.0020)	(0.0035)	.	(0.0256)	.	(0.0019)	.	(0.0046)
agri3sq	.	7.6E-06	-6.4E-06	-0.0005***	.	-0.0042***	.	4.4E-06	.	-0.0002*
	.	(6.7E-06)	(1.9E-05)	(0.0001)	.	(0.0015)	.	(1.1E-05)	.	(0.0001)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.

[b] Robust standard errors are given in parenthesis.

Table 3.D6. Coefficient estimates for woody wetlands within 3 buffers

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
wetland11	.	.	.	0.0014***[a]	0.0211***	-0.0266***	.	0.0439***	.	0.0523***
	.	.	.	(0.0005)[b]	(0.0040)	(0.0062)	.	(0.0039)	.	(0.0074)
wetland11sq	.	.	.	-3.7E-06	4.4E-05	0.0002	.	3.1E-05	.	4.3E-05**
	.	.	.	(9.0E-06)	(3.9E-05)	(0.0002)	.	(4.1E-05)	.	(2.2E-05)
wetland12	.	.	.	0.0194***	0.0787***	0.0495***	.	0.0450***	.	0.0261***
	.	.	.	(0.0011)	(0.0045)	(0.0122)	.	(0.0046)	.	(0.0045)
wetland12sq	.	.	.	3.3E-05***	-2.6E-05	0.0003*	.	0.0012***	.	-2.6E-05
	.	.	.	(1.0E-05)	(0.0001)	(0.0002)	.	(0.0002)	.	(2.8E-05)
wetland13	.	.	.	0.0691***	0.0218***	0.0792***	.	0.0176***	.	0.0274***
	.	.	.	(0.0025)	(0.0037)	(0.0125)	.	(0.0026)	.	(0.0042)
wetland13sq	.	.	.	-0.0001***	-0.0002***	0.0001	.	0.0006	.	0.0001***
	.	.	.	(1.3E-05)	(0.0001)	(0.0003)	.	(0.0004)	.	(4.7E-05)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are given in parenthesis.

Table 3.D7. Coefficient estimates for emergent wetlands within 3 buffers

Variable	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
wetland21	.	.	.	0.0025*** [a]	0.0330***	-0.0155	.	0.0347***	.	0.0547***
	.	.	.	(0.0007) [b]	(0.0057)	(0.0103)	.	(0.0039)	.	(0.0076)
wetland21sq	.	.	.	-2.0E-05	-0.0001	-0.0004	.	0.0003***	.	-3.6E-05**
	.	.	.	(1.81E-05)	(0.0001)	(0.0005)	.	(4.6E-05)	.	(0.0001)
wetland22	.	.	.	0.0301***	0.0826***	0.0433***	.	0.0429***	.	0.0256***
	.	.	.	(0.0015)	(0.0049)	(0.0125)	.	(0.0046)	.	(0.0050)
wetland22sq	.	.	.	-0.0002***	-0.0005*	0.0010***	.	0.0016***	.	-0.0001
	.	.	.	(4.4E-05)	(0.0003)	(0.0002)	.	(0.0003)	.	(0.0001)
wetland23	.	.	.	0.0687***	NA	0.0667***	.	0.0352***	.	0.0301***
	.	.	.	(0.0027)	NA	(0.0177)	.	(0.0034)	.	(0.0048)
wetland23sq	.	.	.	-0.0002**	NA	0.0009	.	-0.0006	.	0.0000
	.	.	.	(0.0001)	NA	(0.0012)	.	(0.0004)	.	(0.0001)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are given in parenthesis.
NA indicates that these variables were dropped from the regression due to collinearity.

Table 3.D8. Coefficient estimates for shrub lands in Phoenix (AZ) and orchards in Fresno (CA) within 3 buffers

Variable	Phoenix (AZ)	Fresno (CA)
shrub1	0.0521*** [a]	.
	(0.0017) [b]	.
shrub1sq	-0.0003***	.
	(1.3E-05)	.
shrub2	-0.0058***	.
	(0.0004)	.
shrub2sq	0.0001***	.
	(5.5E-06)	.
shrub3	0.0292***	.
	(0.0009)	.
shrub3sq	4.3E-05***	.
	(5.5E-06)	.
orchard1	.	0.0005
	.	(0.0041)
orchard1sq	.	-0.0001
	.	(0.0002)
orchard2	.	0.0183***
	.	(0.0028)
orchard2sq	.	-0.0004***
	.	(0.0001)
orchard3	.	0.0259***
	.	(0.0048)
orchard3sq	.	-0.0006***
	.	(0.0001)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are given in parenthesis.

Table 3.D9. Coefficient estimates for sale year dummy variables

Sale year[c]	Durham (NC)	Phoenix (AZ)	Fresno (CA)	Tampa (FL)	New Bedford (MA)	Portland (ME)[d]	Patterson (NJ)	Portland (OR)	Pittsburgh (PA)	Milwaukee (WI)
yr2006	-0.0392**[a]	0.0205***	0.0316***	0.0474***	0.0206*	.	0.0796***	-0.0874***	-0.0159**	0.0168***
	(0.0046)[b]	(0.0018)	(0.0050)	(0.0019)	(0.0110)	.	(0.0104)	(0.0016)	(0.0061)	(0.0035)
yr2007	-0.0623***	-0.0292***	0.0257***	0.0146***	0.0284***	-0.0233	0.0961***	-0.0915***	-0.0171**	0.0041
	(0.0050)	(0.0021)	(0.0058)	(0.0024)	(0.0107)	(0.0437)	(0.0130)	(0.0017)	(0.0062)	(0.0038)
yr2008	-0.0524***	-0.0301***	0.1273***	0.0762***	-0.0021	-0.1397***	-0.0296	-0.0813***	0.0090***	-0.0301***
	(0.0053)	(0.0028)	(0.0060)	(0.0028)	(0.0121)	(0.0434)	(0.0179)	(0.0019)	(0.0064)	(0.0043)
yr2009	-0.0100***	-0.0561***	0.0249***	0.0918***	-0.0626***	-0.1539***	-0.2402***	-0.0753***	0.0543***	-0.0527***
	(0.0057)	(0.0031)	(0.0051)	(0.0027)	(0.0119)	(0.0398)	(0.0233)	(0.0020)	(0.0064)	(0.0044)
yr2010	0.0570***	-0.0173***	0.0541***	0.1008***	-0.0679***	-0.1178***	-0.3485***	-0.0334***	0.0749***	-0.0646***
	(0.0061)	(0.0030)	(0.0049)	(0.0028)	(0.0125)	(0.0421)	(0.0203)	(0.0022)	(0.0065)	(0.0051)
yr2011	0.0879***	0.0017***	0.0405***	0.1017***	-0.1275***	-0.0649	-0.3558***	-0.0305***	0.1000***	-0.0963***
	(0.0068)	(0.0032)	(0.0060)	(0.0030)	(0.0135)	(0.0405)	(0.0201)	(0.0023)	(0.0066)	(0.0058)
yr2012	0.0732***	-0.0198***	-0.0336***	0.0460***	-0.1126***	-0.0841**	-0.4777***	-0.0528***	0.1156***	-0.1012***
	(0.0063)	(0.0028)	(0.0065)	(0.0028)	(0.0132)	(0.0377)	(0.0227)	(0.0021)	(0.0067)	(0.0052)
yr2013	0.0395***	0.0077***	-0.1071***	0.0379***	-0.1350***	-0.0583	-0.5633***	-0.0610***	0.1199***	-0.1107***
	(0.0060)	(0.0026)	(0.0049)	(0.0027)	(0.0118)	(0.0370)	(0.0192)	(0.0019)	(0.0064)	(0.0051)
yr2014	0.0121	0.0309***	-0.1039***	0.0454***	-0.1223***	-0.0482	-0.5995***	-0.0759***	0.1254***	-0.1131***
	(0.0078)	(0.0031)	(0.0074)	(0.0040)	(0.0172)	(0.0391)	(0.0294)	(0.0025)	(0.0078)	(0.0075)

[a] Single asterisk indicates significance at 10 percent level; double asterisk indicates significance at 5 percent level; triple asterisks indicate significance at 1 percent level.
[b] Robust standard errors are given in parenthesis.
[c] Sale year of 2005 is the excluded category.
[d] In Portland (ME), sales data were not available for the year 2005. Therefore, sale year 2006 is the excluded category.

Chapter 4

Cooperative management of invasive species in landscapes with mixed land ownerships: the case of Emerald ash borer control in multiple jurisdictions in Twin Cities, Minnesota

Abstract

Bio-invasions in an urban landscape encompass multiple jurisdictions and optimal control decisions, in terms of where, when and what intensity to control, require interaction among multiple stakeholders. In this context, "Cooperative agreements" at neighborhood scale or landscape levels are frequently applied in managing trans-boundary resources shared among neighboring owners/agents. With increasing infestations of Emerald ash borer (EAB) in Twin cities, MN, optimal strategies for regional management of the insects are evaluated in a limited number of studies via models that use information on spatial and temporal population dynamics of insects and host trees and economic data on management. These studies highlight the importance of cooperation among the multiple jurisdictions and show how bargaining power and insect dynamics affect the cooperative management of EAB. However, these studies do not evaluate how the cooperative behavior of local governments is affected by the public and private land ownerships. This study develops a model to analyze management efforts of counties with mixed land ownerships in the neighborhood of Twin Cities, when a transferable payment scheme is involved in the cooperative agreement. The results suggest that when the infested municipality has more public lands and when the transfer payments are efficiently used to implement greater control, the municipalities are more likely to commit to bargaining, and smaller transfer payments paid over a longer span of time are sufficient for optimal control of the spread of invasive species across the municipalities.

Key words: Nash bargaining, land ownership, Invasive species control

4.1 Introduction

Bio-invasions on urban trees cause significant economic losses to communities as they spread across the landscape over time (Holmes et al., 2006; Sydnor et al., 2007; Kovacs et al, 2011)[17]. In areas with mixed land ownerships such as wildland–urban interface (WUI) where private properties meet or intermingle with undeveloped wildland vegetation and in communities with forested land areas (for example street trees) among the private properties- control of bio-invasions involves interaction and decisions making by multiple owners -public land managers and private land owners. Optimal control decisions, in terms of where, when and what intensity to control, depend on the land owners' costs and benefits incurred in the control activities by each land owner. Control of bio-invasion by a land owner restricting the spread of invasion to neighboring lands generates positive externalities to his neighbors. Therefore, land owners, in general, tend to under-control the invasions, leading to higher invasion across the landscape (Wilen, 2007). In order to internalize stock and diffusion externalities arising from these non-cooperative activities and to reach socially optimal control, market-based approaches such as taxes, permits, subsidies, and transfer payments are implemented.

In the context of managing a trans-boundary resource shared among neighboring owners/agents, "Cooperative agreements" at neighborhood scale or landscape levels are frequently applied. Further, self-enforcing mechanisms are encouraged as no external body exists to enforce "binding" agreement by each agent (Kaitala and Pohjola, 1988). These agreements can take the form of a transfer payment scheme that allows sharing costs/benefits among the agents, thereby discouraging defects from cooperative control of the invasion (Bhat and Huffaker, 2007). Transfer payment can be

[17] Holmes et al. (2006) evaluated the impact of the hemlock woolly adelgid, an exotic forest pest, on the value of residential properties in Sparta, New Jersey. They found that defoliation of hemlock trees by the invasive species diminishes property values by 1 percent. Sydnor et al. (2007) estimated that removal and replacement cost of Ash trees in 67 communities in Ohio in 2005 due to invasion of Emerald ash borer, an exotic phloem-feeding beetle, was $1.0-4.2 billion. Kovacs et al. (2011) projected economic costs of invasion of Emerald ash borer in 25 states (centered on Detroit) for 2010-2020. Their simulations predicted that mean discounted cost of treatment, removal and replanting in the region to be nearly $1 billion per year.

made as lump-sum payments (Munro, 1979), fixed transfer payments (FTP) Kaitala and Pohjala, 1988; Sumaila, 1997) which are decided ex ante and paid annually or variable transfer payments (VTP) which allow for renegotiation of the contact (Bhat and Huffaker, 2007).

Previous bio-economic work on cooperative management of bio-invasions has evaluated how contacting agents behave under transferable payment schemes. For example, a differential game involving a FTP was developed by Kaitala and Pohjala (1988) for two countries managing a single stock of trans-boundary marine resource. They found that the country which harvests the resource more efficiently pays the other to optimize its profits until a breach is occurred resulting in a non-cooperative Nash strategy without transfer payments. A bio-economic model with a variable transfer payment scheme was developed by Bhat and Huffaker (2007) to control the dispersion of two-small mammal population over time on two neighboring land parcels. Comparison are made among the cooperative and non-cooperative strategies, FTP and VTP schemes, ex ante and ex post negotiations and contacts with different levels of self-enforcement. The authors conclude that the changing circumstance shifts the bargaining strength of the contracting agents, thus a VTP scheme is preferred as it allows the agents to refine their agreement in response to the behavior of other agents and natural variability of mammal populations.

This paper evaluates the cooperative management of Emerald ash borer (EAB) invasions using a transfer payment scheme that facilitates a self-enforcing contract between neighboring jurisdictions in Twin Cities, MN. Emerald ash borer (*Agrilus planipennis*) (hereafter EAB) is a non-native highly invasive forest pest that has infested on ash trees (*Fraxinus* spp.) throughout the U.S. (Anulewicz et al. 2008). In the twin cities, MN, EAB infestations have been detected in 2009, and by the end of the 2014 localized insect populations have been reported in the in the neighborhood of twin cities (Olmsted, Winona, Houston, Hennepin, and Dakota counties) (Minnesota Department of Agriculture, 2014). To control these infestations, systemic insecticides are applied to ash trees to kill EAB adults and infected trees are removed to destroy larvae. Also transport of ash firewood, logs of nursery stocks of ash is regulated in quarantine areas. The EAB invasions have caused the land owners and local governments to spend billions of dollars on treatment and removal or replacement of ash trees (Kovacs et al., 2010; Kovacs et al., 2011).

At present the control of invasions takes place at the municipality level and there is little coordination exists among the municipalities (Dunens et al, 2013). In response to the increasing interest in developing optimal control strategies to control the EAB in the twin city area, Kovacs et al (2014) developed a spatial-dynamic model and analyzed the optimal regional control of EAB infestations via centralized control strategies for 17 municipal jurisdictions in the Twin cities metropolitan area. The analysis was based on the dynamics of the insects and ash tree populations and the spatial variation in the ownership of land, benefits and cost of controlling the EAB infestations and the budgets of the municipalities. The authors found that centralizing the budgets across the jurisdictions increases total net benefits rather than increasing budget by any one municipality. This finding highlights the importance of coordinated control activities among the jurisdictions in controlling the EAB invasions. Recent paper by Cobourn et al. (2016) evaluated the cooperative management of EAB by two adjacent municipalities-one infested municipality and one un-infested municipality- when bi-lateral bargaining occurs over a fixed transfer payment from the uninfected municipality to the infested municipality which encourages greater control of EAB. The authors compared the Nash bargaining outcome with the myopic and social optimal solutions and found that relative bargaining power of the municipalities and the efficacy of control affects the bargaining outcome.

This paper extends the analysis of cooperative control of EAB by evaluating the effect of the land ownership on the bargaining outcome. Ash trees in risk of EAB infestations in Twin Cities are owned by both public and private property owners, and the control strategies applied by both these entities influence the spread of EAB within and across the municipalities. Local governments may have limited or no access to private lands within their jurisdictions to implement the control activities. When there are more public lands and/or when accessibility of private lands to the local government is high, the municipality is more committed to control the EAB infestation. Similarly, when there are more public lands, the municipalities are more likely to cooperate with each other via transfer payments to control the infestations. This paper models how municipalities with different states of EAB invasion and mixed land ownerships bargain via a fixed transfer payment.

Following Cobourn et al. (2016), a dynamic model is developed to obtain optimal control strategies for two neighboring counties-one with EAB invasions and the other without invasion. First, we use this model to assess the effect of land ownership on the social cost associated with a fixed transfer payment made by the uninfested municipality to the infested municipality to encourage controlling of EAB infestation within the infested municipality. Second, a Nash bargaining framework with fixed transfer payment is incorporated with the dynamic model to evaluate the effect of land ownership on the optimal path of bargaining between the two municipalities. The results suggest that infested municipalities with more public lands and those who efficiently use the transfer payments to implement greater control, are more likely to commit to bargaining. In that case, smaller transfer payments paid over a longer span of time ensure complete control of the invasive species within the infested municipality. These findings imply that landownership plays a vital role in cooperatively management of forest resources in urban communities, and provide new insights for future management efforts.

The remainder of this paper is organized as follows. Section 4.2 describes the modeling framework for the social planner’s problem and bargaining problem. Section 4.3 describes data and the simulation approach we used to solve the numerical optimization problems for varying level of land ownership ratios. Section 4.4 presents the results and Section 4.5 concludes the findings of the paper.

4.2. The model

Suppose there are two adjacent municipalities (*i=1,2*); one infested and another un-infested comprising of a mix of public and private lands within their jurisdictions. Let the two municipalities be identical except for the initial state of infestations. The uninfested municipality faces risk of invasion of EAB from the infested municipality with positive probability ($p(t)$) of EAB spreading at time *t* and this probability of spread is given as

$$\dot{p}_t = f(p(t)) \tag{4.1}$$

where $f(\cdot)$ is the rate of growth in probability of spread of EAB and $f' > 0$.

With no cost sharing for control from the uninfested municipality, the infested municipality may under-control the EAB invasions which increases the probability of EAB spread from the infested municipality to the uninfested municipality. The uninfested municipality may provide incentives to the infested municipality to increase the level of control with bargaining over a transfer payment $\tau(t)$ made at each time period *t*.

The bargaining occurs over the transfer payment between the public land managers of the municipality given control activities by private owners in both the municipality. Control of bio-invasion in public lands restricts the spread of EAB to adjacent private lands generating positive externalities to private owners. Similarly control of EAB in private lands too reduces the spread of EAB within and across the municipalities. However, private land owners have no incentive to consider these external benefits associated with their control decisions. Therefore, it is assumed that *private land owners implement too little* self-protecting measures *and their behavior is not affected by public control or by the bargaining agreements between the public managers*. Also it is assumed that control activities by private owners are known to the public managers.

Control of EAB is implemented in both publicly-owned and privately-owned lands (*k=1,2*) within each municipality. Suppose the control cost of EAB is the same across private and public lands, however benefits of controlling EAB may vary across the land ownership. Ash trees provide a suite of non-market benefits of biodiversity, improving air quality, reducing stormwater runoff and carbon sequestration, and private amenity values such as scenic views and shade which are location dependent and capitalized into private property value.

Suppose q_1 *and* q_2 respectively are the proportion of public lands in public ownership within the infested municipality and uninfested municipality $((0 \leq q_1 \leq 1), (0 \leq q_2 \leq 1))$[18]**.** With no bargaining agreement, public land owners in the infested municipality implement less control, and maximizes net benefits over time by choosing to control of EAB in public lands given private control. Then, in the absence of a bargaining agreement, net benefits to the infested municipality over time can be written as;

$$d_I = \int_{t=0}^{T} e^{-\rho t}[q_1 V(0)_1^g + (1-q_1)V(0)_1^p]dt \tag{4.2}$$

where $V(0)_1^g$ *and* $V(0)_1^p$ respectively are the annual net benefits from controlling EAB infestations to public and private land owners in the infested municipality when no bargaining occurs. The expected net benefits of the uninfested municipality in each period depend on the probability of spread of EAB from the infested municipality. With no bargaining, the expected net benefits to the uninfested municipality are given by equation 3 below.

$$d_U = \int_{t=0}^{T} e^{-\rho t}[((1-p(t)_{\tau=0})(q_2\overline{V}^g + (1-q_2)\overline{V}^p)) + (p(t)|_{\tau==0}\ (q_2 V(0)_2^g + (1-q_2)V(0)_2^p))]dt \tag{4.3}$$

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[18] Here we assume that q_1 and q_2 are exogenously given because when the probability of spread changes over time so does the proportion of public land to private lands as trees on different land ownerships may be affected differently.
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where $\bar{V}^g$ and $\bar{V}^p$ respectively are the annual net benefits of controlling to the public and private land owners in the uninfested municipality when EAB does not spread (probability (1-$p_t|_{\tau=0}$)). Similarly $V(0)_2^g$ and $V(0)_2^p$ respectively are the annual net benefits from controlling EAB infestations to public and private land owners in the uninfested municipality when EAB spread with probability $p_t|_{\tau=0}$[19].

Bargaining over transfer payment induces the control by the infested municipality which affects the probability of spread of EAB. How much the bargaining outcome affects the control level by the infested municipality thus the probability of spread of EAB depends on the relative abundance of public lands in the infested municipality. The effect of q_1 on the probability of spread is two-fold.

1) Extensive margin effect: as q_1 increases, more land is subject to bargaining, which should decrease the probability of spread.

2) Intensive margin effect: as q_1 increases, a dollar of transfer payment yields less benefit because it is spread over a greater land base, therefore, the effect of transfer payment on controlling the spread declines. As a result, the probability of spread decreases at a lower rate as q_1 increases.

Then probability of spread changes over time as follows:

$$\dot{p}_t = f(p(t)) - q_1 b(q_1)\tau(t) \tag{4.4}$$

In equation 4, q_1 in the second term on the right hand side represents the extensive margin effects. The intensive margin effect is captured by $b(q_1)$ where $b'(q_1) < 0$, so that an increase in q_1 results in a declining marginal control effect for a dollar of transfer payment.

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[19] In this model we assume that the two municipalities are the same except for the initial state of infestation. Therefore, the net benefit functions are the same for the public and private land owners in the two municipalities when they are infested under no bargaining, ($V(0)_1^g = V(0)_2^g$ and $V(0)_1^p = V(0)_2^p$). Net benefits to the uninfested municipality decline when it gets infested as the infestation results in loss of non-market benefits and/or increase in control costs. Therefore $\bar{V}^g > V(0)_2^g$ and $\bar{V}^p > V(0)_2^p$ for the uninfested municipality.

The net benefit of infested municipality after switching to bargaining is the sum of net benefits from implementing more control activities, transfer payment in each period and the net benefits from private control[20].

$$J_I(\tau(t)) = \int_{t=o}^{T} e^{-\rho t}[(q_1 V(\tau(t)) + \tau(t)]dt + \int_{t=0}^{T} e^{-\rho t}(1-q_1)V(0)_1^p)dt \tag{4.5}$$

where $V(\tau(t))$ is the annual net benefits of controlling to public land owners in the infested municipality when bargaining agreement occurs. Transfer payments compensate for more control activities in the infested municipality. More control increases the cost of control and also decreases the non-market benefits via removal of infected host trees. Therefore, following Cobourn et al (2016), the net benefit function for the infested municipality is defined as a decreasing and concave function of transfer payment $(V' > 0\, ; V'' < 0)$ [21]. Net benefits to the uninfected municipality in the bargaining becomes,

$$J_U(\tau(t)) = \int_{t=0}^{T} e^{-\rho t}[((1-p_t)(q_2\bar{V}^g + (1-q_2)\bar{V}^p)) + (p_t(q_2 V(0)_2^g + (1-q_2)V(0)_2^p)) - \tau(t)]dt \tag{4.6}$$

For bargaining to occur, the transfer payments received by the infested municipality at any time period should exceed the losses incurred due to their increased control efforts, and the transfer payments of the uninfested municipality should not exceed the gains due to decreased risk of

[20] In this model we assume that bargaining only affects the control activities, thus the net benefits of the public land owners. Following Cobourn et al. (2016) we assume that level of control and transfer payment are closely related and specify the net benefit function to the public land owner as a function of transfer payment only. Control activities by the private land owners under bargaining are assumed to be the same as to those under no bargaining. Therefore, the net benefit functions for the private land owners are the same for with and without bargaining.

[21] Here the transfer payment is assumed to be an index which is closely related to the level and intensity of control activities. Non-market benefits function of Ash trees is increasing and concave in transfer payment; cost of controlling the invasion is decreasing and convex; therefore, the net benefit function is decreasing and concave in transfer payment.

infestation. The bargaining region (bargaining contract curve) depends on the path of transfer payment, net benefits to municipalities and probability of spread as shown below.

$$q_1\left[V(0)_1^g - V(\tau(t))\right] \le \tau(t) \le \left(p(t)\,|_{\tau=0} - p_t\right)\left[\left(q_2\bar{V}^g + (1-q_2)\bar{V}^p\right) - \left(q_2V(0)_2^g + (1-q_2)V(0)_2^p\right)\right]$$

The upper bound of the transfer payments satisfying the bargaining contract curve increases when the probability of spread of invasion under uncoordinated control increases relative to that under bargaining $\left(p(t)\,|_{\tau=0} - p_t\right) > 0$ and/or the potential losses from the infestation to the uninfested municipality with bargaining increases relative to losses with no bargaining. The lower bound is determined by the relative difference of the gains to the infested municipality under uncoordinated control and bargaining. The range of the bargaining region decreases when $V(0)_1^g$ and q_1 increases.

4.2.1. Social planner's problem (Full cooperation)

Social planner choses the transfer payment over time to maximize net benefits of both the municipalities,

$$\max_{\tau(t)}(J_I(\tau(t)) + J_U(\tau(t))) \tag{4.7}$$

subject to

$$\dot{p}_t = f(p_t) - q_1 b(q_1)\tau(t)$$

and initial condition $p(0) = p_0$.

The Hamiltonian for this problem can be written as,

$$H(p,\tau^{sp},\lambda,t,q_1,q_2)=\left[\left(q_1V(\tau(t)^{sp})+\tau(t)^{sp}\right)+(1-q_1)V(0)_1^p\right]+$$
$$\left[((1-p_t)(q_2\bar{V}^g+(1-q_2)\bar{V}^p))+(p_t(q_2V(0)_2^g+(1-q_2)V(0)_2^g))-\tau(t)^{sp}\right]+$$
$$\lambda(t)\left[f(p_t)-q_1b(q_1)\tau(t)^{sp}\right]$$

where $\tau(t)^{sp}$ is the path of transfer payment that solves (7).

Necessary and sufficient conditions for this problem are given below.

$$\frac{\partial H(.)}{\partial\tau(t)^{sp}}=q_1V'(\tau(t)^{sp})-q_1b(q_1)\lambda(t)=0 \tag{4.8}$$

$$\frac{\partial H(.)}{\partial p_t}=\left(q_2(\bar{V}^g-V(0)_2^g)\right)+\left((1-q_2)(\bar{V}^p-V(0)_2^p)\right)-\lambda(t)f'(p_t)=\dot{\lambda}(t)-\rho\lambda(t) \tag{4.9}$$

$$\lambda(T)=0 \tag{4.10}$$

From (8) $\lambda(t)=\dfrac{V'(\tau(t)^{sp})}{b(q_1)}$ and $\dot{\lambda}(t)=\dfrac{V''\dot{\tau}(t)^{sp}}{b(q_1)}$

Then equation (9) becomes

$$\left(q_2(\bar{V}^g-V(0)_2^g)\right)+\left((1-q_2)(\bar{V}^p-V(0)_2^p)\right)-\frac{V'(\tau(t)^{sp})}{b(q_1)}f'(p_t)=\frac{V''\dot{\tau}(t)^{sp}}{b(q_1)}-\rho\frac{V'(\tau(t)^{sp})}{b(q_1)}$$

Then, the path of socially optimal transfer payment $(\dot{\tau}(t)^{sp})$ is

$$\dot{\tau}(t)^{sp}=b(q_1)\frac{\left(q_2(\bar{V}^g-V(0)_2^g)\right)+\left((1-q_2)(\bar{V}^p-V(0)_2^p)\right)}{V''}+\frac{(\rho-f')V'}{V''} \tag{4.11}$$

The rate at which the path of socially optimal transfer payment $(\dot{\tau}(t)^{sp})$ increasing or decreasing over time depends on the magnitudes of the first and second term in the left-hand side of the equation 11. Particularly the difference between the discount rate and the growth rate of probability of spread $(\rho-f')$, the amenity values of public and private lands in the uninfested municipality, and the intensive margin effects of the proportion of public lands$(b(q_1))$ in the infested municipality determine the time path of the transfer payment.

When the discount rate is greater than the growth rate of probability of spread ($(\rho-f')>0$), the second term in the right hand side is negative implying that the path of transfer payment decreases over time. However, the intensive margin has an opposite effect on the time path of transfer payment. Recall that $b'(q_1) < 0$. Therefore, an increase in q_1 decreases the rate at which the path of transfer payment changes over time. When there are more publicly-owned lands in the infested municipality, the intensive margin of public control decreases therefore the efficacy of control decreases. This increases the probability of EAB spreading to the uninfested municipality. Therefore, optimal control of EAB needs transfer payments taking place over a relatively longer period of time.

4.2.2 Nash Bargaining problem

The two municipalities bargain over a transfer payment to maximize the product of the net gains from bargaining.

$$\max_{\tau(t)} (J_I(\tau(t)) - d_I)^{\gamma_I} (J_U(\tau(t)) - d_U)^{\gamma_U} \tag{4.12}$$

subject to

$$\dot{p}_t = f(p_t) - q_1 b(q_1)\tau(t)$$

and initial condition $p(0) = p_0$.

$0 \le \gamma_I \le 1; 0 \le \gamma_U \le 1; \gamma_I + \gamma_U = 1$ where γ_I and γ_U respectively are bargaining power of the infested and uninfected municipalities.

Following Ethamo et al (1988), the Hamiltonian for this problem can be written as,

$$\begin{aligned} H(p, \tau^B, \lambda, t, q_1, q_2, \mu_I, \mu_U) = {} & \mu_I \left[\left(q_1 V(\tau) + \tau(t)^B \right) + (1-q_1)V(0)_1^p - d_I \right] + \\ & \mu_U \left[((1-p_t)(q_2 \bar{V}^g + (1-q_2)\bar{V}^p)) + (p_t(q_2 V(0)_2^g + (1-q_2)V(0)_2^p)) - \tau(t)^B - d_U \right] + \\ & \lambda(t) \left[f(p_t) - q_1 b(q_1)\tau(t)^B \right] \end{aligned}$$

where $\mu_I = \gamma_I (J_I(\tau(t)^B) - d_I)^{\gamma_I - 1} (J_U(\tau(t)^B) - d_U)^{\gamma_U}$

$$\mu_U = \gamma_U (J_I(\tau(t)^B) - d_I)^{\gamma_I} (J_U(\tau(t)^B) - d_U)^{\gamma_U - 1}$$

μ_I and μ_I are weights[22] for the infested and uninfested municipality which are functions of relative net gains from bargaining and bargaining power coefficients; $\tau(t)^B$ is the path of transfer payment that solves (12).

Necessary and sufficient conditions for this problem are given below.

$$\frac{\partial H(.)}{\partial \tau(t)^B} = \mu_I [q_1 V'(\tau(t)^B) + 1] - \mu_U - q_1 b(q_1)\lambda(t) = 0 \tag{4.13}$$

$$\frac{\partial H(.)}{\partial p_t} = \mu_U \left(q_2(\overline{V}^g - V(0)_2^g)\right) + \left((1-q_2)(\overline{V}^p - V(0)_2^p)\right) - \lambda(t) f'(p_t) = \dot{\lambda}(t) - \rho\lambda(t) \tag{4.14}$$

$$\lambda(T) = 0 \tag{4.15}$$

From (13) $\lambda(t) = \dfrac{\mu_I [q_1 V'(\tau(t)^B + 1)] - \mu_u}{q_1 b(q_1)}$ and $\dot{\lambda}(t) = \dfrac{\mu_I [q_1 V'' \dot{\tau}(t)^B]}{q_1 b(q_1)}$

Then equation (14) becomes

$$\mu_U \left(q_2(\overline{V}^g - V(0)_2^g)\right) + \left((1-q_2)(\overline{V}^p - V(0)_2^p)\right) - \frac{\mu_I [q_1 V'(\tau(t)^B) + 1] - \mu_U}{q_1 b(q_1)} f'(p(t)) = \frac{\mu_I [q_1 V'' \dot{\tau}(t)^B]}{q_1 b(q_1)} - \rho \frac{\mu_I [q_1 V'(\tau(t)^B) + 1] - \mu_U}{q_1 b(q_1)}$$

Then, the path of optimal transfer payment $(\dot{\tau}(t)^B)$ under bargaining is

[22] These Hamiltonian weights are defined in a manner that smaller weights are associated with the municipality that is more likely to get gains from the bargaining (i.e. the municipality with lower bargaining power), so that the bargaining outcomes favor the municipality with lower net gains.

$$\dot{\tau}(t)^B = \frac{\mu_I}{\mu_U}\left[b(q_1)\frac{\left(q_2(\bar{V}^g - V(0)_2^g)\right)+\left((1-q_2)(\bar{V}^p - V(0)_2^p)\right)}{V''}\right] + \frac{(\rho - f')V'}{V''} + \left(\frac{(\rho - f')}{q_1 V''}\right)\left[\frac{\mu_I - \mu_U}{\mu_I}\right] \tag{4.16}$$

In contrast to the first-best solution, now the path of transfer payment is affected by both the extensive and intensive margins of the ratio of public land to private lands in the infested municipality. However, bargaining solution path is similar to that of the first-best solution when $\mu_I = \mu_U$. If the discount rate is greater than the growth rate of probability of spread $((\rho - f') > 0)$, then the direction of the time path depend on how the net benefits of each municipality are weighted in the bargaining via μ_I and μ_U. If $\mu_I > \mu_U$, the path of transfer payment decreases over time. When $\mu_I < \mu_U$, relative magnitudes of intensive margin and extensive margin effects determine the time path. The comparative statistics for these effects are derived by differentiating the equation 16 with respect to of q_1 as follows.

$$\frac{\partial \dot{\tau}(t)^B}{\partial q_1} = \left[\frac{\mu_I}{\mu_U} b'(q_1)\left(\frac{\left(q_2(\bar{V}^g - V(0)_2^g)\right)+\left((1-q_2)(\bar{V}^p - V(0)_2^p)\right)}{V''}\right)\right] - \left[\frac{1}{q_1^2}\left(\frac{(\rho - f')}{V''}\right)\left(\frac{\mu_I - \mu_U}{\mu_I}\right)\right] \tag{4.17}$$

The first term in the right-hand side of the equation 17 shows the influence of intensive margin effect while the second term shows the influence of extensive margin effect on the time path of transfer payment under bargaining. The first term is positive indicating positive effects from intensive margin on the rate of transfer payment path; this effect is qualitatively similar to that of the social planner's problem. The sign of the second term changes with the signs of $(\rho - f')$ and $(\mu_I - \mu_U)$. When $(\rho - f') > 0$ and $\mu_I > \mu_U$, influence of extensive margin effect on the time path of transfer payment is negative. Relative magnitudes of intensive margin and extensive margin effects determine the rate at which the path of transfer payment declines over time. If the influence of intensive margin is greater (less) than that of the extensive margin, the path of transfer payment decline less (more) rapidly. When $(\rho - f') > 0$ and $\mu_I < \mu_U$, influence of extensive margin effect on the time path of transfer payment becomes positive while intensive margin effects remain the same.

4.2.3 Comparison of social planner's and Nash bargaining paths

Equation (4.18) shows how the time paths of transfer payment and bargaining deviate from each other depending on the difference between the discount rate and the growth rate of probability of spread $(\rho - f')$, the bargaining weights (μ_I and μ_U), the parameters of extensive margin effect (*q)* and the intensive margin effect (*b(q)*) on the transfer payment.

$$\dot{\tau}(t)^{sp} - \dot{\tau}(t)^{B} = \frac{\mu_I - \mu_U}{\mu_I}\left[\left(b(q_1)\left(\frac{\left(q_2(\bar{V}^{g} - V(0)_2^{g})\right) + \left((1-q_2)(\bar{V}^{p} - V(0)_2^{2})\right)}{V''}\right)\right) - \left(\frac{(\rho - f')}{q_1 V''}\right)\right] \quad (4.18)$$

When $\mu_I = \mu_U$ paths of transfer payment are identical. When $\mu_I \neq \mu_U$ and, the difference of paths are determined by the relative influence of extensive and intensive margins and the difference between the discount rate and the growth rate of probability of spread $(\rho - f')$. Suppose, the growth rate of the spread probability is greater than the discount rate $(\rho - f') > 0$ and the Nash bargain weights favor the infested municipality ($\mu_I > \mu_U$), the extensive margin effect is positive while intensive margin effects is negative. Then, the two time paths get closer if the absolute effect of extensive and intensive margins becomes similar in magnitude. If the intensive margin effect is greater (smaller) than the extensive margin, then the time path of transfer payments in Nash bargaining changes more (less) rapidly than the time path of social planner's solution.

Social cost associated with the bargaining solution can be calculated by assessing the difference in social planner's value function evaluated at the social optimal $\tau(t)^{S*}$ and the optimal bargaining solution $\tau(t)^{B*}$.

4.3. Numerical simulation

The system of necessary and sufficient conditions for the first-best and bargaining problems above were solved in discrete time in GAMS to evaluate how the efficacy of EAB control is affected by the public and private land ownership under with and without negotiation between the municipalities[23]. Each numerical model was solved for a time period of 10 years[24]. The optimal path of transfer payment and probability of spread for the myopic (uncoordinated) outcome were simulated and using these disagreement outcomes, the bargaining problem was solved following the solution method as of Ethamo et al (1988). In this approach, bargaining outcome is obtained via iterating over the Hamiltonian weights and optimal transfer payment path.

For the base case simulation, initial conditions of the two municipalities are considered the same except the state of the infestation. For example, we assume the public-private land ratio, net benefits of heathy hosts trees and the control cost of EAB (cost of insecticide treatment, removal and replanting) are the same across land owners and across municipalities. Also we assume that benefits of host trees and control costs are the same across public and private land owners. These initial values are based on existing data related to the EAB control costs and economic values of Ash trees in the Twin

[23] Complementary slackness conditions for the system of equations include bounds on the transfer payment $(\tau(t) \geq 0)$and probability of spread $(0 \leq P(t) \geq 1)$.

[24] This terminal period was determined based on the predicted rate of EAB spread as of Kovacs et al (2014).

cities in Minnesota (Coubourn et al. (2016))[25]. The initial values for the ratio of public-private land in the municipalities (q_1=q_2=0.3) are obtained from Kovacs et al (2014)[26].

Following Cobourn et al (2016), we assume a quadratic net benefit function for public land owner. We specify this function as $V(\tau(t))^g = V(0)^g + c\tau(t) + d\tau(t)^2$, $c, d < 0$ which implies that a positive transfer payment reduces to the net benefits to the infested municipality as transfer payments encourage more control activities by the infected municipality. The initial probability of spread was assumed to be 0.5. Further, the intensive margin parameter ($b(q_1)$) that represents efficiency of transfer payment in reducing the probability of spread was fixed at values between 1 and zero. $b(q_1)$ =1 indicates that all transfer payments received by the infested municipality are spent on EAB control in all the public lands within the municipality, and zero indicates that none of the transfer payments are used. In the base case scenario, this intensive parameter was set at 0.5. For the bargaining problem, the base case scenario was evaluated setting the bargaining parameters of each municipality equals to 0.5. Parameters used in the base case simulation are given in Table 4.1 below.

In order to evaluate the effect of land ownership on the socially optimal and bargaining outcomes, simulations are performed for varying level of the proportion of public lands in the infested municipality (q_1). A series of simulations is performed to identify the extensive margin and intensive margin effects of land ownership in these scenarios. Sensitivity of the model outputs are evaluated for free-riding by private land owners in the infested municipality and relative bargaining power of the two municipalities.

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[25] In Coburn et al (2016), the net benefits for each municipality was calculated assuming a municipality having 20,000 Ash trees in the public domain and the non-market benefits per tree is $94 which gives net benefits of a municipality when there is no infestation is $1.88 million. When infested, a municipality spends about $1million annually, and then the net benefits decrease to $0.8 million.

[26] Kovacs et al. (2014) considered street trees in residential and non-residential areas as public goods and calculated that 30 percent of ash trees in Twin Cities belong to this category. Following these authors, we consider 30 percent of host trees are in public land 70 percent in the private lands.

Table 4.1. Parameter values used in the base case simulations

Parameter	Description	Initial value
q_1, q_2	Public land to private land ratio (0,1)	0.3
P	Discount rate	0.02
$\bar{V}^g$	Annual net benefits to public land owners in the municipality when it remains uninfected ($ million)	1.88
$V(0)_i^g$	Annual net benefits to public land owners when i^{th} municipality is infested and there is no transfer payment ($ million)	0.88
$\bar{V}^p$	Annual net benefits to private land owners in the i^{th} municipality when it remains uninfected ($ million)	1.88
$V(0)_i^p$	Annual net benefits to private land owners when a municipality is infested and there is no transfer payment ($ million.)	0.88
c	Linear parameter, net benefits of ash trees in infested municipality as a function of transfer payments	–0.273
D	Quadratic parameter, net benefits of ash trees in infested municipality as a function of transfer payments	–0.826
P_0	Initial probability of spread	0.5
r	Growth rate in the probability of spread	0.08
B	Intensive margin parameter of public-private land ratio on efficacy of in reducing probability of spread	0.5
$\gamma_{I,U}$	Bargaining power coefficients	0.5

4.4. Results

This section presents the major results from the numerical simulation. First it discusses the results for the model simulated using the initial parameters in Table 4.1. Then the extensive and extensive margin effects on the bargaining outcome are explained following a discussion of sensitivity analysis of parameters of interest.

4.4.1 Results for the base case

Table 4.2 shows the simulation results of the uncoordinated problem, social planner's problem and the Nash bargaining problem for the base case scenario[27]. As to the findings in Table 4.2, the optimal path of transfer payment in both the social planner's problem and bargaining problem decreases over time, however, the decline of the transfer payment path in the social planner's problem is more rapid than that of the bargain problem. The theoretical model for the social planer's problem suggests that the intensive margin effects cause the declining time paths for the transfer payments. The extra effect from of the extensive margin is the reason for the less rapid decline in the transfer payment path in the bargaining problem. The empirical results confirm the theoretical expectation of the opposite effects of extensive and intensive margin effects of land ownership on the efficacy of control activities.

In the base case scenario, the uncoordinated outcome does not involve a transfer payment across the municipalities and both the municipalities are worse-off relative to the social optimum and also to the bargain outcome. Social cost of uncoordinated outcome is about 5.8 million which exceeds the total transfer payments in each of the first-best and bargain outcomes. When the municipalities are not coordinating the control activities, the pest spread from the infested municipality to the uninfested municipality with 100 percent probability within 8 years. This is in contrast to the expectation of social planner where a transfer payment from the uninfested municipality during the first 4 years completely controls the EAB infesting the uninfested municipality.

[27] The base case bargaining problem converged after 12 iterations. Final Hamiltonian weights were 0.436 and 0.573 for the infested and uninfested municipalities, respectively.

Table 4.2. Results for the base case scenario (q_1=0.3, b=0.5)

Time periods	Uncoordinated problem	Social planner's problem		Bargaining problem	
(years)	p(t)	p(t)	tau(t)	p(t)	tau(t)
1	0.54	0.309	1.541	0.367	1.155
2	0.583	0.163	1.136	0.254	0.945
3	0.63	0.063	0.755	0.163	0.748
4	0.735	0.008	0.397	0.091	0.563
5	0.793	-	0.061	0.04	0.388
6	0.857	-	-	0.01	0.225
7	0.925	-	-	-	0.071
8	1	-	-	-	-
9	1	-	-	-	-
10	1	-		-	-
Total transfer payments [a]	-	3.89		4.095	
Net benefits, infested	8.063	10.486		10.892	
Net benefits, uninfested	10.213	12.877		12.366	
Total net benefits	18.276	23.363		23.258	
Social costs	5.83	-		0.105	

[a] Transfer payments and social costs values are given in million dollars.

Outcome from the bargaining involves higher total transfer payments, longer time span to reach complete control of the invasions compared to the social optimum. However, social cost of bargaining is relatively smaller compared to that of the uncoordinated control and bargaining generates more net benefits to both the municipalities than the uncoordinated control. These results suggest that uncoordinated outcome is less efficient and needs to be avoided for the optimal control of EAB in these municipalities.

4.4.2 Simulation results for varying level of public-private land ownership in infested municipality (q_1)- extensive margin effect

In order to evaluate the effect of the extensive margin effect of public-private land ownership on the bargaining outcome, simulation was performed for the base case scenario at varying levels of q_1 holding all the parameters constant at their initial values. In this exercise, the intensive parameter (*b*) was held constant at the initial value of 0.5 to identify the extensive margin effect of efficacy of control on the bargaining outcome. The results for this exercise given in the Table 4.3 below suggest that uncoordinated control efforts are to be avoided at all the levels of public-private land ownership and bargaining between the municipalities yields benefits to both the parties[28]. It is noted that when proportion of public lands within infested municipality increases, total transfer payments that maximize benefits decreases. As suggested by our theoretical model, when the relative abundance of public lands in the infested municipality increases, the rate at which the transfer payment changes over time decreases. When the proportion of public lands in the infested municipality increases, more public lands are subjected to control efforts (extensive margin effect). As a result, the risk of invasion to the uninfested municipality and the need for control decrease, therefore, optimal control can be achieved with relatively smaller transfer payments made through out time. If the infested municipality has a smaller proportion of public lands, larger transfer payments are required to encourage control efforts. This implies that having more public lands within infested municipality encourages cooperative action by the municipalities.

Figure 4.1 below represents the time paths of optimal transfer payment for first-best and bargain outcomes and the bargaining region (upper and lower bounds for the transfer payment) for the

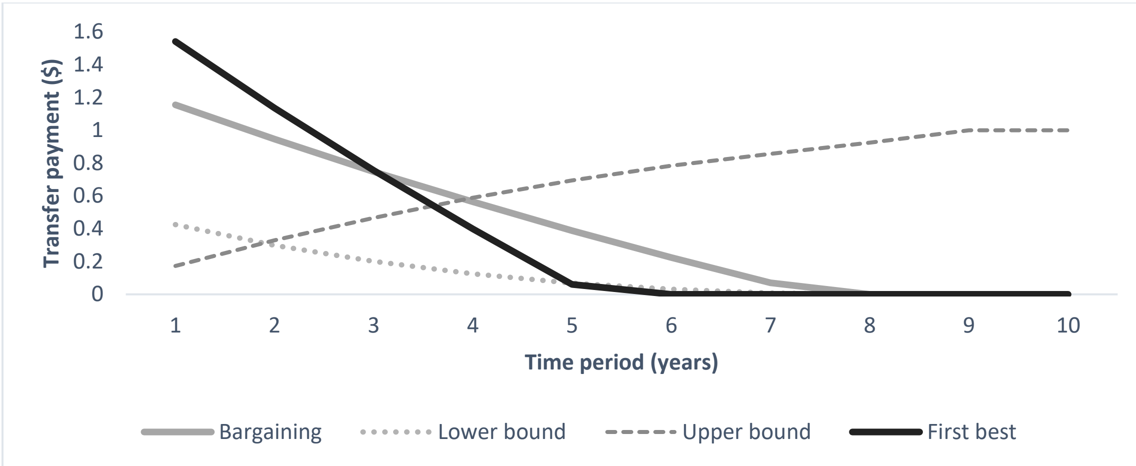
[28] For bargaining to take place, the objective functional for municipalities should exceed the threat point, i.e. $J_I(\tau(t)^B) > d_I$ and $J_U(\tau(t)^B) > d_U$. When q_1<0.3, these conditions did not hold, thus the simulation model did not converge. Similarly, for the intensive margin effect, the model did not converge when b<0.4.

base case and varying level of public-private land ownerships. For the base case (q_1=0.3), the optimal time path for the bargain problem lies outside the bargain region until the fourth year. It falls inside the bargaining region thereafter indicating that it takes 4 years to reach a bargaining agreement between the two municipalities. When q_1 increases to 0.5, bargaining agreement is reached after 3 years. With q_1=0.9, it takes 2 years for the transfer payment paths to fall within the bargaining region. These results suggest that infested municipalities with high public land ownerships are more committed for the bargaining agreement and take less time to reach to an agreement with other parties.

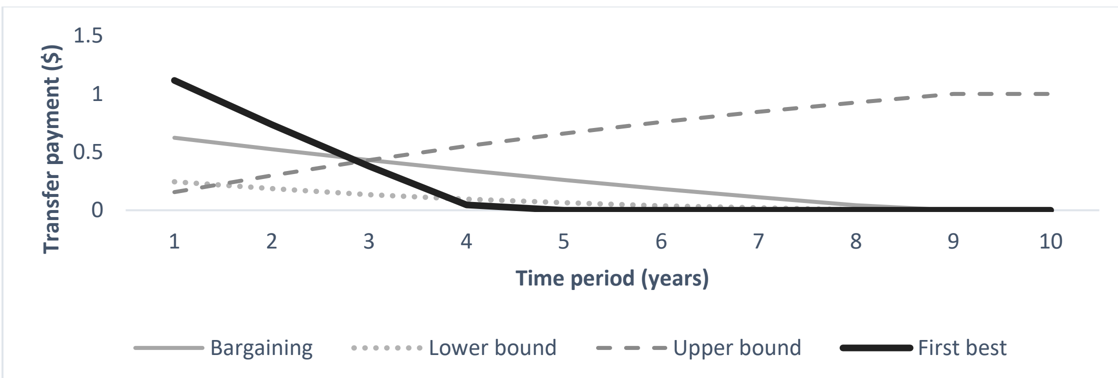
Table 4.3. Simulation results for the varying level of public-private land ownership (*b*=0.5)

Time period	q_1=0.3		q_1=0.5		q_1=0.7		q_1=0.9	
(year)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)
1	0.367	1.155	0.384	0.623	0.389	0.430	0.393	0.326
2	0.254	0.945	0.284	0.524	0.293	0.365	0.300	0.278
3	0.163	0.748	0.199	0.431	0.210	0.303	0.219	0.233
4	0.091	0.563	0.129	0.343	0.141	0.245	0.151	0.190
5	0.040	0.388	0.075	0.261	0.086	0.191	0.096	0.150
6	0.010	0.225	0.035	0.183	0.044	0.139	0.053	0.112
7	-	0.071	0.010	0.111	0.016	0.091	0.023	0.077
8	-	-	-	0.042	0.001	0.046	0.005	0.043
9	-	-	-	-	-	0.003	-	0.012
10	-	-	-	-	-	-	-	-
Total transfer payments [a]		4.095		2.518		1.813		1.421
Net benefits, infested municipality		10.892		9.714		9.166		8.858
Net benefits, uninfested municipality		12.366		13.725		14.343		14.668
Net benefits, total		23.258		23.439		23.509		23.526
Social cost, Bargaining		0.105		0.383		0.549		0.677
Social cost, Uncoordinated		5.087		5.546		5.782		5.958

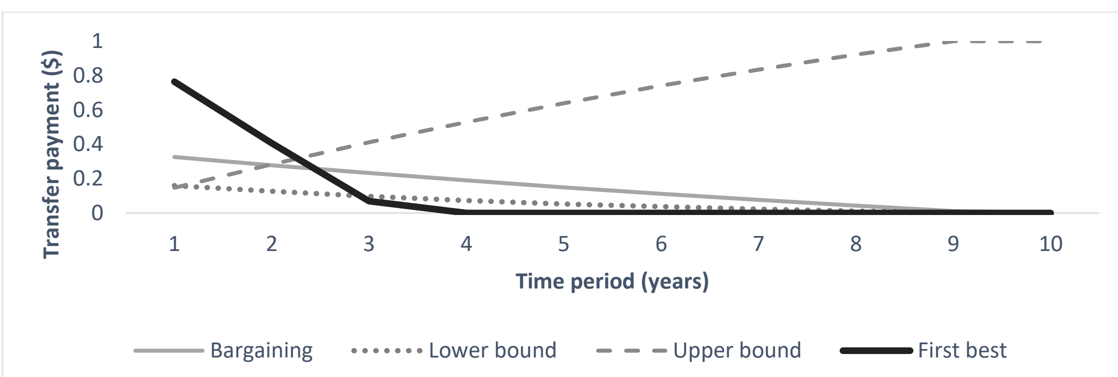
[a] Transfer payments and social costs values are given in million dollars.



(a) Base case q_1=0.3, b=0.5



(b) q_1=0.5, b=0.5



(c) q_1=0.9, b=0.5

Figure 4.1. Time paths of optimal transfer payment for first-best and bargain outcome and bargaining regions with varying levels of land ownership in the infested municipality

4.4.3 Simulation results for varying level of efficacy of public-private land ownership (*b*)-intensive margin effect

To identify the intensive margin effects of land ownership, numerical solutions were obtained for different values of intensive margin effect parameter while holding all other parameters of the base case at their initial level (q_1 is held constant at 0.3 to highlight the intensive margin effect). The results for this exercise are given in Table 4.4 and are consistent with the theoretical expectations. With higher intensive margin effects (when the parameter *b* is large), lower levels of transfer payments in total are required to encourage effective control of EAB. Further, the optimal transfer payment path declines at a lower rate with larger value of *b*. This is because when the amount of transfer payment spent on the control activities per acreage of public lands is high, more control activities are implemented resulting in less risk of spread of the pest across municipalities. Relatively small transfer payments paid over larger span of time can motivate the infected municipality to control the pest. However, at very low levels of intensive margin where the efficacy of transfer payment on control is low, the transfer payment becomes an ineffective instrument for EAB control. For example, when b=0.4, a total of 4.3 million dollars is paid to the infested municipality over a 6-year time period, however, the efficacy of control is too low that the probability of spread of the invasion does not reach zero at the end of the bargaining time period.

Figure 4.2 below represents the time paths of optimal transfer payment for first-best and bargain outcome and bargaining region for the base case and varying level of intensive margin parameter (*b*). When the intensive parameter is high or when the transfer payments are effectively used in control activities by the infested municipality, a bargain agreement is reached sooner. For example, when b=0.5, the two municipalities agree for committing the cooperative control within 4 years and it decreases to less than 4 years when b>0.5. Similar to the extensive margin effects, the empirical results for the intensive margin effects suggest that efficient use of transfer payments allows better control of invasive pests across municipalities and ensures commitment to bargain by parties involved.

4.4.4 Sensitivity analysis

Simulation results for bargaining with free-riding by private land owners

Control efforts in the public land in the infested municipality reduce the spread of disease to neighboring private lands. Therefore, private land owners may under-control the infestation in their properties. This may reduce the overall efficacy of control within the infested municipality and encourage the risk of invasion spread to the uninfested municipality affecting the coordinated control. To evaluate this, we simulate the effect of free-riding by the private landowners in the infested municipality on the bargain outcome. With free-riding, the total net benefits to the infested municipality arise only from the public control and the net benefit function in equation 5 becomes

$$J_I(\tau(t)) = \int_{t=o}^{T} e^{-\rho t}[(qV(\tau(t)) + \tau(t)]dt \qquad (4.19)$$

Numerical simulation results for the base case with this adjustment to the net benefit function of the infested municipality and with varying level of private land ownership are summarized in Figure 4.3 below. These results suggest that bargaining outcome is significantly affected by inefficiencies associated with free-riding. Simulation results for the probability of spread in panel (a) of Figure 4.3 confirms that with zero control efforts from the private land owners, transfer payment is less effective in controlling the spread of invasion to the uninfected municipality, specifically at lower levels public land ownership within the infested municipality. For example, with free-riding in the base case scenario and with lower levels of public lands (q_1=0.4), complete control of the spread of invasion cannot be achieved during the 10-year time period we considered in this analysis. With less contribution to control of the invasion by the private land owners, invasion spread from the infested municipality to the uninfested municipality at 100 percent probability by the end of this period. If the infected municipality consists of more public lands and more public lands are subjected to control activities, efficacy of control increases

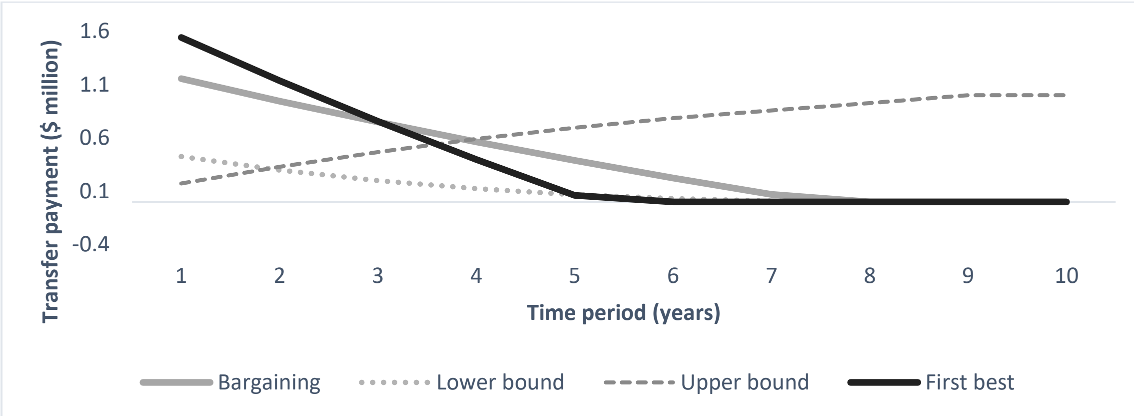
restricting the spread of invasion to the uninfested municipality. In this case, smaller transfer payments made over relatively longer time span compared to the bargaining without free-riding case would successfully control the infestation. For example, when q_1 increases from 0.3 to 0.5, the infestation is contained within the infested municipality by the end of year 9 resulting in increasing net benefits especially to the uninfested municipality (See Appendix A for more details of the simulation results).

With free-riding by the private land owners, incentives to bargain decline and total transfer payments and net benefits to municipalities decrease. However, these effects decline when there more public lands become available for control activities in the infested municipality (panel (a), Figure 4.3). For example, at the initial level of public land ownership of q_1=0.3, total transfer payments decrease by 93 percent, net benefits to infested and uninfested municipalities decrease by 76 percent and 16 percent respectively with free-riding compared to those in the base case without free-riding. When q_1 increases to 0.7, total transfer payments and net benefits to infested and uninfested municipalities only reduce by 43, 53 and 6 percent respectively (See Appendix 4A). However, compared to the coordinated control without free-riding, infested municipality receives less amount of total transfer payment and both the municipalities receives less net benefits at all levels of the land ownership due to free-riding. These results highlight the importance of internalizing the private benefits to achieve optimal control of the invasion.

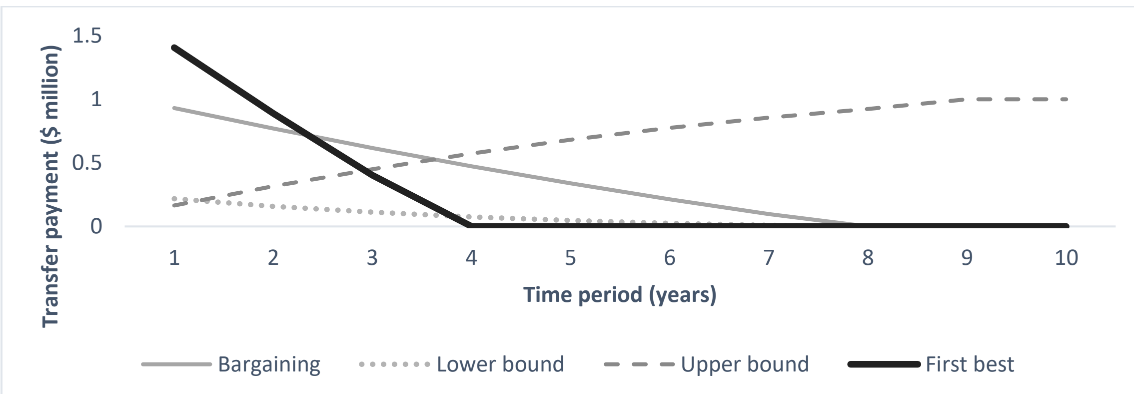
Table 4.4. Simulation results for the varying level of intensive margin parameter (q_1=0.3)

Time period	*b*=0.4		*b*=0.5		*b*=0.6		*b*=0.7		*b*=0.9	
(year)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)
1	0.371	1.411	0.367	1.155	0.372	0.931	0.375	0.787	0.375	0.686
2	0.267	1.108	0.254	0.945	0.264	0.769	0.268	0.653	0.269	0.569
3	0.190	0.822	0.163	0.748	0.174	0.617	0.178	0.526	0.180	0.460
4	0.139	0.555	0.091	0.563	0.103	0.473	0.107	0.407	0.109	0.357
5	0.114	0.303	0.040	0.388	0.050	0.339	0.054	0.296	0.055	0.260
6	0.115	0.066	0.010	0.225	0.016	0.213	0.018	0.191	0.019	0.169
7	0.124	-	-	0.071	-	0.097	-	0.092	0.0005	0.083
8	0.134	-	-	-	-	-	-	-	-	0.003
9	0.145	-	-	-	-	-	-	-	-	-
10	0.156	-	-	-	-	-	-	-	-	-
Total transfer payments [a]		4.265		4.095		3.439		2.952		2.587
Net benefits, infested municipality		10.826		10.892		10.564		10.283		10.051
Net benefits, uninfested municipality		11.440		12.366		12.957		13.405		13.751
Net benefits, total		22.266		23.258		23.522		23.688		23.802
Social cost, Bargaining		0.480		0.105		0.235		0.341		0.426
Social cost, Uncoordinated		4.470		5.087		5.481		5.753		5.952

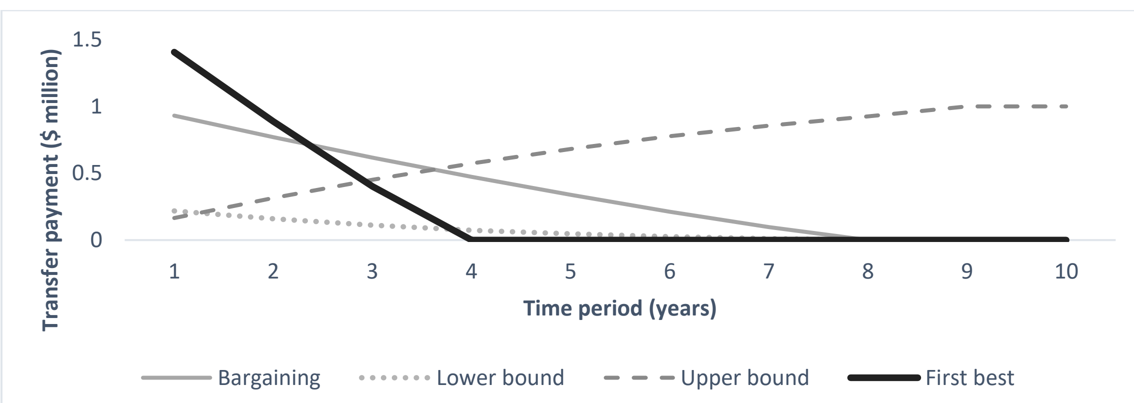
[a] Transfer payments and social costs values are given in million dollars.



(a) Base case q_1=0.3, b=0.5

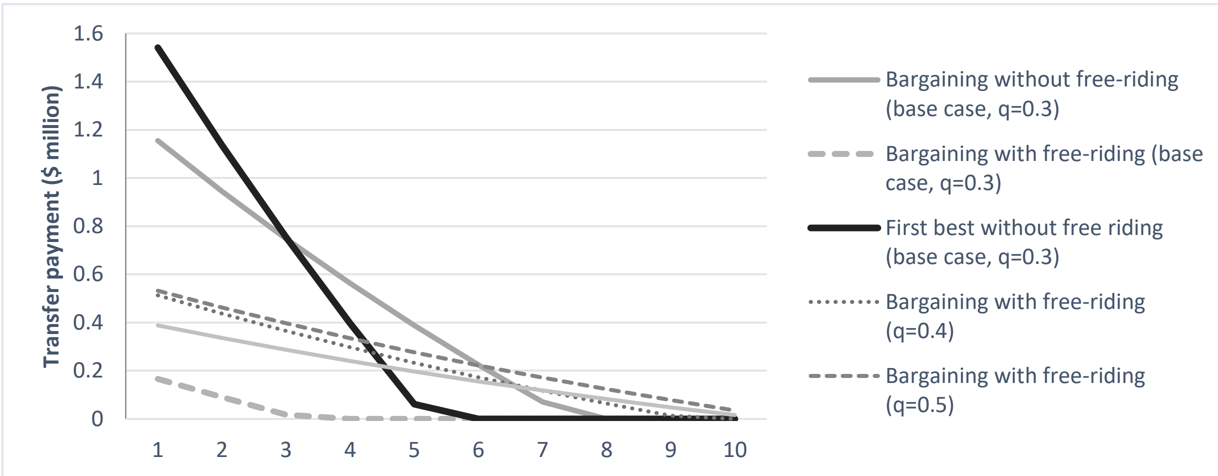


(b) q_1=0.3, b=0.7

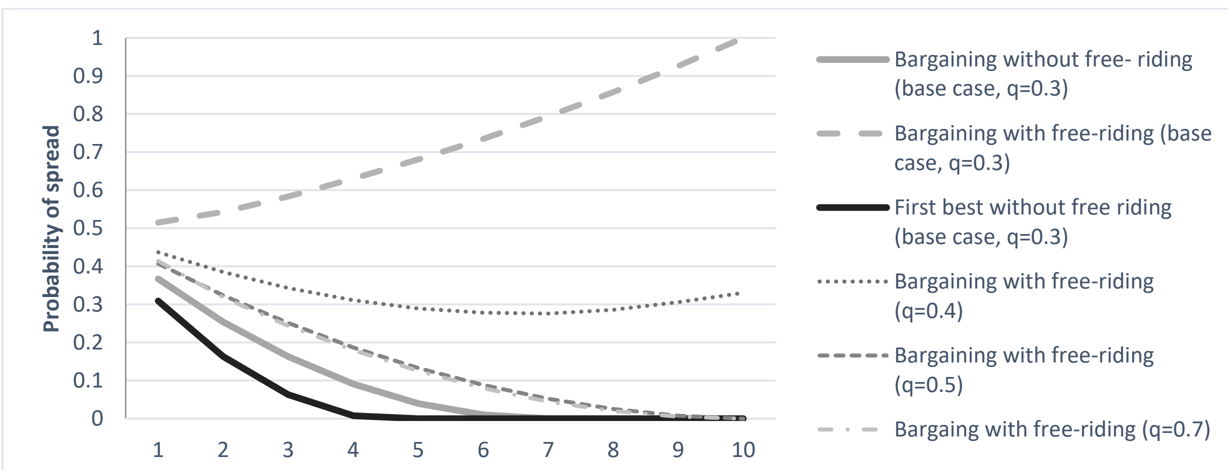


(c) q_1=0.3, b=0.9

Figure 4.2. Time paths of optimal transfer payment for first-best and bargain outcome and bargaining regions for varying level of intensive margin effect parameter (b)



(a) Transfer payment paths



(b) Probability of spread of invasion

Figure 4.3. Time paths of optimal transfer payment and probability of spread for first-best and bargain outcome with free-riding by private land owners in the infested municipality

Bargaining power of municipalities

Numerical solutions for the base case discussed above are obtained assuming the infested and uninfected municipalities have same bargaining power (γ_1=0.5). However, this assumption may not hold in actual conditions as municipalities are more likely to be different from each other in terms of the bargaining power. For example, the infested municipality is more likely to have low bargaining power because it needs to implement costly control to eradicate the invasion already existing there regardless of the transfer payments received from the uninfested municipality. In fact, the bargaining power of municipalities decides which municipality's objectives are more weighted in maximizing gains from bargaining, thereby affects the bargaining outcome. In order to evaluate these effects, we simulate our bargain problem augmenting the base case model with varying levels of bargaining power parameter, and explore how extensive and intensive margin effects influence the optimal transfer payments.

Table 4.5 below summarizes the bargaining outcomes when bargaining power of infested municipality (γ_I) increases and shows how the extensive and intensive margin effects are influenced by bargaining power. The first 3 columns in this table compare transfer payment paths when the bargaining power of the infested municipality increases from 0.3 to 0.7 holding public land ownership in the infested municipality constant at q_1=0.3. The results suggest that when bargaining power of the infested municipality increases, the time path of transfer payments becomes longer, and gains from bargaining to the uninfested municipality increases while gains to the infested municipality decreases as more weight is given in the bargaining problem (via Hamiltonian weights) to the net benefits of the uninfested municipality. However, when the uninfested municipality gains the bargaining power, i.e. γ_I decreases, the bargaining outcome reaches the social optimum as indicated by lower social costs of bargaining associated with lower $\gamma_{I.}$, and implies that the uninfested municipality having more power to bargain over the transfer payment is better for the society.

Comparison of the transfer payment paths in Table 4.5 at lower public land ownership (q_1=0.3) (in columns 1-3) and higher public land ownership (q_1=0.5) (in columns 4-6) highlights how extensive margin effects changes with varying level of bargaining power. At each level of bargaining power, an increase in public lands in the infested municipality makes the bargaining agreement to take place over a longer period time. When extensive margin effects increase, total transfer payments decrease with increasing bargaining power of the infested municipality. For example, when public lands in the infested municipality increases, total transfer payments made to infested municipality decreases by 39, 38 and 36 percent respectively at γ_I =0.3, 05, and 0.7. On average, net benefits to the infested municipality declines by 10.5 percent, while net benefits to uninfested municipality increases by 10 percent. Further, social cost of bargaining increases significantly due to extensive margin effect.

Simulation results at higher values of intensive margin parameters (eg. b=0.7, in columns 7-9) and at lower values (eg. b=0.5, in columns 1-3) implies that the influence of bargaining power on intensive margin effects are qualitatively similar to those for the extensive margin effects. When intensive effect parameter (b) increases from 0.5 to 0.7, transfer payments are made over longer time span at all levels of bargaining power. On average total transfer payments increases by 27 percent, and net benefits to infected municipality increases by 5 percent while net benefits to the uninfested municipality decreases by 7 percent when bargaining power of infected municipality increases from 0.3 to 0.7.

Table 4.5. Extensive and intensive margin effects on bargaining outcome at varying level of bargaining power

Time period (year)	q1=0.3, b=0.5			q1=0.5, b=0.5			q1=0.3, b=0.7		
	γ_I=0.3 γ_I=0.7	γ_I=0.5 γ_I=0.5	γ_I=0.7 γ_I=0.3	γ_I=0.3 γ_I=0.7	γ_I=0.5 γ_I=0.5	γ_I=0.7 γ_I=0.3	γ_I=0.3 γ_I=0.7	γ_I=0.5 γ_I=0.5	γ_I=0.7 γ_I=0.3
1	1.447	1.155	1.019	0.811	0.623	0.482	1.023	0.787	0.614
2	1.096	0.945	0.861	0.632	0.524	0.427	0.778	0.653	0.537
3	0.766	0.748	0.712	0.463	0.431	0.376	0.548	0.526	0.464
4	0.455	0.563	0.572	0.305	0.343	0.327	0.332	0.407	0.396
5	0.163	0.388	0.441	0.155	0.261	0.281	0.128	0.296	0.331
6	-	0.225	0.317	0.015	0.183	0.238	-	0.191	0.271
7	-	0.071	0.201	-	0.111	0.198	-	0.092	0.214
8	-	-	0.092	-	0.042	0.16	-	-	0.161
9	-	-	-	-	-	0.125	-	-	0.11
10	-	-	-	-	-	0.091	-	-	0.063
Total transfer payments[a]	3.927	4.095	4.215	2.381	2.518	2.705	2.809	2.952	3.161
Net benefits, infested municipality	10.581	10.892	11.058	9.502	9.714	9.909	10.075	10.283	10.494
Net benefits, uninfested municipality	12.781	12.366	12.069	14.222	13.725	13.047	13.864	13.405	12.749
Net benefits, total	23.362	23.258	23.127	23.725	23.439	22.956	23.939	23.688	23.243
Social cost, Bargaining	0.0005	0.105	0.236	0.097	0.383	0.866	0.09	0.341	0.786
Social cost, Uncoordinated	5.087	5.087	5.087	5.546	5.546	5.546	5.753	5.753	5.753

[a] Transfer payments and social costs values are given in million dollars

4.5 Conclusion

In this paper, we have evaluated how bargaining can be used for effective control of invasive species in the municipalities with mixed land ownership. We have used a model that incorporates the dynamics of the invasive species and negotiation between the adjacent municipalities to analyze how public-private land ownership in the municipalities affects the bargaining outcome. We have modeled the bargaining between an infested municipality and an uninfested municipality over fixed transfer payments paid to the former by the latter to encourage greater control of the invasive species in the infested municipality.

Following Cobourn et al. (2016), we have used a Nash bargaining scheme to represent the negotiation between the two municipalities. The model is specified using the information on the bargaining power of each municipality in the negotiation and the threat points at which the municipalities may deviate from the cooperative control. Information on the public-private land ownership of the municipalities are incorporated into the model via the specification of the net benefit functions of each municipality, and the extensive and intensive margin effects of the land ownership in the infested municipality on the optimal control of the bio-invasion are evaluated.

The model suggests that the time path of optimal transfer payment decline over time; extensive margin and intensive margin has opposite effects thus their relative magnitudes determine the rate at which the transfer payment path changes over time. The extensive margin has a negative effect on the rate at which the transfer payment path declines. The extensive margin effects imply that when more public lands in the infested municipality are subjected to control activities, the risk of invasion decreases, thus smaller transfer payments made over a longer time span are sufficient for optimal control. In contrast, when more public lands are available, the intensive margin effects decreases, thus, the efficiency of using the transfer payment on control activities decreases resulting in increases risk of invasion spreading to the uninfested municipality. Therefore, larger transfer payments are paid within the initial periods of invasion implying that the path of transfer payment declines rapidly over time.

We have performed a numerical simulation using data on the Emerald Ash Borer (EAB) invasion in the Twin Cities, Minnesota. The study area comprises of municipalities at various levels of EAB invasion and the local governments implement control activities at various intensities within the municipal boundaries. These local governments do not cooperate with adjacent municipalities; thus the overall control of invasion is less efficient. Moreover, availability and access to lands to implement control activities also affect the efficacy of the control. The municipalities in the study area have different public-private land ownerships within the municipality boundaries; therefore, the uncoordinated control activities implemented by the local governments may be suboptimal. We have used our model to characterize how municipalities with mixed land ownerships can reach optimal control via bargaining as opposed to the uncoordinated control.

The simulation results confirm the use of transfer payment as an effective means for optimal control of bio-invasion at lower social costs compared to the uncoordinated outcome. Extensive margin and intensive margin effects on the bargaining outcome are consistent with theoretical expectations and suggest that having more public lands within infested municipalities encourages greater control via cooperation. Evaluation of the bargaining contract curves implies that infested municipalities with more public lands reach to a bargaining agreement with other parties as soon as the infestations starts and are more committed to the bargaining agreement. Similarly, infested municipalities that efficiently use transfer payments are more likely to implement greater control. Further, our analysis reveals that free-riding by the private land owners decreases the incentive to bargaining, however these effects decline when there are more public lands in the infested municipality are subjected to control efforts. Bargaining power of each municipality also affects the extensive and intensive margin of land ownership. These findings provide insights to local planners and policy makers in future efforts to control bio-invasions.

References

Anulewicz, A.C., D.G. McCullough, D.L. Cappaert, and T.M. Poland, 2008. “Host range of the emerald ash borer (*Agrillus planipennis Fairmaire*) (Coleoprete: Buprestidae) in North America: results of multiple-choice field experiments”. *Environmental Entomology*, 37, 230-241.

Bhat, M.G., and H.G. Huffaker, 2007. “Management of a transboundary wildlife population: a self-enforcing cooperative agreement with renegotiation and variable transfer payments”. *Journal of Environmental Economics and Management*, 54-67.

Couborn, K. M., G.S. Amacher and R.G. Haight, 2016. “Cooperative management of invasive species: a dynamic Nash bargaining approach”. Working paper. Virginia Tech, Blacksburg.

Dunens, E., R. Haase, J. Kuzma and K.Quick, 2013. “Facing the Emerald Ash Borer in Minnesota: stakeholder understandings and their implications for communication and engagement”. Humphrey School of Public Affairs, University of Minnesota.

Ehtamo, H., J. Ruusunen, V. Kaitala, and R.P. Hamalainen, 1988. “Solution for a dynamic bargaining problem with an application to resource management”. *Journal of Optimization Theory and Applications*, 59:391-405.

Epanchin-Niell, R.S., M.B. Hufford, C.E. Aslan, J.P. Sexton, J.D. Port, and T.M. Waring, 2010. “Controlling invasive species in complex social landscapes,” *Frontiers in Ecology and the Environment*, 8:210-216.

Holmes, T.P., E.A. Murphy and K.P. Bell, 2006. “Exotic forest insects and residential property values”. *Agricultural and Resource Economics Review*, 35(1):155-166.

Kaitala, V. and M. Pohjola, M. 1988. “Optimal recovery of a shared resource stock: a differential game model with efficient memory equilibria”. Natural *Resource modelling,* 3: 91-117.

Kovacs, K.F., R.G. Haight, D.G. McCullough, R.J. Mercader, N.W. Siegert and A.M. Leibhold, 2010. “Cost of potential emerald ash borer damage in U.S. communities, 2009-2019”. *Ecological Economics*, 69: 569-578.

Kocavs, K.F., R.J. Mercader, R.G. Haight, N.W. Siegert, D.G. McCullough, D.G. and A.M. Leibhold, 2011. “The influence of satellite populations of emerald ash borer on projected economic costs in U.S. communities, 2010-2020”. *Journal of environmental management*, 92: 2170-2181.

Kovacs, K.F., R.G. Haight, R.J. Mercader, D.G. McCullough. (2014). “A bio-economic analysis of an Emerald ash borer invasion of an urban forest with multiple jurisdictions,” Resource and Energy Economics, 36:270-289.

McPherson, E.G., J.R. Simpson, P.J. Peper, S. Maco, S. Gardner and S. Cozad, 2005. “City of Minneapolis, Minnesota municipal tree resource analysis”. Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station.

Minnesota Department of Agriculture (2014). “Status of Emerald ash borer in Minnesota”. Available at http://files.dnr.state.mn.us/publications/fid/2015/feb/status-eab-minnesota-mda.pdf (accessed 10.14.2015).

Munro, G.R. (1979). “The optimal management of transboundary renewable resources”. *Canadian journal of Economics,* 12: 355-377.

Sydnor, T.D., M. Bumgardner and A. Todd, 2007. “The potential economic impacts of Emerald ash borer (*Agrilus planipennis*) on Ohio, U.S., Communities”. *Arboriculture & Urban Forestry,* 33(1):48–54.

Wilen, J., 2007. “Economics of spatial-dynamic processes”. *American journal of agricultural economics,* 98: 1134-1144.

Appendix 4.A Simulation results for bargaining with and without free-riding

Table 4.A1. Simulation results for bargaining with and without free-riding by private land owners in the infested municipality

Time periods (years)	First-best (base case)		Bargaining without free riding (base case)		Bargaining with free riding (base case, q=0.3)		Bargaining with free riding (q=0.4)		Bargaining with free riding (q=0.5)		Bargaining with free riding (q=0.7)	
	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)	p(t)	tau(t)
1	0.309	1.541	0.367	1.155	0.515	0.166	0.437	0.513	0.407	0.532	0.414	0.388
2	0.163	1.136	0.254	0.945	0.543	0.090	0.385	0.437	0.324	0.462	0.319	0.336
3	0.063	0.755	0.163	0.748	0.583	0.018	0.343	0.365	0.251	0.397	0.244	0.287
4	0.008	0.397	0.091	0.563	0.630	-	0.311	0.297	0.187	0.335	0.180	0.240
5	-	0.061	0.04	0.388	0.681	-	0.289	0.233	0.133	0.277	0.125	0.197
6	-	-	0.01	0.225	0.735	-	0.278	0.173	0.088	0.222	0.080	0.156
7	-	-	-	0.071	0.794	-	0.276	0.117	0.052	0.171	0.045	0.118
8	-	-	-	-	0.857	-	0.286	0.064	0.025	0.123	0.020	0.082
9	-	-	-	-	0.926	-	0.306	0.014	0.008	0.078	0.005	0.048
10	-	-	-	-	1	-	0.330	-	-	0.035	-	0.016
Transfer payments [a]		3.890		4.095		0.274		2.213		2.632		1.868
Net benefits, infested		10.486		10.892		2.660		4.860		5.809		6.805
Net benefits, uninfested		12.877		12.366		10.378		12.122		13.312		14.080
Total net benefits		23.363		23.258		13.038		16.983		19.121		20.885

[a] Transfer payments and social costs values are given in million dollars

Chapter 5

Conclusion

This dissertation focuses on the application of hedonic price models to estimate economic values of trees in private and public lands in urban residential areas, and application of bio-economic models to characterize the forest management decisions by local communities across the landscape in risk of bio-invasions. Novel research on these topics is presented in three essays in this dissertation. The first study is an external-meta analysis performed using data from previous hedonic studies. The novel aspect of this study is that it synthesizes previous results to provide general rules and to identify the determinants of the tree cover value in residential areas. The second study extends the analysis of tree cover values and home owner preferences for tree cover by estimating the hedonic models using high resolution data from multiple study locations across the U.S. The third study develops a dynamic bargaining model to study how two neighboring communities with mixed land ownership cooperatively control an invasion from a forest pest.

Chapter 2 uses implicit price data from previous hedonic study in various locations in U.S. to evaluate the relationship between the implicit price of tree cover and the amount of tree cover at property-level and in county-level, and other location-specific factors that may affect home owner's preference for tree cover. Going beyond the traditional meta-analyses, this study augments the analysis by incorporating auxiliary data at county-level so that more accurate and informative estimates can be obtained. The study concludes that tree cover in both landscape matrixes adds value to properties implying that home owners consider trees as an amenity. However, the implicit price changes non-linearly with the quantity of tree cover and the effects are different in vicinity and in general area (county-level). The study shows that a tree cover of about 30 percent on property and within 1km from property and a county level tree cover of 38 percent maximize the property values suggesting home owners may prefer less tree cover on or near property than in broader landscape.

This meta-analysis assumes that preference for tree cover on or near property are constant across the neighborhood of 1km at residential property. However, previous studies prove otherwise. They found preference for trees have a spatial variation even within 1km. Chapter 3 attempts to study this heterogeneity so that more informative estimates can be obtained. This is achieved by evaluating the tree cover at 3 different buffer areas of 0-100m, 101-500m and 501-1000m distance from each property. Similar datasets and methods were used to estimate price equations in multiple study areas which makes it possible to summarize study-specific estimates using an internal-meta analysis. This study's findings confirm that trees within 1km of property have a positive effect on property values and the effects are non-linear. In contrast to the assumption of constant preferences across landscapes, this study suggests they do vary within three buffer areas evaluated within the 1km neighborhood. These refined results, in fact, are useful to evaluate how changes of tree cover in urban areas impact its residents.

Implicit price estimates obtained in Chapter 2 provides opportunities for future studies to explore more on these topics. Results from this study indicate that each property markets we considered are unique, well-defined being geographically segregated and implicit prices vary across the study locations. Therefore, a second-stage hedonic property model is feasible to estimate using this data to estimate demand for tree cover. These parameters can be used to estimate the welfare effects associated with non-marginal changes of tree cover in in urban communities due to development, wildfire and forest pest invasions. Further, the meta-analysis in Chapter 2 suggest that the optimal tree cover estimates in that study are sensitive to the data obtained from the original studies, thus the meta-analysis results should be interpreted as preliminary and with caution. It recommends to add spatial breadth and location-specific depth of implicit price estimates to confirm its findings by merging data from more studies. Implicit price estimates results presented for multiple study locations in Chapter 3 can be used in a future study to improve on the meta-analysis.

Chapter 4 applies concepts of game theory to analyze how public land managers cooperatively control an invasion in community forests via a dynamic bargaining model. Novelty of this study comes from the evaluation of how availability of public lands within the municipality affects the efficacy of control by the local governments and thereby the bargaining outcome. This model assesses how an infested municipality and an uninfested municipality with multiple land ownerships bargain over a transfer payment to induce greater control by the infested municipality in public lands so that the infestations does not spread to the other. There are several interesting results from this study. It finds that the composition public and private land within the local jurisdictions indeed affects the cooperative control. Further, local governments with more public lands or higher accessibility to private lands are more likely to commit to bargaining however smaller transfer payments paid over longer time span are required to induce greater control.

Overall, this dissertation studies several important issues related to urban forest resources and provide new insights for future forest management in urban communities.